Search for $^6_\Lambda H$ hypernucleus by the $(\pi^-, K^+)$ reaction at J-PARC

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Abstract. We have carried out an experiment to produce the neutron-rich hypernucleus $^6_\Lambda H$ by the $(\pi^-, K^+)$ 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 $\Lambda$ binding energy of the hypernucleus, we also measured the $^{12}\mathrm{C}(\pi^+, K^+)^{13}_\Lambda \mathrm{C}$, $p(\pi^-, K^+)\Sigma^-$ and $p(\pi^+, K^+)\Sigma^+$ reactions. The experiment was performed at the K1.8 beam line of J-PARC Hadron Experimental Facility. The overall collected data sample corresponds to an integrated beam intensity of $1.4 \times 10^{12}$ pions.

1. Introduction
One of the most important topics in strangeness nuclear physics is the study of neutron-rich $\Lambda$ hypernuclei [1, 2]. It is expected that a $\Lambda$ 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 $\Lambda N-\Sigma N$ coupling can resolve the over binding problem in $^5_\Lambda \mathrm{He}$ [6] and that such a coupling is enhanced in a neutron-excess environment.

2. Spectroscopy of $\Lambda$ hypernuclei
One of the important subjects in studying $\Lambda$ hypernuclei in the past was the precise measurements of the level structures of the $\Lambda$ hypernuclei, which made possible to discuss the underlying hyperon-nucleon strong interaction. The similarity of the $\Lambda$ hyperon with the nucleon is one of the key properties which brings the rich spectra of $\Lambda$ hypernuclei. Another important property is the additional binding energy due to the $\Lambda$ 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 $(K^-, \pi^-)$ and the $(\pi^+, K^+)$ reactions to produce $\Lambda$ hypernuclei. Figure 1(b) shows the hypernuclei which have ever produced in the $\Lambda \leq 15$ region: purple colored ones were directly produced via the $(K^-, \pi^-)$ and the $(\pi^+, K^+)$ 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 \((K^-,\pi^+)\) and \((\pi^-,K^+)\) reactions.

![Hypernuclear chart](image)

**Figure 1.** (a) chart of light ordinary nuclei. (b) chart of Λ hypernuclei ever produced in the \(A \leq 15\) region. Purple boxes correspond to directly produced hypernuclei via the \((K^-,\pi^-)\) and \((\pi^+,K^+)\) 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 \((K^-,\pi^+)\) and \((\pi^-,K^+)\) reactions on stable targets.

3. Study of double charge-exchange reactions
3.1. \((K^-_{\text{stopped}},\pi^+)\) reaction
A pilot experiment aiming to produce Λ hypernuclei was performed at KEK-PS by using the \((K^-_{\text{stopped}},\pi^+)\) reaction [7]. In that experiment, only upper limits were obtained for the production rate of neutron-rich Λ hypernuclei \({}^6\Lambda\text{He}, {}^{12}\Lambda\text{Be}\) and \({}^{16}\Lambda\text{C}\) 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 \({}^6\Lambda\text{He}, {}^7\Lambda\text{H}, {}^9\Lambda\text{He}\) and \({}^{12}\Lambda\text{Be}\) hypernuclei by the FINUDA Collaboration at Frascati-DAΦNE [8, 9]: they claimed the observation of 3 events of \({}^6\Lambda\text{H}\) hypernuclei and their mesonic weak decays [10].

3.2. \((\pi^-,K^+)\) reaction
Another promising DCX reaction to produce the neutron-rich Λ hypernuclei is the \((\pi^-,K^+)\) reaction. An attempt to produce the neutron-rich Λ hypernucleus \(^{10}\Lambda\text{Li}\) was carried out at KEK-PS by exploiting the \((\pi^-,K^+)\) 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 \(^{10}\text{B}(\pi^-,K^+)\) reaction. The production cross section of the \(^{10}\Lambda\text{Li}\) hypernucleus was estimated to be very small (\(\sim 10\) nb/sr), roughly \(10^{-3}\) of that of the \((\pi^+,K^+)\) reaction (typically \(10\) \(\mu\)b/sr). Compared with the \((K^-_{\text{stopped}},\pi^+)\) reaction, the \((\pi^-,K^+)\) reaction is almost background free in the Λ bound region.

4. J-PARC E10 experiment
The J-PARC E10 experiment was proposed to produce the neutron-rich Λ-hypernucleus \(^8\Lambda\text{H}\) by using the \(^6\text{Li}(\pi^-,K^+)\) reaction at 1.2 GeV/c and to study its structure. The experiment was performed at the K1.8 beam line of the J-PARC Hadron Experimental Facility. The K1.8 beam line spectrometer and the Superconducting Kaon Spectrometer (SKS) were used. Fig. 2 shows the K1.8 beam line and the SKS spectrometers.
The K1.8 beam line spectrometer consists of a gas Čerenkov counter (GC), a scintillating fiber tracker (BFT), QQDQQ magnets, two drift chambers (BC3 and BC4) and a timing plastic scintillation hodoscope (BH2).

The SKS spectrometer consists of a scintillating fiber tracker (SFT), three drift chambers (SDC2, SDC3 and SDC4), a superconducting magnet, a timing plastic scintillator hodoscope (TOF) and two threshold type Čerenkov counters (LAC and LC).

An enriched $^{6}\text{Li}$ target (95.54%) of 3.5 g/cm$^2$ in thickness, 70 mm in width and 40 mm in height was used. To reconstruct the reaction vertex point precisely and to find the right combination of upstream and downstream tracks for multi-track events, silicon strip detectors (SSD) were installed just upstream of the target.

5. Results
Table 1 shows a run summary of the 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 $\Sigma^-$ and $\Sigma^+$ production reactions from hydrogen on a (CH$_2$)$_n$ target at a beam momentum of 1.37 GeV/c. By using this way, we could calibrate momenta measured by the beam line spectrometer and SKS with a systematic error of 1.34 MeV/c. The $\pi$ beam intensity at the target position was typically $4.1 \times 10^6$/spill (2.0 s spill length) for the $^{12}\text{C}(\pi^+, K^+)^{12}\Lambda$C and the $p(\pi^+, K^+)\Sigma^+$ reactions and $1.3 \times 10^7$/spill for the $p(\pi^-, K^+)\Sigma^-$ and the $^6\text{Li}(\pi^-, K^+)^6\text{H}$ 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 $^6\text{Li}$ 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 and the SKS spectrometers.
Table 1. Run Summary of the J-PARC E10 experiment

| reaction                   | momentum (GeV/c) | intensity (/spill) | time (hour) |
|----------------------------|------------------|--------------------|-------------|
| $^{12}$C($\pi^+, K^+$)$_\Lambda^{12}$C | 1.2              | $4.1 \times 10^6$  | 24          |
| $p(\pi^-, K^+)\Sigma^-$       | 1.37             | $1.3 \times 10^7$  | 4           |
| $p(\pi^+, K^+)\Sigma^+$        | 1.37             | $3.5 \times 10^6$  | 1           |
| beam-through                | 0.8, 0.9, 1.0, 1.2 | ~$10^4$            | 2           |
| $^6$Li($\pi^-, K^+$)$_\Lambda^6$H | 1.2              | $1.2-1.4 \times 10^7$ | 276         |

Figure 3. Excitation energy spectrum of the $^{12}$C($\pi^+, K^+$)$_\Lambda^{12}$C reaction at the beam momentum of 1.2 GeV/c. The ground ($s_\Lambda$) and excited ($p_\Lambda$) states are clearly observed. The missing-mass resolution is estimated by fitting the ground and known excited states. The dashed curves show the best fit Gaussian functions for these states and the solid curve is the sum.

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($\pi^-, K^+$) reaction. As the final result, the number of pions delivered to the experiment reached $1.4 \times 10^{12}$ taking into account the DAQ efficiency.

Figure 3 shows the excitation energy spectrum of the ($\pi^+, K^+$) reaction on the graphite target. The ground ($s_\Lambda$) and excited ($p_\Lambda$) states of the $^{12}$C hypernucleus are clearly observed. The ground state region is fitted with three Gaussian functions corresponding to the ground and to known excited states at 2.833 and 6.050 MeV[12]. A same width of the Gaussian function is used for the three states. The missing-mass resolution is estimated to be 3.2 MeV (FWHM).

Figure 4 shows the missing-mass spectrum of the $^6$Li($\pi^-, K^+$) reaction. The vertical axis shows the double differential cross section in the laboratory frame averaged over the scattering angle from $2^\circ$ to $14^\circ$, $d^2\sigma_{lab}/d\Omega/dM$ in a unit of nb/sr/(MeV/c$^2$). The scattering angle region has small ambiguity in spectrometer acceptance. The continuum of the unbound $\Lambda$ formation reaction and the component of the $\Sigma^-$ quasi-free production reaction are observed in the missing-mass regions of 5810–5880 MeV/c$^2$ and above 5880 MeV/c$^2$, respectively. A magnified view in the missing-mass range of 5795–5830 MeV/c$^2$ is shown in the inset. Around the $^4$H+2$n$ particle decay threshold indicated by the arrow (5801.7 MeV/c$^2$), no significant peak structure is observed.

There were 3 events in bound region with missing-mass window of 5.4 MeV which range is $2\sigma$ of the mass resolution of $^{12}$C. An upper limit was estimated by using the Poisson statistics. We employ upper limit of 6.68 events at a 90% confidence level coming from the background free hypothesis as a conservative estimation. As shown in Fig. 4, the differential cross sections were 0.18 nb/sr for 1 event. By using this value, the upper limit of the differential cross section averaged in the scattering angle from $2^\circ$ to $14^\circ$ is estimated to be 1.2 nb/sr at a 90% confidence level.
6. Discussion

In our spectrum, neither significant peak structure nor a large yield is observed around the $^4\Lambda H + 2n$ particle decay threshold. The $^6\Lambda H$ hypernucleus is believed to have the $^4\Lambda H + 2n$ structure dominantly and have the $0^+$ ground and the $1^+$ excited states which are analogous to the $0^+$ and $1^+$ spin-doublets in $^4\Lambda H$. Our reaction should favor the $1^+$ state direct population at forward angles, because the dominant spin non-flip amplitude of the $(\pi^-, K^+)$ reaction would not change the spin of $^4\Lambda H$ with the same spin of $^6\Lambda Li$. As far as the FINUDA result is concerned, the observed $^6\Lambda H$ candidate events were interpreted as the primary population of the excited $1^+$ state by the $(K_{\text{stopped}}, \pi^+)$ reaction followed by the $\gamma$-ray transition to the ground $0^+$ state because the direct population of the $0^+$ state should be suppressed due to the small spin-flip amplitude in the $(K_{\text{stopped}}, \pi^+)$ reaction. The FINUDA results indicate that the excited $1^+$ state, whose excitation energy is considered to be about 1 MeV, should be particle bound, otherwise the $\gamma$-ray transition to the $0^+$ ground state should be impossible. If the $1^+$ state was bound and the production cross section was comparable with that for $^6\Lambda Li$ of 11.3 nb/sr, more than 60 events should be observed as a peak in the $\Lambda$ bound region. Therefore, our observation is in conflict with the FINUDA observation.

The FINUDA collaboration also discussed another scenario for the spectrum of $^6\Lambda H$ in which two out of the three candidate events came from the population of the spin-triplet states, $1^+$, $2^+$, and $3^+$, at around 3 MeV excitation [13]. With this scenario, it is interesting to compare our upper limit, 1.2 nb/sr, with quantitative theoretical estimations of the production cross sections because the cross sections are sensitive to the binding energies and the wave-functions of the low-lying states.

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