The result of search for $^6\Lambda H$ via the $^6\text{Li}(\pi^-, K^+)$ reaction in J-PARC E10

Outline

- Introduction
- J-PARC E10 experiment
- Latest analysis result
- Summary

Ryotaro Honda
(Osaka University.)
For the J-PARC E10 collaboration.
Hyperon mixing in inner core of neutron star.


Possible internal structures of neutron star
Large contribution of $\Lambda N-\Sigma N$ mixing is expected

- B.F. Gibson et al. PR C6 (1972) 741

- Large overlap in nucleon part only if $N \neq Z$ ($I_{\text{core}} \neq 0$)
  Pauli blocking may be small

How large $\Lambda N-\Sigma N$ mixing in neutron-rich $\Lambda$ hypernuclei?
Physics motivation – $^6_{\Lambda}H$ neutron-rich hypernucleus

Production of the extremely neutron-rich hypernuclei.
- The glue like role of the $\Lambda$ particle in nuclei could stabilize the unbound $^5H$ system.

$\Lambda$-$\Sigma$ mixing in the neutron-excess environment.
- The coupling effect is expected to be enhanced in the neutron-excess environment by summed up coherently.

Variety of experimental results

$^5H + \Lambda$

$t + 2n + \Lambda$

$^4_{\Lambda}H + 2n$

$^6_{\Lambda}H$

Bound state exists?
How deeply bound?
$^6\Lambda H$ search by FINUDA collaboration

$^6\text{Li}(K_{\text{stop}}^-, \pi^+) \Lambda H \rightarrow ^6\text{He} + \pi^-$

FINUDA: M. Agnello et al. PRL 108 (2012) 042501
- Study of the $^6\text{Li}(K_{\text{stop}}^-, \pi^+)$ reaction

Cut on kinetic energy sum consistent with kinematics

One to one correspondence to missing-mass of $^6\text{Li}(K_{\text{stop}}^-, \pi^+)X$

Three candidates of $^6\Lambda H$
Present theoretical expectation and result

$[\text{MeV}] \ t + 2n + \Lambda$

$0.0$

-0.9 $\rightarrow$ Hiyama [4]

$-2.0$

$4^\Lambda H + 2n$

-2.5 $\rightarrow$ Dalitz, Majling [1]

-2.8 $\rightarrow$ Gal and Millener [2]

-4.1 $\rightarrow$ Akaishi and Yamazaki [3]

$6^\Lambda H$

Global mean of FINUDA result

-2.3

J-PARC E10 experiment
J-PARC E10 Experiment

Missing mass spectroscopy at J-PARC K1.8 carried out in 2012 and 2013

The $^6\text{Li}(\pi^-, K^+)X$ reaction @ 1.2 GeV/c with $^6\text{Li}$ target (3.5 g/cm$^2$, 95.54% enriched).

**Expected production cross section of $^6\Lambda\text{H}$ hypernucleus.**
- 10 nb/sr. (From KEK-PS E521)

A large number of pion beams ($3 \times 10^{12}$) using 10 M/spill beam (spill length = 2 s.)
## Data summary

<table>
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<th>Reaction</th>
<th>Beam mom (GeV/c)</th>
<th>Target</th>
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<td>Production run</td>
<td>(π⁻, K⁺)</td>
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<td>¹²ΛC production</td>
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<td>Σ⁻ production</td>
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</tr>
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### Production run

- Finally, the effective number of pions were $1.4 \times 10^{12}$ in 13 days beam time using 10 - 12 M/spill beam.

### ¹²ΛC production

- Estimate missing-mass resolution.

### Σ⁺⁻ production

- Calibrate momentum.
- Confirm correctness of our analysis by comparing with the past experimental data.
$\Sigma^−/\Sigma^+$ analysis

Missing mass spectrum of $\pi^\pm + p \rightarrow K^+ + X$ reactions

Beam and scattered particles momenta were calibrated by masses of $\Sigma^\pm$. Present missing-mass uncertainty around bound state of $^6\Lambda H$ was 350 keV/c²
The spectrum was fitted by 3 Gaussian functions.

**Missing mass resolution**
- $2.9 \pm 0.2$ MeV (FWHM)

The bound state of $^6\Lambda$H was searched with this missing mass resolution.
Latest analysis results of production run
$^6$Li(\(\pi^-, K^+\)) event selection

\(\pi^-\) beam selection
- Beam \(\pi^-\) were already well separated by double ESSs in the K1.8 beam line.

\(K^+\) selection
- \(M^2\) distribution
- \(dE/dx\) distribution of TOF counter

Vertex selection

Actual target thickness ± 5 mm were selected as $^6$Li target.
$^6\text{Li}(\pi, K^+)$ event selection

**M^2 distribution of scattered particles**

![Graph showing M^2 distribution for scattered particles with low and high momentum regions.]

- **(a)** $\pi$ K Low momentum region
- **(b)** High momentum region (Including bound region)

**dE/dx distribution of TOF counter**

- **Red events were selected by M^2.**
- **dE/dx were selected according to blue lines.**
Production cross section of $^6\text{Li}(\pi^-, K^+)X$ reaction

No event was seen below the $^4\Lambda\text{H}+2n$ threshold

Upper limit
0.56 nb/sr (90% C.L.)
The last event we observed was roughly 4 MeV far from the FINUDA result.

The present upper limit was 20 times smaller than our expectation. Quite difficult to produce the $^6\Lambda\text{H}$ hypernucleus by this experimental method.

On the other hand, several events were seen between $^4\Lambda\text{H}+2n$ and $p+4n+\Lambda$ threshold. Some excited states may exist, but at least 10 times statistics is necessary to observe them.
Summary

• The J-PARC E10 experiment was proposed to produce the quite neutron-rich $\Lambda$ hypernuclei, in which the property of the $\Lambda N$ ($\Lambda NN$) interaction should be enhanced, via the ($\pi^-$, $K^+$) reaction.

• The E10 experiment was carried out in 2012 and 2013. The $^6$Li target (3.5 g/cm$^2$, 95.54% enriched) was irradiated with the $1.4 \times 10^{12}$ pion beams in total.

• We searched the $^6\Lambda H$ bound state with the missing-mass resolution of 2.9 MeV/c$^2$ (FWHM) and the missing-mass scale uncertainty of 350 keV/c$^2$.

• We obtained upper limit of 0.56 nb/sr (90% C.L).
• This is roughly 20 times smaller than our expectation.
Back up
Production via the double-charge exchange reaction

The KEK-PS E521 experiment

$^{10}_A$Li production via the $^{10}$B($\pi^-$, $K^+$)X reaction at 1.05 and 1.20 GeV/c.

The ($\pi^-$, $K^+$) reaction is suitable to produce the hypernuclei with quite small cross section because of its back ground free property.

The production of the neutron-rich hypernucleus was observed, but no peak was seen.

Integrated cross section of bound region

$11.3 \pm 1.9$ nb/sr

$^{12}_\Lambda C$ analysis

Relative cross section base
$^{12}_\Lambda C$ spectrum

Count base
$^{12}_\Lambda C$ spectrum
\[\Sigma^+\] production data

\[6\text{Li}\] data

(a) Pion

(b) Kaon

(c) Proton

(d) Pion

(e) Kaon

(f) Proton
Angular distribution of \( \Sigma^- \) production (2 – 14 deg (Lab.))

Angular distribution of \( \Sigma^+ \) production (2 – 14 deg (Lab.))

Preliminary
Reduce BG events using fiber tracker

Timing difference between BH2 and SFT

Since this is almost beam TOF between BH2 and SFT, it should make one peak.

2\textsuperscript{nd} peak over 2 ns was made due to the wrong BH2 timing.

Timing information between the time0 counter and the fiber tracker.
Count base missing-mass spectrum

Back ground level
0.39 counts/(MeV/c²) (PLB result)

0.07 counts/(MeV/c²) (Present)
Last analysis result

H. Sugimura et al., PLB 729 (2014) 39-44

No peak structure.
Only 3 events around the $^4_Λ\Lambda H + 2n$ mass threshold.

Upper limit : $1.2 \text{ nb/sr (90\% C.L.)}$

It was not concluded that these events were really whether signal or background.

Improvements in the latest analysis.
- Missing mass resolution
  - To set the narrower integral region if events are remained.
- Background level
  - To confirm these events are signal or background.