Study of $\Lambda$ hypernuclei close to neutron drip-line

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for the J-PARC E10 Collaboration
Some properties of $\Lambda$ hypernuclei

- Property 1: "glue-like role" of $\Lambda$ hyperon
- Some examples of the "glue" effect

$\Lambda$ hyperon plays "glue-like role" attractive $\Lambda N$ interaction
$\Lambda$ is free from Pauli blocking

these diagrams show the "glue" effect is a general phenomenon in $\Lambda$ hypernuclei

boundary of stability of nuclei may be extended by the "glue" effect
Property 2: effect of “$\Lambda N-\Sigma N$ mixing”

- Discussed by Gibson, Goldberg and Weiss in 1972
  - mixing could be large due to relatively small energy gaps in hypernuclei

$m(\Delta N) - m(NN) \approx 293$ MeV/c$^2$

$m(\Sigma^- p) - m(\Lambda n) \approx 80.5$ MeV/c$^2$
$m(\Sigma^0 N) - m(\Lambda N) \approx 77.0$ MeV/c$^2$
$m(\Sigma^+ n) - m(\Lambda p) \approx 75.0$ MeV/c$^2$

- Quantitative discussions made only for several hypernuclei
  - $A=3-5$ ($^4\Lambda H$, $^4\Lambda He$ and $^5\Lambda He$), $Z=5$ ($^{10}\Lambda B$ and $^{11}\Lambda B$)
- “$\Lambda N-\Sigma N$ mixing” is also general phenomenon
- Non-zero isospin of core nucleus is essential in mixing
- Studies of mixing effect in neutron-rich hypernuclei are inevitable to understand properties of the mixing effect
ΛN-ΣN mixing effect in detail

- Different shells contribute differently to the mixing
  - $\Lambda(\Sigma)$ is in s-shell for low-lying states
  - Nucleons are in s-shell and higher-shells

- s-shell and higher-shell contributions may be different, and we wish to separate these contributions if possible

- Separation may be possible by neutron-rich hypernuclei
  - Pure s-shell: s-shell hypernuclei (e.g., $^4_Λ$H and $^4_Λ$He)
  - Pure p-shell: p-shell neutron-rich hypernuclei (e.g., $^9_Λ$He)
  - Interplay: s-shell neutron-rich hypernuclei (e.g., $^6_Λ$H)
Aims of J-PARC E10 experiment

- **Aim 1**: extend boundary of stability of nuclei
  - Planning to produce $^6_\Lambda H$ and $^9_\Lambda He$

We wish to produce these hypernuclei close to neutron drip-line
Aim 2: investigation of $\Lambda N-\Sigma N$ mixing

- Precise measurement of binding energy of $^6\Lambda H$

Suggestion of the calculation

Normal $\Lambda N$ interaction
$B_\Lambda \sim 4.4$ MeV

Coherent $\Lambda N-\Sigma N$ mixing
$B_\Lambda \sim 4.4 + 1.4$ MeV

Difference is considerably large experimentally accessible

Our basic idea

Precise measurement of B.E. → estimate mixing effect
How to produce n-rich hypernuclei?

- Use double charge-exchange (DCX) reactions
  - Category of reactions to produce $\Lambda$ hypernuclei
    - NCX: $(\pi^+, K^+)$ and $(K^-, \pi^-)$ reactions
    - SCX: $(e, e'K^+)$, $(\pi^-, K_S)$, $(K^-, \pi^0)$ reactions, etc.
    - DCX: $(\pi^-, K^+)$ and $(K^-, \pi^+)$ reactions

\[
\pi^- + p + p \rightarrow K^+ + \Lambda + n
\]

The reaction has two-step nature tiny cross section, $\sim 1/1000$ of NCX

DCX reaction

\[
\pi^- + p + p \rightarrow K^+ + \Lambda + n
\]
Previous experiments with DCX

- Experiments by the \textbf{(stopped-}K^{-},\pi^{+})\textbf{) reaction}

  - \textbf{KEK-PS:} K. Kubota et al. NP A602 (1996) 327
    - \textbf{Upper-limits} of BR(DCX) for $^9\Lambda\text{He}$, $^{12}\Lambda\text{Be}$ and $^{16}\Lambda\text{C}$
    - \textbf{Upper-limits} of BR(DCX) for $^6\Lambda\text{H}$ and $^7\Lambda\text{H}$
  - \textbf{FINUDA:} M. Agnello et al. PRL 108 (2012) 042501
    - observation of \textbf{3 candidate events} of $^6\Lambda\text{H}$ bound state
    - $\text{BR(DCX) / BR(NCX,}^{12}\Lambda\text{C)} \sim 3\times10^{-3}$

- Confirmation and precise determination of mass (or binding energy) are necessary in E10 experiment

- Experiments by the \textbf{(}\pi^{-},K^{+}\textbf{) reaction}

  - \textbf{KEK E521:} S. Pranab et al. PRL 94 (2005) 052501
    - \textbf{Pilot experiment} for J-PARC E10 experiment
KEK E521 experiment

- Demonstrated production of n-rich hypernuclei by DCX
- Measured the $^{10}\text{B}(\pi^-,\text{K}^+)^{10\Lambda}\text{Li}$ reaction
  - core nucleus $^9\text{Li}$ is bound, we are sure $^{10\Lambda}\text{Li}$ is well bound
  - good hypernucleus to evaluate DCX reaction

We wish to extend study at J-PARC

high intensity pion beams to override tiny cross section

- clear population in the $\Lambda$ bound region
- almost no event in $B_\Lambda>15\text{MeV}$ region
  - the $(\pi^-,\text{K}^+)$ reaction is very clean

$B_\Lambda=0$
Experimental Setup of E10

- **K1.8 beam line in hadron-hall of J-PARC 50GeV PS**

- **1.2GeV/c pion beams, typical intensity ~10M/spill**
- **Momentum resolution of beam line \( \frac{dp}{p} \approx 3 \times 10^{-4} \)**
Detector upgrades for higher beam intensity

- 5M pion/spill $\rightarrow \sim 10M$ pion/spill

K1.8 beam line spectrometer

1mm fiber tracker (ready)

Fiber tracker (new)

Upgrades are in progress
BFT (beam fiber tracker) design

- **1mm φ scintillating fibers**
  - 2 layers staggered by 0.5mm
  - $160 \times 2 = 320$ fibers
- **Read out**
  - MPPC+EASIROC
  - Flexible and easy to handle

Developed by K. Miwa, S. Hasegawa and R. Honda (Tohoku Univ. and JAEA)
• SKS for kaon measurement
  • Mom. resolution $dp/p \sim 10^{-3}$
  • Large acceptance $\sim 100\text{msr}$
  • Moved KEK $\rightarrow$ J-PARC

• Detector upgrades done

**SKS @KEK-PS K6**

**SKS @J-PARC K1.8**

January 2010 before earthquake (photo by K. Tanaka)

tracking and trigger detectors were enlarged to make momentum acceptance wider
Prospects of E10 experiment

- $^6_\Lambda$H production run in Dec. and Jan. (E10 1st phase)
- E10 run conditions and expected yields

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion beam momentum</td>
<td>1.2 GeV/c</td>
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<tr>
<td>Pion beam intensity</td>
<td>10 M/spill</td>
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<tr>
<td>Total number of pions (run for 3 weeks)</td>
<td>3T pions</td>
</tr>
<tr>
<td>Target thickness ($^6\text{Li}$)</td>
<td>3.5 g/cm²</td>
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<td>DCX cross section (assumed)</td>
<td>10 nb/sr</td>
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<tr>
<td>SKS acceptance</td>
<td>100 msr</td>
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<tr>
<td>Spectrometer efficiency</td>
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<tr>
<td>Analysis efficiency</td>
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<tr>
<td>Estimated $^6_\Lambda$H yield</td>
<td>265</td>
</tr>
</tbody>
</table>

- About 6 times larger yields than KEK E521

*High intensity beams*

*Optimized for yield and resolution*

*Large acceptance*
Binding energy measurement

- Prospect of B.E. measurement of $^{6}_{\Lambda}H$

**Simulated Spectrum**

- 2.5 MeV (FWHM)
- g.s.
- $^{6}_{\Lambda}H$
- QF
- Ex (MeV)

**Assumptions**

- Missing-mass resolution
  - $\approx 2.5$ MeV (FWHM)
- $^{6}_{\Lambda}H$ yield
  - $\approx 300$ events
- $^{6}_{\Lambda}H/QF$ ratio (Ex $< 23$ MeV)
  - $\approx 1/10$
  - Estimated from $^{4}_{\Lambda}He$ and $^{10}_{\Lambda}Li$

- Peak is well separated from QF
- Statistical error of B.E. $< 0.1$ MeV
Summary

- Properties of $\Lambda$ hypernuclei
  - “glue-like role” of $\Lambda$ hyperon in hypernuclei
  - effect of “$\Lambda N-\Sigma N$ mixing”

- Aims of J-PARC E10 experiment
  - Extend the boundary of stability of nuclei by the “glue” effect
  - Estimate $\Lambda N-\Sigma N$ mixing from B.E. of neutron-rich hypernuclei
  - Produce neutron-rich hypernuclei: $^6_\Lambda H$ and $^9_\Lambda He$

- E10 prospects (E10 phase-1 in December and January)
  - 6 times larger yield than previous E521 experiment
  - precise measurement of B.E. of $^6_\Lambda H$ is possible