E10 experiment on neutron-rich hypernuclei

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J-PARC E10 collaboration


Politecnico di Torino, Pusan National University, RCNP, Tohoku University, KEK, Seoul National University, Osaka University, JINR, INFN, Kyoto University, Osaka Electro-Communication University, JAEA, BARC, Virginia Military Institute, RIKEN
Λ hypernuclei and ΛN interaction

- **Λ hypernucleus** and hypernuclear studies
  - System made of a Λ hyperon and a nucleus(A)
  - ΛN interaction strong enough to form a bound state
  - Properties of ΛN interaction were extensively studied by measurements of hypernuclear structures

- How far can we extend the hypernuclear chart?
  - Importance of “glue-like role” of Λ hyperon
  - ΛN interaction also stabilize host nucleus

- How about the ΛNN 3-body force?
  - Prediction of a strong ΛNN 3-body force
  - Force comes from ΛN-ΣN mixing process
Aims of J-PARC E10 experiment

- **Aim 1**: $\Lambda$ hypernuclei close to the neutron drip-line
  - E10 may produce highly neutron-rich $\Lambda$ hypernuclei
    - $^6\Lambda\mathrm{H}$ (1p, 4n and 1$\Lambda$), $^9\Lambda\mathrm{He}$ (2p, 6n and 1$\Lambda$)
  - Exotic hypernuclei we have never seen clearly
  - “glue-like role” of $\Lambda$ hyperon is critical in such loosely bound hypernuclei

- **Aim 2**: $\Lambda\Lambda$ interaction at the extreme condition
  - Effect of $\Lambda\Lambda$-$\Sigma\Lambda$ mixing or $\Lambda\Lambda\Lambda$ 3-body force may be observed in structures of neutron-rich hypernuclei
  - Neutron-rich $\Lambda$ hypernuclei are good laboratories to study these effects
**ΛN-ΣN Mixing and n-rich Λ Hypernuclei**

- Strong mixing of ΛN and ΣN pairs
  - B.F. Gibson et al. PR C6 (1972) 741

![Diagram showing mixing of ΛN and ΣN pairs](image)

- Overall conservation of isospin is required.
- Nucleus is a buffer of isospin.
- Larger mixing in host nucleus with larger $I_A$.

**How large mixing in n-rich hypernuclei?**

**BB spectrum**
Mixing and n-rich hypernucleus $^6_{\Lambda}H$

- Possible observation of mixing effect in $^6_{\Lambda}H$ structure

**Prediction of Akaishi and Yamazaki**

- Normal $\Lambda N$ interaction ("glue" effect)
  \[ B_{\Lambda} \sim 4.4 \text{ MeV} \]
- Coherent $\Lambda N$-$\Sigma N$ mixing
  \[ B_{\Lambda} \sim 4.4 + 1.4 \text{ MeV} \]

**Prediction of Gal and Millener**

- Coherent $\Lambda N$-$\Sigma N$ mixing
  \[ \Delta B_{\Lambda N-\Sigma N} \sim 0.1 \text{ MeV} \]

Structure of $^6_{\Lambda}H$ should be investigated experimentally


Structure of $^6_{\Lambda}H$ hypernucleus

- FINUDA reported 3 candidate events of $^6_{\Lambda}H$ production
- Sensitive to $\Lambda N$ interaction and also properties of $^5H$

FINUDA data have ambiguities. Complementary measurement is awaited.
Studies of n-rich hypernuclei by DCX

- Experiments by the \((\text{stopped-K}^-,\pi^+)\) reaction
  - **FINUDA**: M. Agnello et al. PRL 108 (2012) 042501
  - reported 3 candidate events of \(^6_\Lambda\)H production
  - measured production and decay to reduce background
    \[ ^6\text{Li}(\text{stopped-K}^-,\pi^+)_{\Lambda}\text{H} \rightarrow ^6\text{He} + \pi^- \]
    \[ \text{BR}(\text{DCX},_{\Lambda}\text{H})/\text{BR}(\text{NCX}) \approx 2 \times 10^{-3} / \text{event} \]

- Experiment by the \((\pi^-,K^+)\) reaction
  - **KEK E521**: P.K. Saha et al. PRL 94 (2005) 052501
  - successfully produced \(^{10}_\Lambda\)Li
  - background free, only production was measured
    \[ \frac{d\sigma}{d\Omega}(\text{DCX},_{\Lambda}\text{Li}) \approx 10 \text{nb / sr} \]
    \[ \frac{d\sigma}{d\Omega}(\text{DCX}) / \frac{d\sigma}{d\Omega}(\text{NCX}) \approx 10^{-3} \]
Production of neutron-rich $\Lambda$ hypernuclei

- How to produce in E10?
  - Employ the double charge-exchange ($\pi^-, K^+$) reaction

$$\pi^- + p + p \rightarrow K^+ + \Lambda + n$$

$^6\text{Li} \left(\pi^-, K^+\right) ^6\Lambda\text{H}$

$Z=3 \quad \Delta Z=-2 \quad Z=1$

Challenge was the tiny production cross section

$\sim 10\text{nb/sr} \ ({}^{10}\Lambda\text{Li case})$

$\sim 1/1000$ of Non Charge-Exchange reaction

produce $^6\Lambda\text{H}$ as the phase-1 of E10
Design of E10 Experiment

- **Location in J-PARC 50GeV PS**
  - **K1.8 beam line** in Hadron-hall

- **Method**
  - **Missing mass spectroscopy** for the $^6\text{Li}(\pi^-, K^+)X$ reaction
    - **K1.8 beam line spectrometer**: $\pi^-$ beams at 1.2 GeV/c
    - **SKS spectrometer**: produced $K^+$ around 0.9 GeV/c
Setup of E10 experiment

- **K1.8 beam line spectrometer**
  - 1.2 GeV/c pion beams
  - **Tracking** of beam pions
    - Scintillating fiber tracker: BFT
    - Drift chambers (3mm wire pitch): BC3, BC4
    - 3rd order transfer matrix → \( \frac{dp}{p} \sim 3.3 \times 10^{-4} \)
- **Trigger** counters
  - Timing hodoscopes: BH1, BH2
- **Key issue in E10 experiment**
  - Handling of high rate pion beams
    - Typical beam rate: 12M - 14M/spill
Setup of E10 experiment

- **SKS spectrometer**
  - 0.9 GeV/c produced K^+

- **Tracking** of scattered particles
  - Scintillating fiber tracker: SFT
  - Drift chambers: SDC2, SDC3, SDC4
  - \(\frac{dp}{p} \sim 10^{-3}, \ d\Omega \sim 100 \text{ msr}\)

- **K^+ PID** made by time-of-flight BH2-TOF

- \((\pi^-, K^+)\) reaction vertex reconstruction
  - Silicon strip detector: SSD in front of the target

- **Targets** (~3.5 g/cm^2)
  - \(^6\text{Li}\) for production runs, C and \((\text{CH}_2)_n\) for calibrations
Run conditions proposed and achieved

- Used **high intensity pion beams** as proposed
- **50% beamtime**, analysis efficiency slightly lower

<table>
<thead>
<tr>
<th>Run conditions</th>
<th>Values</th>
<th>E10 proposal</th>
<th>E10 achievements</th>
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</thead>
<tbody>
<tr>
<td>Pion beam momentum</td>
<td>1.2 GeV/c</td>
<td>1.2 GeV/c</td>
<td>1.2 GeV/c</td>
</tr>
<tr>
<td>Pion beam intensity</td>
<td></td>
<td>10M/spill</td>
<td>12-14M/spill</td>
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<tr>
<td>Beamtime for production run</td>
<td>500 hours</td>
<td></td>
<td>240 hours</td>
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<tr>
<td>Total number of pions</td>
<td>3T pions</td>
<td></td>
<td>1.4T pions</td>
</tr>
<tr>
<td>Target thickness ($^6$Li)</td>
<td>3.5 g/cm$^2$</td>
<td></td>
<td>3.5 g/cm$^2$</td>
</tr>
<tr>
<td>DCX cross section (assumed)</td>
<td>10 nb/sr</td>
<td></td>
<td>10 nb/sr</td>
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<tr>
<td>SKS acceptance</td>
<td>100 msr</td>
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<td>100 msr</td>
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<tr>
<td>K decay loss</td>
<td>0.5</td>
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<td>0.5</td>
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<tr>
<td>Analysis efficiency</td>
<td>0.5</td>
<td></td>
<td>0.3</td>
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<tr>
<td>Estimated $^6\Lambda$H yield</td>
<td>265</td>
<td></td>
<td>90</td>
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Sensitivity: $\sim 0.1$ nb/sr
Calibration runs with $\Sigma^-$ and $\Sigma^+$

- **Momentum calibrations** of beam $\pi^-$ and scattered $K^+$
  - **Momentum adjusted**: $\Sigma^-$ and $\Sigma^+$ come to known mass
  - Cross section was compared with existing data

5 hours at 13M/spill

$p(\pi^-, K^+)\Sigma^-$

$p_{\text{beam}} = 1.37$ GeV/c

$\Delta M_X: 2.5\text{MeV (FWHM)}$

$\cos \theta_{\text{cm}} = 0.8 - 1.0$

$\frac{d\sigma}{d\Omega} [\text{nb/sr}]$

$\sigma_{\text{cm}}$ vs Beam Momentum [GeV/c]
Systematic error and resolution

- Beam through runs at 0.8, 0.9, 1.0 and 1.2 GeV/c
  - Systematic error of beam momentum was 1.34 MeV/c
  - Missing mass resolution was estimated by $^{12}_\Lambda C$

1 hour (8 settings)

13+6 hours at 4.1M/spill

$\pi^+$ beam through

$p_{K1.8}=0.9$ GeV/c

$^{12}_\Lambda C(\pi^+,K^+)X$

$^{12}_\Lambda C$ g.s.

$\Delta B_\Lambda$: 3.2 MeV (FWHM)

$\Delta p=p_{K1.8}-p_{SKS}$ [MeV/c]
Results of production runs

- Reaction vertex reconstruction
  - $^6$Li target (95.54% enriched) packaged in dry Ar-gas
    - thickness: $3.5\text{g/cm}^2(77\text{mm})$, cross section: $70^W \times 40^H \text{mm}^2$
  - Vertex reconstruction and $^6$Li target selection
    - cut values: $Z \ 77+40\text{mm}$, $X \ 70\text{mm}$, $Y \ 40\text{mm}$
Results of production runs (2)

- PID of scattered $K^+$ is very important
  - No physics background. Background from miss-PID.
  - Current background level $\sim 1/100$
  - Momentum dependent selection of Kaon ($2\sigma$ cut)

$^6\text{Li}(\pi^-,h^+)X$ ($\pi^-,K^+$) trigger, $p<1.1\text{GeV/c}$

\[ 6\text{Li}(\pi^-,h^+)X \]

\[ 2\sigma \text{ cut} \]
Results of production runs (3)

- Missing-mass spectrum of the $^6\text{Li}(\pi^-,K^+)X$ reaction
  - Systematic error of missing-mass 1.26 MeV/$c^2$
  - Tentative angle cut 2-14 degrees is applied
    - Same as KEK-E521 and SKS acceptance is well known

\[ ^6\text{Li}(\pi^-,K^+)X \], \( \theta_{\text{LAB}} = 2-14 \text{ deg.} \]

No clear peak of $^6\Lambda\text{H}$ production

Yield was extremely smaller than we expected
Results of production runs (4)

- Estimation of cross section upper-limit
  - Calculation of double differential cross section

\[ \frac{d\sigma}{d\Omega} \bigg|_{2^\circ-14^\circ} < 1.2 \text{ nb/sr} \ (90\% \ confidence \ level) \]

3 events around \(^4\Lambda\)H+2n threshold

Background due to miss-PID

\[ 0.39 \pm 0.05 \text{ event/(MeV/c}^2) \]

Expected number of background is \(~2\) events

1 event \(~0.18 \text{ nb/sr} \)
Short summary of current status

- **FINUDA data**
  - 3 candidate events: \( \text{BR}(DCX, {}_{\Lambda}^6H)/\text{BR}(NCX) \approx 6 \times 10^{-3} \)
  - Need reaction processes effective only for stopped-K\(^-\)
    - e.g. \( K^- pp \rightarrow \Lambda^* p(\Sigma^0 p) \rightarrow \pi^+ \Lambda n \) (just my personal guess)

- **E10 data**
  - Upper-limit for \( {}_{\Lambda}^6H \): \( \frac{d\sigma}{d\Omega}(DCX, {}_{\Lambda}^6H)/\frac{d\sigma}{d\Omega}(NCX) < 10^{-4} \)
  - Can we interpret the strong suppression by the reaction mechanism or by the structure of \( {}_{\Lambda}^6H \)?
  - Need theoretical estimations for further discussions.

- **E521 data**
  - \( {}_{\Lambda}^{10}\text{Li} \) cross section: \( \frac{d\sigma}{d\Omega}(DCX, {}_{\Lambda}^{10}\text{Li})/\frac{d\sigma}{d\Omega}(NCX) \approx 10^{-3} \)
Summary

- Phase-1 beamtime of J-PARC E10 experiment
  - Run at high beam intensity as proposed: 10M-12M/spill
  - 1.4 T pion beams on target (about 50% of proposal)
- All calibration runs were done ($\Sigma^\pm$ and $^{12}_\Lambda C$)
  - Systematic error of missing-mass scale is 1.26 MeV/c²
  - Missing-mass resolution is 3.2 MeV/c² (FWHM)
- Analysis of $^6_\Lambda H$ production data was done
  - No clear peak was observed in the threshold region
  - Cross section upper-limit is 1.2 nb/sr (90% C.L.)
  - Studies are still in progress to improve the sensitivity