Experimental study of double hypernuclei at J-PARC

Junya Yoshida (Advanced Science Research Center, JAEA)
On behalf of J-PARC E07 Collaboration
NAGARA, double $\Lambda$ hypernucleus (2001)

PHYSICAL REVIEW C 88, 014003 (2013)

$\Xi^- + ^{12}\text{C} \rightarrow _{\Lambda\Lambda}^6\text{He} + ^4\text{He} + t$

$^6\text{He} \rightarrow _\Lambda^5\text{He} + p + \pi^-$

$B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV

KISO, $\Xi$ hypernucleus (2013)

Prog. Theor. Exp. Phys. 2015, 033D02

$\Xi^- + ^{14}\text{N} \rightarrow _\Xi^{15}\text{C} \rightarrow _\Lambda^{10}\text{Be} + _\Lambda^5\text{He}$

$\rightarrow _\Lambda^{10}\text{Be}^* + _\Lambda^5\text{He}$

$B_{\Xi^-} = 1.03 \pm 0.18$ or $3.87 \pm 0.21$ MeV

Potential in a nucleus
Photographic emulsion sheet for double strangeness nuclei

* Thick sheets: Thickness =~1 mm -> ~0.5 mm (after photographic development)
* Optical microscope with computer controlled stage and digital image sensor
Focal depth: 6 μm, equal to 18 μm before dev.

Emulsion sheet for E07

Thickness: 1.0 mm → 0.6 mm after dev.

Under 20x objective lens
Focal depth: 6 μm, equal to 18 μm before dev.

Thickness: 1.0 mm → 0.6 mm after dev.
Focal depth: 6 μm, equal to 18 μm before dev.

Thickness: 1.0 mm → 0.6 mm after dev.

Emulsion sheet for E07

Under 20x objective lens
Under 20x objective lens

Emulsion sheet for E07

Thickness : 1.0 mm → 0.6 mm after dev.

Focal depth: 6 μm, equal to 18 μm before dev.
Under 20x objective lens

Hypernuclei are observed as multiple vertex topology

Emulsion sheet for E07

Focal depth: 6 \( \mu \text{m} \), equal to 18 \( \mu \text{m} \) before dev.

Thickness: 1.0 mm \( \rightarrow \) 0.6 mm after dev.
Hybrid emulsion method

- Tagging $\Xi^-$ production by $K^+$ spectrometer
- Tracking the $\Xi^-$ with SSD-tracker
- Detecting the $\Xi^-$ track in the 1st emulsion sheet
- Detecting double hypernucleus at the endpoint of $\Xi^-$ track
KEK-PS E176  (1988-89)

* ~80 $\Xi^-$ stop events
* Existence of double Lambda hypernucleus has been confirmed


* At least ~650 $\Xi^-$ stop events
* NAGARA, KISO

J-PARC E07  (2016-17)

* ~10k $\Xi^-$ stop events
* Systematic study of $S=-2$ system
J-PARC E07
J-PARC Hadron hall K1.8 beamline

Diamond target
SSD
KURAMA Magnet
Spectrometer for outgoing K+
Emulsion module
Spectrometer for incoming K-
J-PARC Hadron hall K1.8 beamline

Emulsion cassette

SSD

Emulsion mover

Emulsion sheets

0.4 mm Thickness * 2
1.0 mm Thickness * 11

Air pressure

SUS 100 μm

Rubber sheet

O-ring

beam direction
"Emulsion mover" for J-PARC E07

\[ K^- \text{ beam } 1.8 \text{ GeV/c} \]

Beam size:
\[(\sigma_X, \sigma_Y) = \sim(10, 6) \text{ mm}\]

* Track density < \(10^6/\text{cm}^2\) (Observable limit)
* Sliding emulsion module spill by spill
* 6 hours / module
“Emulsion mover” for J-PARC E07

K^- beam 1.8 GeV/c
Beam size: 
(\sigma_X, \sigma_Y) = ~(10, 6) \text{ mm}

* Track density < 10^6/cm^2 (Observable limit)
* Sliding emulsion module spill by spill
* 6 hours / module
### Beam exposure

2016 May-Jun.
- KURAMA Commissioning: 5.0 days
- Physics: 4.9 days

2017 4/15 - 4/19 (44 kW)
- Emulsion exposure: 50 h
- Calibration: 19 h

2017 5/25 - 6/29 (10 - 37.5 kW)
- Emulsion exposure: 23.4 days
- Calibration: 8.5 h

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**Table:**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>42</td>
<td>260</td>
<td>81%</td>
<td>6.5</td>
<td>0.92</td>
<td>83%</td>
<td>18</td>
</tr>
<tr>
<td>2017</td>
<td>44</td>
<td>310</td>
<td>83%</td>
<td>5.6</td>
<td>1.0</td>
<td>84%</td>
<td>8</td>
</tr>
<tr>
<td>2017</td>
<td>37.5</td>
<td>280</td>
<td>82%</td>
<td>6.0</td>
<td>1.0</td>
<td>89%</td>
<td>78</td>
</tr>
<tr>
<td>2017</td>
<td>10 - 35</td>
<td>120 - 270</td>
<td>50% - 82%</td>
<td>6.5 – 9.0</td>
<td>0.52 – 1.0</td>
<td>89-92%</td>
<td>14</td>
</tr>
</tbody>
</table>

Jul. 1\(^{st}\) 2017, Run end photo @K1.8 counting room

118 emulsion modules * 13 emulsion sheets
Photographic processing: completed in Feb. 2018

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam Exposure</th>
<th>Photographic proc.</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2018</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **1st physics run**: 18 modules
- **2nd physics run**: 100 modules

**Photographic processing**: completed in Feb. 2018

**13 sheets * 118 modules**

**Hanger for photographic processing**

**Washing work after Photographic processing**
Track following for $\Xi^-$ stop event

- Disassembling
- Photographic developing

- ~440 predictions of $\Xi^-$ tracks per module

- Emulsion module (13 emulsion sheets)

- Volume for readout:
  - 0.4 mm Thin-type
  - $\sim(\pm 100 \mu m)^2$
  - 1.0 mm Thick-type

- Beam direction

Automated Track Following (Sample Movie)
https://youtu.be/3fiWl5tDx2U
### Found event list (2019 Aug.)

<table>
<thead>
<tr>
<th>Event Type</th>
<th>KEK-PS E373</th>
<th>J-PARC E07</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^-$ stop with nuclear fragment</td>
<td>430</td>
<td>1.8k</td>
</tr>
<tr>
<td>$S=-2$ system</td>
<td>9</td>
<td>30</td>
</tr>
</tbody>
</table>

#### 12 double Lambda events
![Images of double Lambda events](image1)

#### 11 twin events
![Images of twin events](image2)

#### 7 others
![Images of others](image3)

*Found on 2019/07/23*

*Found on 2019/08/06*
**Found event list (2019 Aug.)**

<table>
<thead>
<tr>
<th>Event Description</th>
<th>KEK-PS E373</th>
<th>J-PARC E07</th>
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<tr>
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<table>
<thead>
<tr>
<th>Event Category</th>
<th>KEK-PS E373</th>
<th>J-PARC E07</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 double Lambda events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 twin events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 others</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Examples of Event Types:**

- **MINO event**

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19
MINO event
ID: 22381499289376

Production of Double Lambda hypernucleus

\[
p + \Xi^- \rightarrow \Lambda + \Lambda + 28 \text{ MeV}
\]
How we identify the nuclides?

Step 1: Measurement of geometrical feature by image processing

By H. Ekawa
How we identify the nuclides?

Step 2: Evaluation of kinematic consistency for all possible cases.

Taking all possible combinations of nuclide for the parent and daughter particles.

<table>
<thead>
<tr>
<th>Type</th>
<th># of case</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daughters without strangeness</td>
<td>65</td>
<td>$\pi^-, p, d, t, ^3\text{He}, ^4\text{He}, ^4\text{He}, \ldots, ^{19}\text{B}, ^{19}\text{C}, ^{19}\text{N}, \text{or} ^{19}\text{O}$</td>
</tr>
<tr>
<td>Neutral particles</td>
<td>10</td>
<td>n, 2n, 3n, $\pi^0, \pi^0+n, \pi^0+2n, \Lambda, \Lambda+n, \Lambda+2n, \text{or none}$</td>
</tr>
<tr>
<td>Single $\Lambda$ hypernuclei</td>
<td>41</td>
<td>$^3\Lambda\text{H}, ^4\Lambda\text{H}, ^4\Lambda\text{He}, ^5\Lambda\text{He}, \ldots, ^{17}\Lambda\text{N}, \text{or} ^{18}\Lambda\text{N}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single-$\Lambda$ hypernucleus (#2)</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>$\chi^2$</th>
<th>Range (#9) [\mu m]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4$He</td>
<td></td>
<td></td>
<td>3He</td>
<td>p</td>
<td>$\pi^-$</td>
<td>33.1</td>
</tr>
<tr>
<td>$^5$He</td>
<td>3He</td>
<td>p</td>
<td>$\pi^-$</td>
<td>5.23</td>
<td>16.270</td>
<td></td>
</tr>
<tr>
<td>$^4$Li</td>
<td></td>
<td></td>
<td>$^6$Li</td>
<td>d</td>
<td>$\pi^-$</td>
<td>93.6</td>
</tr>
<tr>
<td>$^9$Li</td>
<td></td>
<td>7Li</td>
<td>$\pi^-$</td>
<td>105</td>
<td>10.660</td>
<td></td>
</tr>
</tbody>
</table>
\[ {^{16}\text{O}} + \Xi^- \rightarrow (\Lambda\Lambda\text{Be}, \Lambda\text{Be}, \Lambda\Lambda\Lambda\text{Be}) + ^4\text{He} + (t, d, p), \]
\[ \leftarrow ^5\Lambda\text{He} + (p, d, t) + p + x\pi, \]
\[ \leftarrow ^4\text{He} + p + \pi^-. \]

Possible interpretations

<table>
<thead>
<tr>
<th>Possible interpretations</th>
<th>B_{\Lambda\Lambda} [MeV]</th>
<th>kinematic fitting $\chi^2$ (DOF=3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^- + ^{16}\text{O} \rightarrow \Lambda\Lambda\Lambda\text{Be} + ^4\text{He} + t$</td>
<td>15.05 +- 0.11</td>
<td>11.5</td>
</tr>
<tr>
<td>$\Xi^- + ^{16}\text{O} \rightarrow \Lambda\Lambda\Lambda\text{Be} + ^4\text{He} + d$</td>
<td>19.07 +- 0.11</td>
<td>7.3</td>
</tr>
<tr>
<td>$\Xi^- + ^{16}\text{O} \rightarrow \Lambda\Lambda\Lambda\text{Be}^* + ^4\text{He} + p$</td>
<td>13.68 +- 0.11 + $E_{\text{ex}}$</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- $\Lambda\Lambda\Lambda\text{Be}^*$ is the most probable in term of kinematic analysis.
New information on $\Lambda\Lambda$ interaction in other nuclide

|---------------------|------------------|

<table>
<thead>
<tr>
<th>$\Lambda\Lambda^\Lambda \Lambda [\text{MeV}]$</th>
<th>$\Delta B_{\Lambda\Lambda} [\text{MeV}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{He}$</td>
<td>$0.67 \pm 0.17$</td>
</tr>
<tr>
<td>$^\Lambda^\Lambda^\Lambda \Lambda$</td>
<td>$\pm 0.13 \text{ MeV}$</td>
</tr>
<tr>
<td>$^\Lambda^\Lambda^\Lambda^\Lambda$</td>
<td>$1.63 \pm 0.14$</td>
</tr>
<tr>
<td>$^\Lambda^\Lambda^\Lambda^\Lambda$</td>
<td>$1.87 \pm 0.37$</td>
</tr>
<tr>
<td>$^\Lambda^\Lambda^\Lambda^\Lambda^\Lambda^\Lambda$</td>
<td>$-2.7 \pm 1.0 + E_{\text{ex}}$</td>
</tr>
</tbody>
</table>

where, $B_{\Xi^-} = 0.13 \text{ MeV}$

where, $B_{\Xi^-} = 0.23 \text{ MeV}$
## Found event list (2019 Aug.)

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### 12 double Lambda events

![Double Lambda events](image)

### 11 twin events

![Twin events](image)

### 7 others

![Others](image)

---

**IBUKI event**
IBUKI event

ID: 20864938633496

Possible interpretation

$\Xi^- + ^{14}\text{N} \rightarrow ^{15}\text{C} \rightarrow \Lambda^{10}\text{Be} + \Lambda^5\text{He}$

Condition:
$(\Xi^- + ^{12}\text{C}, ^{14}\text{N}, \text{or} ^{16}\text{O}) \rightarrow 2 \text{ single } \Lambda \text{ hypernuclei (+ neutrons)}$

- Only "$\Lambda^{10}\text{Be} + \Lambda^5\text{He}$" was accepted at the 1st vertex
- The decay of #1 and #2 are consistent with that of $\Lambda^{10}\text{Be}$ and $\Lambda^5\text{He}$

Measured $B_{\Xi^-}$ is significantly larger than that of atomic 3D state (0.174 MeV) → $\Xi$ hypernucleus!

<table>
<thead>
<tr>
<th>Possible interpretation</th>
<th>$B_{\Xi^-}$ [MeV]</th>
<th>uncertainty of $B_{\Xi^-}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^- + ^{14}\text{N} \rightarrow ^{15}\text{C} \rightarrow \Lambda^{10}\text{Be} + \Lambda^5\text{He}$</td>
<td>~1.3</td>
<td>~0.2</td>
</tr>
</tbody>
</table>
* $B_{\Xi}$ of IBUKI is determined without uncertainty due to the excitation of daughters.

* Multiple candidates of $\Xi$ hypernucleus ($B_{\Xi} > 3D$ atomic level) are found.
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</table>

| 12 double Lambda events                  | 11 twin events | 7 others |

#### 12 double Lambda events
- ![Image 1](image1.png)
- ![Image 2](image2.png)
- ![Image 3](image3.png)

#### 11 twin events
- ![Image 4](image4.png)
- ![Image 5](image5.png)
- ![Image 6](image6.png)

#### 7 others
- ![Image 7](image7.png)
- ![Image 8](image8.png)
- ![Image 9](image9.png)
Double $\Lambda$ event (D004)

- Possible candidates are 3 listed above.
- The uncertainties of $B_{\Lambda\Lambda}$ of these candidate modes are large (more than 1 MeV).
- Anyway, something $\Lambda\Lambda C$ was produced.

$$\Xi^- & {}^{16}\text{O} \rightarrow \Lambda\Lambda{}^{14}\text{C} + p + 2n$$
$$\Xi^- & {}^{16}\text{O} \rightarrow \Lambda\Lambda{}^{14}\text{C} + d + n$$
$$\Xi^- & {}^{16}\text{O} \rightarrow \Lambda\Lambda{}^{15}\text{C} + p + n$$
### Nuclides of found double $\Lambda$ hypernuclei

<table>
<thead>
<tr>
<th></th>
<th>Captured by</th>
<th>Daughter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{12}$C</td>
<td>$^{14}$N</td>
</tr>
<tr>
<td>Danysz</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>E176#15-03-37</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>NAGARA</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>MIKAGE</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>DEMACHI-YANAGI</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>HIDA</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>Other 3 events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D001</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>D002</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>D003</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>D004</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>D005</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>D006</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>D007, MINO</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>D008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D009</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>D010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D012</td>
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</tbody>
</table>

- ●: Uniquely identified, ○: Multiple interpretations

- Statistical analysis with multiple events will provide information on $\Lambda\Lambda$ and $\Xi N$ interactions.
### Nuclides of found twin single $\Lambda$ events

<table>
<thead>
<tr>
<th></th>
<th>Captured by</th>
<th>Daughter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{12}$C</td>
<td>$^{14}$N</td>
</tr>
<tr>
<td>E176#10-9-6</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>E176#13-11-14</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>E176#14-03-35</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>run429_spill438_1</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>KISO</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>KINKA</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>T001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T002</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>T003</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>T004, atomic</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>T005</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T006, IBUKI</strong></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>T007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T009</td>
<td></td>
<td></td>
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<tr>
<td>T010</td>
<td></td>
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<tr>
<td>T011</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ●: Uniquely identified, ○: Multiple interpretations

- Statistical analysis with multiple events will provide information on $\Lambda\Lambda$ and $\Xi N$ interactions.
J-PARC E07 makes a breakthrough in the study of $S=-2$ system.

New nuclide events and $B_{\Lambda\Lambda}$ and $B_{\Xi^-}$ are being accumulated by event-by-event analysis.

“MINO event” ($\Lambda\Lambda$Be): Prog. Theor. Exp. Phys. 2019, 021D02.
“IBUKI event” ($\Xi^{15}$C): Under preparation for publication

Statistical analysis of double strangeness system is started.

Event hunting is ongoing.
We will detect additional several tens events within a year.

“X-ray measurement from $\Xi^-$ atoms” is ongoing.
X-ray measurement from $\Xi^-$ atom
with Hybrid method combined Ge detector and emulsion

Synchronized

Ge detector

Emulsion sheet

$\Xi^-$ track identification by angle and position consistency

Stop confirmation in emulsion sheets

Stop without nuclear fragment ($\Xi^-$ or proton)

Stop with nuclear fragment (almost $\Xi^-$)

$\Xi^- + Br (~316 \text{ keV})$
$(7, 6) \rightarrow (6, 5)$

$\Xi^- + Ag (~370 \text{ keV})$
$(8, 7) \rightarrow (7, 6)$

Ge detector

SSD

K$^-$

K$^+$

$\Xi^-$

Used

Not used

preliminary

Ge $\cap \Xi^-$ stop with nuclear fragment (1.3k events)

w/o BGO suppression

energy [keV]

count [/keV]
<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
</table>
| Japan      | Gifu University  
CEA  
KEK  
Kyoto University  
Nagoya University  
Osaka University  
RIKEN  
Tohoku University |
| Korea      | Gyeongsang National University  
Korea Research Institute of Standards and Science  
Korea University  
Seoul National University |
| China      | Chinese Academy of Sciences  
Institute of High Energy Physics China  
Shanxi Normal University |
| Germany    | Helmholtz Institute Mainz  
Johannes Gutenberg-Universität |
| Myanmar    | Lashio University  
University of Yangon |
| USA        | Ohio University  
University of New Mexico |
Back up slides:

Physics motivation and design of the experiment.
$\Xi$ hypernuclei detection via “twin $\Lambda$ hypernuclear event (TLH)”

$\Xi$ Hypernucleus formation (lifetime $\sim 10^{-24}$ s?)

Energy conservation

$E_{\text{initial\_state}} = \text{Mass}(^{14}\text{N}) + \text{Mass}(\Xi^-) - B_{\Xi^-}$

Decay with strong interaction

$p + \Xi^- \rightarrow \Lambda + \Lambda + 28$ MeV

Fragmentation

1) $\Xi^-$ stop point
2) decay of the 1$^{\text{st}}$ $\Lambda$ hypernucleus
3) decay of the 2$^{\text{nd}}$ $\Lambda$ hypernucleus

$E_{\text{final\_state}} = \text{SUM(Mass + kinetic energy)}$ for all fragments
ΛΛ hypernuclei (DLH) detection

ΛΛ hypernucleus formation
when both $\Lambda$ stick to the same nuclear fragment.

\[ M(\Lambda^A Z) = M(A-1Z) + M_\Lambda - B_\Lambda \]
\[ M(\Lambda\Lambda^A Z) = M(A-2Z) + 2M_\Lambda - B_{\Lambda\Lambda} \]

Sequential decay
1) $\Xi^-$ stop point
2) decay of the $\Lambda\Lambda$ hypernucleus
3) decay of $\Lambda$ hypernucleus

Energy conservation
\[ \text{Mass}(Z) + \text{Mass}(\Xi^-) - B_{\Xi^-} = \text{SUM(Mass + kinetic energy)} \]
\[ \text{Mass}(Z) = \text{SUM(Mass + kinetic energy)} \]
Nagara event

$\Xi^- + ^{12}\text{C} \rightarrow \Lambda\Lambda^6\text{He} + ^4\text{He} + t$

$\Lambda\Lambda^6\text{He} \rightarrow {}^5\text{He} + p + \pi^-$


$\Delta B_{\Lambda\Lambda} = 0.67 + 0.17\text{ MeV}$

Where, $B_{\Xi^-} = 0.13\text{ MeV}$

$\Delta\Lambda\Lambda$ interaction is weekly attractive

$M(\Lambda^AZ) = M(\Lambda^{-1}Z) + M_\Lambda - B_\Lambda$

$M(\Lambda\Lambda^AZ) = M(\Lambda^{-2}Z) + 2M_\Lambda - B_{\Lambda\Lambda}$

$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_\Lambda$
**Kiso Event:** *PTEP.* (2015) 033D02.

\[ \Xi^- + ^{14}\text{N} \rightarrow \Xi^- ^{15}\text{C} \rightarrow _\Lambda ^{10}\text{Be} + ^5\Lambda \text{He} \]

More deep level than the atomic one
even the daughter \(_\Lambda ^{10}\text{Be}\) was in any excited state.

1.03 +- 0.18 or 3.87 +- 0.21 MeV

Concept: More than 10 times statistics of KEK-PS E373, 10k $\Xi^-$ stop events

<table>
<thead>
<tr>
<th></th>
<th>KEK-PS E373</th>
<th>J-PARC E07 (in proposal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion gel</td>
<td>0.8 tons</td>
<td>2.1 tons</td>
</tr>
<tr>
<td>Purity of K$^-$ beam</td>
<td>25%</td>
<td>$\sim$85%</td>
</tr>
<tr>
<td>$\Xi^-$ stop yield</td>
<td>$\sim$650</td>
<td>10k</td>
</tr>
<tr>
<td>S=-2 hypernuclei</td>
<td>9</td>
<td>$\sim$10$^2$</td>
</tr>
</tbody>
</table>

Physics motivations

- **Subjects:** S=-2 systems
  - s-shell $\Lambda\Lambda$ hypernuclei: $_{\Lambda\Lambda}^4$H, $_{\Lambda\Lambda}^5$He, and $_{\Lambda\Lambda}^5$H
  - spectroscopy of $\Lambda\Lambda$ hypernuclei ($A = 6 \sim 17$)
  - $\Xi$ hypernuclei ($_{\Xi}^{13}$B, $_{\Xi}^{15}$C, and $_{\Xi}^{17}$N)
  - X-ray from $\Xi$-atoms ($\Xi^-+Ag$, or $\Xi^-+Br$)
  - $\Lambda\Lambda$ hypernuclei in excited state

- **Physics:** baryon-baryon interaction
  - $\Lambda\Lambda$ S-wave interaction
  - $\Lambda\Lambda$ P-wave interaction
  - $\Xi N$ interaction
  - $\Lambda\Lambda$-$\Xi N$ coupling

- Production, structure, and decay of S=-2 systems
\(\Lambda\Lambda-\Xi N\) coupling effect

\(^6\Lambda\Lambda\text{He}\)

\(P_{3/2} \quad \downarrow \quad P_{3/2}\)

\(S_{1/2} \quad n \quad n \quad \Lambda \quad \Lambda \quad p \quad p\)

\(\Lambda\Lambda-\Xi N\) coupling

\(\Lambda\Lambda-\Xi N\) coupling effect is small in \(^6\Lambda\Lambda\text{He}\) and the p-shell double \(\Lambda\) hypernuclei

- Khin Swe Myint, S. Shinmura and Y. Akaishi, nucl-th/029090.

\(^4\Lambda\Lambda\text{H}\)

\(P_{3/2} \quad \downarrow \quad P_{3/2}\)

\(S_{1/2} \quad n \quad \Lambda \quad \Lambda \quad p \quad p\)

\(\Lambda\Lambda-\Xi N\) coupling

If the strength of \(\Lambda\Lambda-\Xi N\) coupling is enough large, \(^4\Lambda\Lambda\text{H}\) can be bound.
Comparison between our and other emulsion experiments

**CHORUS**
- Metal plate: 1 mm
- Emulsion layer: 350 \(\mu\)m
- Base film: 90 \(\mu\)m

**OPERA**
- Emulsion layer: 200 \(\mu\)m
- Pb plate: 1 mm
- 44 \(\mu\)m

**J-PARC E07**
- Emulsion layer: 500 \(\mu\)m
- Base film: 40 \(\mu\)m
- Pb plate: 1 mm

**Track density [\(\text{cm}^{-2}\)]**
- \(\mu^-\): \(10^4\)
- Cosmic \(\mu\): \(10^4\)
- Cosmic \(\mu\) for alignment: \(10^2\)
- Compton e: \(10^5\)
- \(\pi^-\) or K\(^-\) beam: \(10^6\)
- 2\(\gamma\) particles: \(10^5\)

J. Yoshida et al., N. I. M. A 847 (2017) 86–92
## Long walk to J-PARC E07

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Emulsion experiment BNL E964 was accepted</td>
</tr>
<tr>
<td>2006</td>
<td>E964 was cancelled</td>
</tr>
<tr>
<td>2007</td>
<td>J-PARC E07 was accepted</td>
</tr>
<tr>
<td>2011</td>
<td>Earthquake</td>
</tr>
<tr>
<td>2013</td>
<td>Radiation leak accident</td>
</tr>
<tr>
<td>2016</td>
<td>1\textsuperscript{st} physics run</td>
</tr>
<tr>
<td>2017</td>
<td>2\textsuperscript{nd} physics run</td>
</tr>
</tbody>
</table>

2013-2014 Emulsion sheet making  
2014-2017 Storage in Kamioka mine  
2016-2017 Refreshing
Back up slides:

Event hunting in photographic emulsion sheet
**$\Xi^-$ selection from the ($K^-$, $K^+$) reaction by off-line analysis**

**Diagram:**
- $K^-$ target
- $\Xi^-$ scattered particles
- Momentum
- SSD, SSD2 Emulsion sheets

**Criteria for $\Xi^-$ track selection**

<table>
<thead>
<tr>
<th>Level</th>
<th>$\Xi^-$ stop prediction</th>
<th>$\Xi^-$ stop prediction /mod.</th>
<th>Selection Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9k</td>
<td>52k</td>
<td>High S/N &amp; stop ratio</td>
</tr>
<tr>
<td>2</td>
<td>1k</td>
<td>100k</td>
<td>Realistic selection (+ a few year)</td>
</tr>
<tr>
<td>3</td>
<td>1k</td>
<td>~0.7M</td>
<td>All $\Xi^-$ stop</td>
</tr>
<tr>
<td>4</td>
<td>negligible</td>
<td>~1.9M</td>
<td>All combination</td>
</tr>
</tbody>
</table>

**Scattered particles**
- $K^+$ track
- Charge * mass [GeV/c^2]

**Legend:**
- Entries: 333612
- Mean x: 0.8666
- Mean y: 1.232
- RMS x: 0.2794
- RMS y: 0.3745
- Integral: 3.328e+05
Scanning machine for pl01, scanning time: 2~3 hours

Tracks in X-Y space (1mm)$^2$

Position accuracy: reasonable

Angular accuracy: reasonable

with SSD->pl01 protons

σ: 53μm
σ: 64μm

σ: 26mrad
σ: 23mrad
- Tracking in thick-type sheet

Emulsion sheet (thick-type)

500 micron emulsion layer

40 micron base

500 micron emulsion layer

Objective lens

Tracking with image processing

Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U

Optical microscope system

Objective lens (x50)

Image sensor

Stage

Tracking software
Emulsion sheet (thick-type)

500 micron emulsion layer

500 micron emulsion layer

40 micron base

Objective lens

Case 1. punch through to the next sheet
ID: 25345494908328–0

Case 2. dizzy track -> stop (~30 tracks/sheet)
ID: 23967296641832–0

Around stop point -> eye-check

Tracking with image processing
Observation of endpoint

**Case 1.** $\Xi^-$\( \rightarrow \Lambda \pi^-$ decay

- in-flight decay: $\approx 100$ events / mod
- through and decay: $\Xi^-$

**Case 2.** no visible fragment

- $\approx 100$ events / mod
- $\pi^-$

**Case 3.** with hyperfragment

- a few events / mod
- $\Xi^-$

Captured by...

- with hyperfragment: 3
- with nuclear fragment: 2
- no visible fragment: 1

Estimation by simulation

- $\Xi^-$
- stop in module: 29% captured by C, N, O
- in-flight decay: 50%, 4:6
- through and decay: 21%
- p: 75% captured by Ag, Br
- B.G.: 25%
Progress of track following

Scanned: 80% of emulsion sheets at least once
Found $S=-2$ systems: 30 events
Current event finding efficiency is about **50%**
The Inefficiency is due to...

* Angle and position (x80%)
* Scattering in SSD and SSD-pl01 gap un-uniformity (x60%)

* The correction technique is being developed
Back up slides:

Event by event analysis
\( \Xi^- + ^{14}\text{N} \rightarrow ^{10}\text{Be} + ^{5}\text{He} \)

The Q-value of this decay mode is the highest among any channel producing “Twin single \( \Lambda \) hypernucleus”.

\( \Xi^- + ^{14}\text{N} \rightarrow ^{10}\text{Be} + ^{5}\text{He} \)

Q-value: 22.1 MeV

\( \Xi^- + ^{14}\text{N} \rightarrow ^{11}\text{Be} + ^{4}\text{He} \)

Q-value: 7.3 MeV
A twin single $\Lambda$ hypernuclear event in mod062 pl11

Possible solution:
$\Xi^- + {}^{16}\text{O} \rightarrow \Lambda{}^5\text{He} + \Lambda{}^{12}\text{B}$ ($B_{\Xi^-} = \sim 0.1 \pm 0.1$ MeV)

Consistent to atomic bound state, Not a $\Xi$ hypernucleus.
Alpha decay event search by “Vertex-picker”

“Overall scanning”

Finding vertex-like objects with image processing

vertex-like objects

Classification

Cross-tracks

Beam Intl.

Alpha decay

Density and Shrinkage measurement

\( ^{212}\text{Po} (8.785 \text{ MeV}) \)
Back up slides:

X-ray measurement from Xi atoms by Ge detector
X-ray measurement from Xi atoms

Diamond target
Ge detector: 
Hyperball-X
SSD
KURAMA Magnet
Emulsion module
First measurement of X-ray from $\Xi$-atoms

- $10^4 \Xi^-$-stop events in emulsion sheets, with emulsion analysis.
- Energy resolution for Ge: 2keV FWHM
- Statistical accuracy of shift energies: Br(316 keV): 0.4 keV, Ag(370 keV): 0.2 keV
- BGO suppression (gate 20 ns) $\rightarrow$ 30% BG suppress and 100% signal survival ratio
- $P_{\Xi} = 0.6$

<table>
<thead>
<tr>
<th>$Z(n,l)$</th>
<th>E (keV)</th>
<th>Shift (keV)</th>
<th>Width (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag(8,7)$\rightarrow$(7,6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>370.45</td>
<td>0.28</td>
<td>0.15</td>
</tr>
<tr>
<td>Case 2</td>
<td>3.3</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>Br(7,6)$\rightarrow$(6,5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>315.5</td>
<td>0.73</td>
<td>0.44</td>
</tr>
<tr>
<td>Case 2</td>
<td>5.5</td>
<td>1.74</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Case 1: assuming potential shape to be the same as the nuclear density ($t_\rho$ potential)
Case 2: Nijmegen D model correcting to produce the potential depth of $\sim$ 14 MeV.
Hybrid method: Ge detector and emulsion

Background, to be rejected

X-ray from \(\Xi\) atom

stop confirmation in emulsion sheet
Criteria for $\Xi^-$ track selection

<table>
<thead>
<tr>
<th>Level</th>
<th>$\Xi^-$ stop</th>
<th>prediction/mod.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9k</td>
<td>~440</td>
<td>High S/N &amp; stop ratio</td>
</tr>
<tr>
<td>2</td>
<td>1k</td>
<td>~850</td>
<td>Realistic selection</td>
</tr>
<tr>
<td>3</td>
<td>1k</td>
<td>6.2k</td>
<td>All $\Xi^-$ stop</td>
</tr>
<tr>
<td>4</td>
<td>negligible</td>
<td>16k</td>
<td>All combination</td>
</tr>
</tbody>
</table>

Estimation by simulation

- $\Xi^-$ stop in module: 29% (18% of prediction)
- In-flight decay: 50%
- Through and decay: 21%
- Background (B.G.): 75%
- P: 25%

X-ray emission captured by...

- Ag, Br: ~60%
- C, N, O: ~40%
- H: ~??%
- No X-ray: ~2%
- Not detected: ~98%

~20 count detected
Ge spectra with “1st Criterion” WITHOUT emulsion analysis

[Diagram showing Ge spectra with two lines: one for Criterion 1 and one for Criterion 1 with BGO Compton-suppression.]

- **Br** (7, 6) -> (6, 5)
- **Ag** (8, 7) -> (7, 6)
Back up slides:

Emulsion sheet handling
Emulsion pouring

Pouring melted nuclear emulsion
40 degrees Celsius, 3.1kg

Drying
28 degrees Celsius, 75% R.H., 2 days

Flattened base-film by vacuum

Pouring yard

!!Mock-up!!
The emulsion facility at Gifu University

pouring room

drying room

Tanks for photographic development
Lead shield in Kamioka mine

Cooling at 17 °C.

In a refrigerator in Gifu Univ.: ~400 days

In Kamioka mine.: ~400 days
Refreshing

- 4 days at Temp.: 25 deg C, Humi.: 90%
- Humidification: 2 days + 4 days + drying 2 days
- $4Ag + O_2 + 2H_2O \rightarrow 4Ag^+ + 4OH^-$

Compton-electric Tracks / (100mm)$^3$
- $88.6 \pm 3.4$
- $48.1 \pm 2.5$

Refresh chamber capacity: 100 sheets

!!Mock-up!!
Humidifier
Dehumidifier
Cassette assembling
Vacuum check
Thickness/weight measurement

Entrance

A/C

Darkroom @ J-PARC Hadron Assembly Bldg.

For emulsion sheet handling
3workers*3shifts = 9 workers/24h