Studies for charge symmetry breaking effect in hypernuclei with nuclear emulsion

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1. Gifu University
2. Advanced Science Research Center, JAEA

Revised in slide no. 5, 23 and 24.
Outlines

1. Nuclear emulsion
   - history
   - detector
   - specification

2. Past experiments

3. J-PARC E07 experiment

A hypernucleus
## Very Brief History of nuclear emulsion

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors/Institute</th>
<th>Discovery/Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1910</td>
<td>S. Kinoshita</td>
<td>Observation of alpha particle with photographic emulsion</td>
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<td>G. Rochester et al.</td>
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<td>1977</td>
<td>E531 experiment</td>
<td>First Neutrino oscillation experiment.</td>
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<td>1985</td>
<td>WA75</td>
<td>Detection of open bottom meson with accelerator</td>
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<td>2000</td>
<td>DONUT experiment</td>
<td>Direct observation of $\tau$ neutrino.</td>
</tr>
<tr>
<td>2008-</td>
<td>OPERA experiment</td>
<td>Discovery of $\tau$ neutrino appearance</td>
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</tbody>
</table>
Discovery of $\pi$-meson in cosmic ray (1947)

C. F. Pawell et al. Nature 159 186 (1947)
→ H. Yukawa, Nobel prize in 1949 → C. F. Pawell, Nobel prize in 1950
Detection of antiprotons in nuclear emulsion

E. Segre & O. Chamberlain

The structure of nuclear emulsion plate:

- **Charged particles**
- **Detector elements** = Silver halide crystals $10^{14}$ /cm$^3$
- $\rightarrow$ The highest spatial resolution as tracking detector

- **Gelatin binder**
- **200 nm**
- **0.2 $\mu$m**

Image with electronic microscope developed by Fujifilm.
The ionization following the passage of the charged particles generates electron-hole pairs in the silver bromide crystal.

The electron reduces silver ions and makes a latent image (silver atoms).

\[
\begin{align*}
\text{Ag}^+ + e^- &\rightarrow \text{Ag} \\
\text{Ag} + \text{Ag}^+ + e^- &\rightarrow \text{Ag}_2 \\
\text{Ag}_{n-1} + \text{Ag}^+ + e^- &\rightarrow \text{Ag}_n
\end{align*}
\]

Chemical development:
Supply silver with reducing agent
\[ \text{Ag}^+ + e^- \rightarrow \text{Ag} \]
Grow latent images to an **observable** size

Fixing:
Remove unwanted AgBr
\[ 2 \text{Na}_2\text{S}_2\text{O}_3 + \text{AgBr} \rightarrow \text{Na}_3[\text{Ag}(\text{S}_2\text{O}_3)_2] + \text{NaBr} \]
Very Brief History of nuclear emulsion

1910: S. Kinoshita
Observation of alpha particle with photographic emulsion

1947: C. F. Pawell et al.
Discovery of π-meson in cosmic ray.

1949: G. Rochester et al.
Discovery of $K^+ \rightarrow \pi^+\pi^+\pi^-$ with nuclear emulsion

1955: E. Segre & O. Chamberlain
Detection of antiprotons.

1971: K. Niu et al.
Discovery of open charm meson with cosmic ray.

1977: E531 experiment
First Neutrino oscillation experiment.

1985: WA75
Detection of open bottom meson with accelerator

1988: KEK-PS E176 exp.
Search for double hypernuclei and H dibaryon with counter-emulsion hybrid method

1999-: KEK-PS E373 exp.
Search for double hypernuclei with counter-emulsion method

2000: DONUT experiment
Direct observation of τ neutrino.

2008-: OPERA experiment
Discovery of τ neutrino appearance

25 June 2018
HYP2018 in Portsmouth Virginia, U.S.A.
How to determine the energy and identify the particles

1. Energy-loss: Bethe-Bloch equation

\[-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right].\]

Range-Energy relation
Grain linear density measurement

2. Multiple coulomb scattering

\[\theta_0 = \frac{13.6 \text{ MeV}}{\beta_{cp}} z \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right].\]
Mirror hypernuclei

Normal nuclei

\(^4\text{He}\)

\[\begin{align*}
\Lambda^4\text{He} & \rightarrow \pi^- + ^4\text{He} \\
& \rightarrow \pi^- + ^1\text{H} + ^3\text{H} \\
& \rightarrow \pi^- + ^2\text{H} + ^2\text{H}
\end{align*}\]

\[\begin{align*}
\Lambda^4\text{He} & \rightarrow \pi^- + ^1\text{H} + ^3\text{He} \\
& \rightarrow \pi^- + ^1\text{H} + ^1\text{H} + ^2\text{H}
\end{align*}\]

Hypernuclei

\[\Delta B_\Lambda = B_\Lambda(^4\Lambda\text{He}) - B_\Lambda(^4\Lambda\text{H})\]

Mesonic decays w/o neutron

25 June 2018

HYP2018 in Portsmouth Virginia, U.S.A.
Measurement of $B_{\Lambda}$

$$Q_0 = M_\Lambda + M_{Z^{-1}} - \sum m_i$$

$$B_{\Lambda} = Q_0 - Q$$

Total visible energy in emulsion

1. Range measurement error
2. Emulsion density and shrinkage factor measurement error
3. Range straggling

Emulsion can measure $B_{\Lambda}$ of various nuclides in the same detector. Thus, the other systematic errors will be canceled.
\( B_\Lambda \) past results in nuclear emulsion

### Table 3

Binding energies of light hypernuclei measured in emulsion. In addition to the quoted statistical errors, there are systematic errors (\( \sim 0.04 \) MeV) which have been minimised by measuring \( M_\Lambda \) in the same emulsion stack.

<table>
<thead>
<tr>
<th>Hypernuclide</th>
<th>( B_\Lambda /)MeV</th>
<th>( B_\Lambda /)MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^3\Lambda H )</td>
<td>0.13 ± 0.05</td>
<td>( ^6\Lambda Li )</td>
</tr>
<tr>
<td>( ^4\Lambda H )</td>
<td>2.04 ± 0.04</td>
<td>( ^9\Lambda Be )</td>
</tr>
<tr>
<td>( ^4\Lambda He )</td>
<td>2.39 ± 0.03</td>
<td>( ^9\Lambda B )</td>
</tr>
<tr>
<td>( ^5\Lambda He )</td>
<td>3.12 ± 0.02</td>
<td>( ^{10}\Lambda Be )</td>
</tr>
<tr>
<td>( ^6\Lambda He )</td>
<td>4.18 ± 0.10</td>
<td>( ^{10}\Lambda B )</td>
</tr>
<tr>
<td>( ^7\Lambda He )</td>
<td>\text{not averaged}</td>
<td>( ^{11}\Lambda B )</td>
</tr>
<tr>
<td>( ^7\Lambda Li )</td>
<td>5.58 ± 0.03</td>
<td>( ^{12}\Lambda B )</td>
</tr>
<tr>
<td>( ^7\Lambda Be )</td>
<td>5.16 ± 0.08</td>
<td>( ^{12}\Lambda C )</td>
</tr>
<tr>
<td>( ^8\Lambda He )</td>
<td>7.16 ± 0.70</td>
<td>( ^{13}\Lambda C )</td>
</tr>
<tr>
<td>( ^8\Lambda Li )</td>
<td>6.80 ± 0.03</td>
<td>( ^{14}\Lambda C )</td>
</tr>
<tr>
<td>( ^8\Lambda Be )</td>
<td>6.84 ± 0.05</td>
<td>( ^{15}\Lambda N )</td>
</tr>
</tbody>
</table>


ΔB_Λ past results in nuclear emulsion

<table>
<thead>
<tr>
<th>Multiplet pair</th>
<th>ΔB_Λ/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4^ΛHe–4^ΛH</td>
<td>+0.35 ± 0.04</td>
</tr>
<tr>
<td>8^ΛBe–8^ΛLi</td>
<td>+0.04 ± 0.06</td>
</tr>
<tr>
<td>9^ΛB–9^ΛLi</td>
<td>−0.21 ± 0.22</td>
</tr>
<tr>
<td>10^ΛB–10^ΛBe</td>
<td>−0.22 ± 0.25</td>
</tr>
<tr>
<td>12^ΛC–12^ΛB</td>
<td>−0.57 ± 0.19</td>
</tr>
</tbody>
</table>

The **systematics** error is dominant.
The **statistical** error is dominant.

If we get **an order of magnitude higher events** and apply the latest range and emulsion calibration method, we will discuss ΔB_Λ of the multiplet pairs up to ^12C with **high accuracy**.
Beam exposure
J-PARC E07 in 2016 and 2017

Cover with SSD and Ge detector

Emulsion mover

Diamond target
\((^{12}\text{C})\)

K\(^-\)

1.8 GeV/c

SSD

K\(^-\)

Thin

Thick

Thick

Thin

K\(^+\)
Chemical development for E07 in Gifu Univ.

345mm
~1mm

350mm

Thickness

Presoak 5 deg.
Dev. 5 deg.
Stop 5 deg.
Fix 5 deg.

Main talks on the E07 experiment will be given by J. Yoshida tomorrow.

60 plates/cycle (total 1298 plates)
~5 days/cycle from presoak to fix
J-PARC E07
Nuclear Emulsion

Elemental composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>39.6</td>
</tr>
<tr>
<td>C</td>
<td>20.6</td>
</tr>
<tr>
<td>N</td>
<td>5.9</td>
</tr>
<tr>
<td>O</td>
<td>11.3</td>
</tr>
<tr>
<td>Ag</td>
<td>11.2</td>
</tr>
<tr>
<td>Br</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Density: 3.6 – 3.9 g/cm³
Shrinkage factor: 1.6 – 1.9

Requires calibration using alpha decay (Z=2) and muon (Z=1) from π⁺ decay

Thick emulsion plate after chemical development

34.5 cm x 35.0 cm
Estimation of single hypernuclei

All events = Overall method

Direct process

3 : 1 preliminary
via Ξ⁻ atom

n(K⁻, K⁰) Ξ⁻ = 2 : 1
p(K⁻, K⁺) Ξ⁻

2 : 1

un-triggered

triggered Ξ⁻

Hybrid method

K⁻ beam: \(\sim 10^{10}\) in total

<table>
<thead>
<tr>
<th></th>
<th>Hybrid</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td># of events</td>
<td>1</td>
<td>(~30)</td>
</tr>
<tr>
<td>Area to analyze</td>
<td>1</td>
<td>(~1000)</td>
</tr>
</tbody>
</table>
“Vertex Picker”

Fully automated microscopic stage

High resolution CMOS
2048*1088 pixels
High frame rate
300fps

Wide FOV
x20 dry lens (NA0.35)
565 × 300 μm²

Piezoelectric drive
Stroke 200 micron
Period 1.3 Hz (current)
Picture 32picts /cycle

<table>
<thead>
<tr>
<th>Camera/processor</th>
<th>For hybrid method</th>
<th>For vertex picker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate</td>
<td>60 fps</td>
<td>300 fps</td>
</tr>
<tr>
<td>resolution</td>
<td>512 × 440</td>
<td>2048 × 1088</td>
</tr>
<tr>
<td>Field of view(μm²)</td>
<td>140 × 110</td>
<td>565 × 300</td>
</tr>
<tr>
<td>Image processing</td>
<td>CPU</td>
<td>CPU &amp; GPU</td>
</tr>
</tbody>
</table>
Vertex Picker
Search all region for vertex like event.

Spatial resolution
\( \delta x = 0.9 \text{ um}, \ \delta z = 8 \text{ um} \)

High resolution microscopy
Analyze in detail.

Spatial resolution
\( \delta x = 0.36 \text{ um}, \ \delta z = 1.4 \text{ um} \)

multi vertexes = candidates

Accumulated image

Developed by J. Yoshida
NIM A847 86–92 (2017)
Result of vertex picker

Total 1,718,515 vertex candidates

An E07 emulsion plate
Vertex picker system

vertex candidates
150,334 events

2-vertexes cand.
282 events

2-vertexes
248 events

w/ thin track*
107 events

w/o thin track
141 events

others
34 events

High resolution microscopy

* The thin tracks are not identified as π-meson.
Estimation with all the E07 emulsion plates

~1.7G vertex candidates

~3M two vertexes

~1M two vertexes w/ thin track

Almost all events are single vertex or fake events

Two third will be w/o thin track

It would be to obtain an order of magnitude more events approximately.

cf. 27K mesonic decay
Nuclear Physics B52 (1973) 1-30.
Mesonic decay of single hypernuclear event

<table>
<thead>
<tr>
<th>Track</th>
<th>Range (μm)</th>
<th>Theta θ (deg.)</th>
<th>Phi φ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>5.3 ± 0.5</td>
<td>18.9 ± 2.1</td>
<td>58.2 ± 1.3</td>
</tr>
<tr>
<td>#2</td>
<td>29.0 ± 1.7</td>
<td>132.3 ± 1.8</td>
<td>237.3 ± 1.9</td>
</tr>
<tr>
<td>#3</td>
<td>12520 ± 20</td>
<td>125.1 ± 1.4</td>
<td>193.1 ± 3.3</td>
</tr>
</tbody>
</table>

Invariant mass [MeV/c²]

<table>
<thead>
<tr>
<th>Measured</th>
<th>3923.3 ± 0.3*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear DB</td>
<td>3922.57 ± 0.04</td>
</tr>
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</table>

*Calibration was not finished.

This decay is only allowed by kinematic analysis.

\[ \Lambda^4H \rightarrow \pi^- + d + d \]

Not confirmed.

25 June 2018

HYP2018 in Portsmouth Virginia, U.S.A.

Analyzed by May Sweet
Summary and prospects

- There are many uncertainties in the past results of the emulsion experiments, and some issues can be solved by increasing events.
- Emulsions can discuss various single hypernuclei in the same detector with sub-MeV accuracy.
- Development and analysis of reading the E07 emulsion plates is ongoing.
- According to the estimate, 1,000K two vertexes w/ thin track will be acquired.
- We plan to start full-scale analysis using the overall method with vertex picker from 2019. The new results of $B_\Lambda$ will be released in a few years.