Future gamma-ray spectroscopic experiment (J-PARC E63) on $^4\Lambda$H

2018/6/26

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KEK IPNS (Japan)
for the E63 collaboration
CSB in s-shell hypernuclear system studied via γ-ray spectroscopy

- γ-ray spectroscopy on $^4_\Lambda$He (J-PARC E13)

Next step: γ-ray spectroscopy on $^4_\Lambda$H (J-PARC E63)

- Previous studies on $^4_\Lambda$H
- Strategy of new measurement
- Present status

Idea of future experiment

γ-ray spectroscopy of p-shell mirror hypernuclei $^{12}_\Lambda$B

Summary
CSB effect in s-shell hypernuclear structure

Level schema of mirror hypernuclei $^{4}_\Lambda H / ^4_\Lambda He$ (before 2014)

Un expectedly large $B_\Lambda$ difference
( 0.07 MeV in theoretical study with NSC interaction model )

→ Need to examine old data with modern technique
Recent experiment for \textbf{s-shell}

Level schema of mirror hypernuclei

$^4\Lambda_H / ^4\Lambda_He$ (before 2014)

$E_\gamma = 1.09 \pm 0.02$

$E_\gamma = 1.24 \pm 0.05$

$E_\gamma = 1.15 \pm 0.04$

$B_\Lambda (^4\Lambda_He(0^+)), 2015$ (MAMI-A1)

$2.157 \pm 0.077$ MeV

(chance to reduce systematic errors)

A. Esser, S. Nagao et al.,
A1 collaboration., NPA 954 (2016) 149

Precise measurement

Emulsion $\rightarrow$ Decay $\pi^-$ spectroscopy

The result supports existence of CSB effect in $B_{\Lambda(\text{g.s.)}}$
Recent experiment for s-shell

Level schema of mirror hypernuclei $^4_\Lambda$H / $^4_\Lambda$He

$E_\gamma$ = 1.09 ± 0.02

$E_\gamma$ = 1.406 ± 0.002 ± 0.002 [present]

1.406 ± 0.004 MeV

In flight (K-,π-) reaction w/ SKS + Ge detector

CSB effect also in excitation energy

Recent experiment for s-shell

Existence of CSB effect was confirmed (B_{\Lambda(g.s)} and \gamma-ray)

- Strongly spin-dependent:
  \[ \Delta B_{\Lambda}(1^+) = 0.03 \pm 0.05 \text{ MeV} \]
  \[ \Delta B_{\Lambda}(0^+) = 0.35 \pm 0.05 \text{ MeV} \]
Recent experiment for s-shell

Level schema of mirror hypernuclei

$^4_\Lambda H / ^4_\Lambda He$

Updated

Need high accurate data to investigate origin of CSB and underlying $\Lambda N$ interaction

Precise $\gamma$-ray spectroscopy is powerful tool to study CSB

We will continue measurement using Ge detector

- Existence of CSB effect was confirmed ($B^{}_{\Lambda(g.s)}$ and $\gamma$-ray)
- Strongly spin-dependent: $\Delta B^{}_{\Lambda}(1^+) = 0.03 \pm 0.05$ MeV
  $\Delta B^{}_{\Lambda}(0^+) = 0.35 \pm 0.05$ MeV
Future measurement
Gamma-ray spectroscopy on $^{4}_{\Lambda}$H (J-PARC E63)
Gamma-ray data on $^4\Lambda$H

Level schema of mirror hypernuclei $^4\Lambda$H / $^4\Lambda$He

We obtained high precision data (J-PARC E13)

Three old data are available

<table>
<thead>
<tr>
<th>Reference</th>
<th>Excitation Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] M. Bedjidian et al. (1976)</td>
<td>1.09 ± 0.03</td>
</tr>
<tr>
<td>[2] M. Bedjidian et al. (1979)</td>
<td>1.04 ± 0.04</td>
</tr>
<tr>
<td>Weighted average</td>
<td>1.09 ± 0.02</td>
</tr>
</tbody>
</table>

rather large deviation
Gamma-ray data on $^4_{\Lambda}H$

We obtained high precision data (J-PARC E13)

Level schema of mirror hypernuclei $^4_{\Lambda}H / ^4_{\Lambda}He$

Three old data are available

$^3H$

$^4_{\Lambda}H$

$^3He$

$B_{\Lambda}$ [MeV]

$^4_{\Lambda}He$

Expected

<table>
<thead>
<tr>
<th>Data Source</th>
<th>$E_\gamma$ [MeV]</th>
</tr>
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rather large deviation
Limitation on old measurement

All $\gamma$-ray measurements on $^4_{\Lambda}$H used
- Stopped $K^-$
- NaI detector

$150 \sim 200 \text{ keV(FWHM)}$ resolution due to detector resolution and Doppler broadening

For higher precision
- Stopped $K^-$ $\rightarrow$ in-flight ($K^-, \pi^-$)
- NaI detector $\rightarrow$ Ge detector

Same strategy as $^4_{\Lambda}$He measurement

Expected resolution: $\sim 40 \text{ keV(FWHM)}$
Previous study via in-flight $^7$Li(K$^-$,π$^-$) @ 0.9 GeV/c

$^4_\Lambda$H (and $^4_\Lambda$He) generates as hyperfragment via the in-flight $^7$Li(K$^-$,π$^-$)$^7_\Lambda$Li reaction

BNL AGS

Moby Dick

M-May, PRL 51(1983)2085

Highly unbound

1.1 MeV

1.4 MeV

$^7_\Lambda$Li

Bound region

They reported $1.108 \pm 0.010$ MeV peak as “mixture of $^4_\Lambda$H and $^4_\Lambda$He”

Nal detector energy resolution : 74 keV(FWHM) + ~80keV Doppler broadening
Previous study via in-flight $^7\text{Li}(K^-,\pi^-) @ 0.9 \text{ GeV/c}$

$^4\Lambda\text{H} (\text{and } ^4\Lambda\text{He})$ generates as hyperfragment via the in-flight $^7\text{Li}(K^-,\pi^-) ^7\Lambda\text{Li}$ reaction

They reported $1.108 \pm 0.010$ MeV peak as “mixture of $^4\Lambda\text{H}$ and $^4\Lambda\text{He}”$

J-PARC E13 $\rightarrow$ 1.4 MeV

BNL AGS

Moby Dick

$^7\Lambda\text{Li}$

Bound region

Highly unbound

Nal detector energy resolution:
74 keV (FWHM) + ~80 keV Doppler broadening

M.May, PRL 51(1983)2085

J-PARC E13 $\rightarrow$ 1.4 MeV

$\gamma$-ray

$^7\Lambda\text{Li}$ target

$^7\Lambda\text{Li}^*$

$^3\text{He}$

$^7\Lambda\text{Li}^*$

$^4\Lambda\text{H}^*$

1.1 MeV

1.4 MeV
Previous study via in-flight $^7$Li($K^-,\pi^-)@0.9\,\text{GeV/c}$

$^4\Lambda\,H$ (and $^4\Lambda\,\text{He}$) generates as hyperfragment via the in-flight $^7$Li($K^-,\pi^-)^7\Lambda\,\text{Li}$ reaction

We chose this reaction for $^4\Lambda\,H$ measurement
γ-ray spectroscopy of $^{4}_{\Lambda}$H (J-PARC E63)

$^{4}_{\Lambda}$H generates as hyperfragment via the in-flight $^{7}$Li($K^{-},\pi^{-})^{7}_{\Lambda}$Li reaction

Similar setup as $^{4}_{\Lambda}$He measurement

SKS spectrometer
- larger acceptance (~100msr)
- + good energy resolution

We can select threshold region of $^{7}_{\Lambda}$Li* → $^{4}_{\Lambda}$H + $^{3}$He [Ex=~20MeV] (Suppress Doppler broadening)

~40 keV (FWHM)

Ge detector array (Hyperball-J)

Good energy resolution
γ-ray spectroscopy of \( ^4_{\Lambda}H \) (J-PARC E63)

\( ^4_{\Lambda}H \) generates as hyperfragment via the in-flight \( ^7\text{Li}(K^-,\pi^-)^7\Lambda\text{Li} \) reaction

Similar setup as \( ^4_{\Lambda}\text{He} \) measurement

- \( ^7\text{Li} \) target
- \( ^7\Lambda\text{Li}^* \) decay
- \( ^3\text{He} \) emission
- \( ^4_{\Lambda}H^* \) decay
- Tagging monochromatic \( \pi^- \) (Support hypernuclear identification)

Beam line spectrometer

SKS spectrometer

Ge detector array (Hyperball-J)

\( \gamma \)-ray

Range counter (additional)
Experimental setup for $^4_\Lambda$H (J-PARC E63)

New detector configuration around target (view from beam upstream)

- **SKS spectrometer**
- **SKS magnet**
- **Exp. Target**
- **Ge detector array**
- **Hyperball-J**
- **Exp. Target**
- **Range counter (additional)**
- **Range counter system**

**Thickness:**
- ~0.5 cm thick

**Layers:**
- >15 layers

**Coverage:**
- $30^W \times 10^H$ cm

**Share with other experiment?**
- (weak decay, etc.)

$E_x (1^+) \text{ will be measured with } <5 \text{ keV accuracy}$
- (w/6 days beam time)
Gamma-Ray Spectroscopy of Light $\Lambda$ Hypernuclei II

31 participants from 12 institutes

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J-PARC
E63 (E13-2)
Submitted in 2015
stage-2 approval

- $^4_\Lambda$H excitation energy
- $^7_\Lambda$Li lifetime
  ($\Lambda$ magnetic moment in nuclear medium)
Byproduct: \( \gamma \)-ray measurement of \(^3\Lambda\)H

Idea from M. Ukai

If \( nn\Lambda \) is bound, \(^3\Lambda\)H (1/2\(^+\), T=1) may be bound

Report from GSI

Chance to measure \( \gamma \)-rays (iso-spin conversion)
Byproduct: γ-ray measurement of $^3\Lambda H$

Idea from M. Ukai

Selecting $E_x > 20$ MeV

$^4\Lambda H$ → $^4He + \pi^-$

$1^+;T=0$

$0^+;T=0$

$^4\Lambda H$ → $^3\Lambda H + \alpha$

$3/2^-;T=1$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$3/2^-;T=0$

$\sim 12$

$\sim 8$

Possible background

Selecting $E_x \approx 10$ MeV

$^3\Lambda H$ → $^3He + \pi^-$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$^3He + \pi^-$

$E_x$ (MeV)

Chance for high statistic (need for $^7\Lambda Li$ lifetime measurement)

$(K^-,\pi^-)$ $p_n \rightarrow p_\Lambda$ substitutional

Tag 40 MeV pion by range counter

Selecting $E_x > 20$ MeV

$^4\Lambda H$ + $^3He$ → $^3\Lambda H + \alpha$

$3/2^-;T=1$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$^4\Lambda H$ → $^{6}\Lambda Li + ^5\Lambda He + d$

$3/2^-;T=1$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$^3\Lambda H + \alpha$

$3.88$

$0.69$

$^7\Lambda Li$

$E_{ex}$ (MeV)

$1/2^+;T=0$

$3/2^-;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$3/2^-;T=0$

$\sim 12$

$\sim 8$

$^4\Lambda H$ + $^3He$ → $^3\Lambda H + \alpha$

$3/2^-;T=1$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$^4\Lambda H$ → $^{6}\Lambda Li + ^5\Lambda He + d$

$3/2^-;T=1$

$1/2^+;T=1$

$3/2^+;T=0$

$1/2^+;T=0$

$^3\Lambda H + \alpha$

$3.88$

$0.69$

$^7\Lambda Li$

$E_{ex}$ (MeV)

$1/2^+;T=0$
0.9 GeV/c K⁻ beam for suppress Doppler broadening and higher cross section → move to J-PARC K1.1 beam line with SKS magnet

J-PARC hadron experimental facility

SKS moved to K1.1

30 GeV proton

Production target (Au)

K1.8BR

K1.8

K1.1

KL

High-p

30 GeV (A line)

Hyperball-J: Established
Range counter: Designing (will be constructed in next year)
Idea of new measurement

Gamma-ray spectroscopy to study CSB effect in \( p \)-shell hypernuclei
Reaction for $\gamma$-ray spectroscopy on mirror hypernuclei

Non-charge exchange reaction

$^{12}\Lambda C(\pi^+, K^+)^{12}\Lambda C^* \rightarrow^{12}\Lambda C + \gamma$

Charge exchange reaction

$^{12}\Lambda C(K^-, \pi^0)^{12}\Lambda B^* \rightarrow^{12}\Lambda B + \gamma$

$\pi^0 \rightarrow \gamma \gamma$

$^{12}\Lambda C(\pi^-, K^0)^{12}\Lambda B^* \rightarrow^{12}\Lambda B + \gamma$

$K^0 \rightarrow \pi^+\pi^- (69\%)$

$^{12}\Lambda C(e, e' K^+)^{12}\Lambda B^* \rightarrow^{12}\Lambda B + \gamma$

Need to extend gamma-ray data to neutron rich side
Reaction for γ-ray spectroscopy on mirror hypernuclei

Need to extend gamma-ray data to neutron rich side

Non-charge exchange reaction

\[ _{12}^\Lambda C(\pi^+, K^+)_{12}^\Lambda C^* \rightarrow _{12}^\Lambda C + \gamma \]

Charge exchange reaction

\[ _{12}^\Lambda C(K^-, \pi^0)_{12}^\Lambda B^* \rightarrow _{12}^\Lambda B + \gamma \]
\[ \pi^0 \rightarrow \gamma\gamma \]

\[ _{12}^\Lambda C(K^0_s, K^0)_{12}^\Lambda B^* \rightarrow _{12}^\Lambda B + \gamma \]
\[ K^0_s \rightarrow \pi^+\pi^- (69\%) \]

\[ _{12}^\Lambda C(e, e'K^+)_{12}^\Lambda B^* \rightarrow _{12}^\Lambda B + \gamma \]

Rather easier!
- Reaction tag with only charged particles
- Reasonable beam intensity (for Ge detectors)

Prof. Alessandro’s talk on Friday
Setup for the gamma-ray spectroscopy

Same setup with $^4\Lambda\text{H}$ measurement
- Beam line spectrometer + SKS
- Hyperball-J
- Range counter (similar configuration)

Beam momentum: $1.05 \text{ GeV/c}$

Setup for the gamma-ray spectroscopy

$^{12}\text{C}(\pi^-, K^0)\rightarrow 12\Lambda B^* \rightarrow 12\Lambda B + \gamma$

$K^0_s \rightarrow \pi^+\pi^- (69\%)$


Designing of detector system is ongoing
CSB in $s$-shell hypernuclear system studied via $\gamma$-ray spectroscopy

- $\gamma$-ray spectroscopy on $^{4}_\Lambda$He (J-PARC E13)
  
  \[ E_x(^{4}_\Lambda\text{He}(1^+)) = 1.406 \pm 0.004 \text{ MeV} \]

  CSB effect also appear in excitation energy + spin-dependence

- Next step: $\gamma$-ray spectroscopy on $^{4}_\Lambda$H (J-PARC E63)
  
  - In-flight $^7\text{Li}(K^-,\pi^-)$ reaction + Ge detector
  - Common setup as $^{4}_\Lambda$He measurement + range counter system
  - Better than 5 keV accuracy w/ 6 days beamtime
    (stage-2 approval)

- Idea of $\gamma$-ray spectroscopy to study CSB in $p$-shell
Backup
Toward the exp. completeness for s-shell

Gamma-ray spectroscopy of $^4_{\Lambda}H$ w/ a few keV accuracy

Our Next step
J-PARC E63

Decay $\pi^-$ spectroscopy ($^4_{\Lambda}H$) [MAMI-C]

Done

Gamma-ray spectroscopy of $^4_{\Lambda}He$ [J-PARC E13]

Done

Counter experiment ($^4_{\Lambda}He$) [J-PARAC HIHR]

Need J-PARC HEF extension
Present status of CSB in s-shell

- Existence of CSB effect was confirmed (\( B_{\Lambda\text{g.s}} \) and \( \gamma \)-ray)
- Difference in 0\(^+\) and 1\(^+\): \( \Delta B_{\Lambda}(1^+) = 0.03 \pm 0.05 \) MeV
  \( \Delta B_{\Lambda}(0^+) = 0.35 \pm 0.05 \) MeV

\[\text{CSB effect calc. w/ } \Lambda \Sigma \text{ mixing}\]

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>( \Delta B_{\Lambda}(1^+) )</td>
<td>0.28(5)</td>
<td>0.03(5)</td>
<td>-0.01</td>
<td>0.03</td>
<td>-0.19</td>
</tr>
<tr>
<td>( \Delta B_{\Lambda}(0^+) )</td>
<td>0.35(5)</td>
<td>0.35(5)</td>
<td>0.07</td>
<td>0.22</td>
<td>0.14</td>
</tr>
</tbody>
</table>


D. Gazda, A. Gal, NPA 954 (2016) 161

\( \Lambda \Sigma \) coupling may be key of CSB effect

High accurate data of CSB effect may provide new information to investigate underlying \( \Lambda N \) interaction

\[\text{Strongly spin-dependent}\]
Yield estimation of $^{4}_\Lambda H$

<table>
<thead>
<tr>
<th></th>
<th>BNL exp</th>
<th>E63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total K-</td>
<td>10 G Kaon</td>
<td>5 G Kaon</td>
</tr>
<tr>
<td>Target thickness</td>
<td>8 g/cm$^2$</td>
<td>15 g/cm$^2$</td>
</tr>
<tr>
<td>$\pi^-$ spectrometer</td>
<td>Moby-dick (18 msr)</td>
<td>SKS (35 msr &lt; 6°)</td>
</tr>
<tr>
<td>$1^+ \rightarrow 0^+ \gamma$ yield</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>$\gamma$-ray Efficiency</td>
<td>6%</td>
<td>3% (× 0.8 live)</td>
</tr>
<tr>
<td>$^4_\Lambda H(1^+)$ yield</td>
<td></td>
<td>12,500</td>
</tr>
<tr>
<td>$^4_\Lambda H(0^+)$ yield</td>
<td></td>
<td>16,200</td>
</tr>
<tr>
<td>Direct + $\gamma$-feeding</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Decay counter configuration for lifetime measurement

PhysRevC.43.849

Range counter system for hypernuclear π- decay in BNL

Plastic scintillator
Total 7.6cm thickness

(A) MWPC

(B) Timing scintillator

(C) Range counter

(D) Veto counter

Optimum missing mass gate of $^7_\Lambda\text{Li}$
Certain states will be enhanced.

Range counter Total E resolution
~ 15%(FWHM) @50 MeV

Lifetimes of $^3_\Lambda\text{H}$, $^4_\Lambda\text{H}$ can be measured

(a) $^3_\Lambda\text{H} \rightarrow ^3\text{He} + \pi$

(b) $^4_\Lambda\text{H} \rightarrow ^4\text{He} + \pi$

(c) $^\Lambda\text{He} \rightarrow \pi^- + \text{other}$

(d) $^6\text{Li} + \Lambda \rightarrow p + \pi^-$ (in-flight)
### CSB data in $p$-shell hypernuclei

**Theoretical study:** $10 \sim 100$ keV CSB effect in $p$-shell


**Existing data on $B_\Lambda$**

<table>
<thead>
<tr>
<th>hypernuclei</th>
<th>$B_\Lambda$ (g.s.)</th>
<th>reaction</th>
<th>$\Delta B_\Lambda$ (g.s.)</th>
<th>with reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7_\Lambda$He</td>
<td>5.16 $\pm$ 0.08</td>
<td>5.60 $\pm$ 0.17 [70, 71]</td>
<td>-</td>
<td>$-0.44 \pm 0.19$</td>
</tr>
<tr>
<td>$^7_\Lambda$Be</td>
<td>5.16 $\pm$ 0.08</td>
<td>-</td>
<td>6.80 $\pm$ 0.03</td>
<td>+0.04 $\pm$ 0.06</td>
</tr>
<tr>
<td>$^8_\Lambda$Be</td>
<td>6.80 $\pm$ 0.05</td>
<td>-</td>
<td>6.84 $\pm$ 0.05</td>
<td>-</td>
</tr>
<tr>
<td>$^8_\Lambda$Li</td>
<td>8.50 $\pm$ 0.12</td>
<td>8.36 $\pm$ 0.16 [72]</td>
<td>$-0.21 \pm 0.22$</td>
<td>$-0.07 \pm 0.24$</td>
</tr>
<tr>
<td>$^9_\Lambda$B</td>
<td>8.29 $\pm$ 0.18</td>
<td>-</td>
<td>9.11 $\pm$ 0.22</td>
<td>$-0.22 \pm 0.25$ (-0.50 $\pm$ 0.21)</td>
</tr>
<tr>
<td>$^{10}_\Lambda$B</td>
<td>8.89 $\pm$ 0.12</td>
<td>8.60 $\pm$ 0.18 [12]</td>
<td>$-0.22 \pm 0.25$</td>
<td>+0.04 $\pm$ 0.21*</td>
</tr>
<tr>
<td>$^{10}_\Lambda$Be</td>
<td>$-0.03 \pm 0.19^*$</td>
<td>$-0.57 \pm 0.19$</td>
<td>$-0.57 \pm 0.19$</td>
<td>$-0.72 \pm 0.18$</td>
</tr>
</tbody>
</table>

**Experiment with $(e,e'K^+)$ reaction (JLAB)**

$\rightarrow A=7, 10$ hypernuclei ($\sim$100 keV accuracy)


**Difficulty:** Need accurate data in both mirror pair
Features

- **Large photo-peak efficiency**
  \[ \varepsilon \sim 6\% \text{ @ } 1 \text{ MeV with 32 Ge detectors} \]
- **Fast readout system**
- **Low temp. Ge detector**
  for radiation hardness
  \[ \text{Mechanical cooling} \]
- **Fast background suppressor**
  \[ \text{PWO counter} \]