First Gamma-Ray Spectroscopy of \( sd \)-shell Hypernucleus, \( {}^{19}_\Lambda F \)

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1. Introduction
Previous Gamm-ray Spectroscopies

- Previous γ-ray spectroscopies for s-shell hypernuclei

*Nal detector

\[ ^4\Lambda H \]

\[ ^4\Lambda He \]

*Ge detector

\[ ^4\Lambda He : 1^+ \rightarrow 0^+ (1406) \]

@PLB, 83, 252 (1979)

@PRL, 115, 222501 (2015)
The next step is awaited for heavier hypernuclei.
Gamma-ray Spectroscopy of $^{19}_{\Lambda}F$

- It is the first $\gamma$-ray spectroscopy for $sd$-shell hypernuclei.
- Energy spacing of ground state doublet ($1/2^+, 3/2^+$)
  - Radial dependency of the $\Lambda N$ spin-spin interaction?
  - $\Lambda N$ spin-dependent interaction with different wave-function?

low-lying energy levels of $^{19}_{\Lambda}F$

*A. Umeya and T. Motoba NPA 116, 122501 (2016).
### 1. Introduction

<table>
<thead>
<tr>
<th></th>
<th>$^4\Lambda$H</th>
<th>$^7\Lambda$Li</th>
<th>$^{19}\Lambda$F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Four-body Cluster model</strong></td>
<td><img src="n+p+%5CLambda" alt="Diagram" /></td>
<td><img src="4He+p+%5CLambda" alt="Diagram" /></td>
<td><img src="16O+p+n+%5CLambda" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Wave-function</strong></td>
<td>$S_NS_\Lambda$</td>
<td>$p_NS_\Lambda$</td>
<td>$(sd)<em>NS</em>\Lambda$</td>
</tr>
<tr>
<td><strong>N, RMS radius [fm]</strong></td>
<td>2.5 (0s)</td>
<td>3.0 (0p$_{1/2}$)</td>
<td>3.4 (1s$_{1/2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.9 (0p$_{3/2}$)</td>
<td>3.5 (0p$_{1/2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.3 (0d$_{5/2}$)</td>
</tr>
<tr>
<td><strong>Λ, RMS radius [fm]</strong></td>
<td>3.5 (0s)</td>
<td>2.6 (0s)</td>
<td>2.3 (0s)</td>
</tr>
<tr>
<td></td>
<td>@by Millener, private communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$\Delta E_x$ (ground state doublet)</strong></td>
<td>1.1 MeV</td>
<td>0.695 MeV ((\Delta_{p_NS_\Lambda}=0.43 \text{ MeV}))</td>
<td>?</td>
</tr>
</tbody>
</table>
2. Experimental Setup
Experimental Setup of J-PARC E13

- Reaction: $^{19}\text{F}(K^-, \pi^-)\Lambda^{19}\text{F}$

- K1.8 Beamline: High intensity and high purity $K^-$ beam
  - Intensity of $K^-$ beam: $\sim 350$ k/spill
  - $K^-/\pi^- = \sim 2.5$
  - 1.8 GeV/c beam momentum

- SKS & K1.8 Beamline Spectrometers
  - High resolution of missing mass
  - Large acceptance for ($K^-, \pi^-$)
  - Good beam decay suppressor (SP0, SMF)

Target:
- Liquid. $\text{H}_2$
- Liquid. $\text{CF}_4$
Hyperball-J

\[ {}^{19}\text{F}(K^{-}, \pi^{-}){}_{\Lambda}^{19}\text{F}^*, {}_{\Lambda}^{19}\text{F}^* \rightarrow \gamma + {}_{\Lambda}^{19}\text{F} \]

- \approx 25 \text{ HPGe detectors} - \Delta E \approx 4.5 \text{ keV @ 1MeV}
- \text{PWO counters} - \text{Fast background suppression}

**Mechanical cooling system**

Crystal temp. \(\sim 70\) K

*a view of K1.8 experimental hall*

@NPA, 835, 3 (2012)
## Data Sample for $^{19}_Λ$F

- **05.2015~06.2015** at the J-PARC K1.8 Beamline

<table>
<thead>
<tr>
<th>Data</th>
<th>Target (Thickness [g/cm$^2$])</th>
<th>Momentum [GeV/c]</th>
<th>Number of K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam through</td>
<td></td>
<td>1.37, 1.5, and 1.8</td>
<td>.</td>
</tr>
<tr>
<td>$\Sigma^+$ and $^{12}_Λ$C</td>
<td>CH$_2$ (6.6)</td>
<td>1.8</td>
<td>0.6 G</td>
</tr>
<tr>
<td>$^{19}_Λ$F</td>
<td>CF$_2$ (6.6)</td>
<td>1.8</td>
<td>2.3 G</td>
</tr>
<tr>
<td>Physics Run</td>
<td>Liquid. CF$_4$ (20)</td>
<td>1.8</td>
<td>63 G</td>
</tr>
</tbody>
</table>
3. Analysis
Vertex Point (z-direction) and Reaction Angle

- CF$_4$ target during physics run

Reaction angle: 2~12 deg.

*CF$_4$ target real length: 125 mm
Particle Identification for \( K^- \) and \( \pi^- \)

- At trigger line, \( K^- \) and \( \pi^- \) are identified by using AC counters. In addition, \( M^2 \) is used for identification of \( \pi^- \).
Calibration run with CH$_2$ target (6.6 g/cm$^2$)

$^1$H$(K^- , \pi^- )\Sigma^+$

MPV: 1.1901±0.0004±0.0001 GeV/$c^2$
FWHM: 0.0060±0.0001±0.0002 GeV/$c^2$

$^12$C$(K^- , \pi^- )^12\Lambda C$

MPV: -11.06±0.18±0.21 MeV
FWHM: 6.04±0.47±0.40 MeV

→ Absolute scale of missing mass: $^{+0.7}_{-0.7}$ MeV level.
→ Expected missing mass resolution (FWHM) with CF$_4$ target: 8.7±0.4 MeV
By using γ rays from normal nuclei, energy resolution (FWHM) and accuracy of absolute energy level are estimated.

Energy Resolution: ~4.5 keV @1.0 MeV (the sum of all germaniums)

γ rays were measured under ~0.5 keV accuracy level at E < 3 MeV.
4. Results
- $-21 \text{ MeV} < -B_\Lambda < -8 \text{ MeV}$ is selected to observe the $\gamma$ rays from low lying energy states.

For $\gamma$ rays from $^{19}_\Lambda F$. 

Threshold of $^{15}_\Lambda N + \alpha$ 

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

**Distribution of $^{19}_\Lambda F$ with CF$_4$ target (20 g/cm$^2$)**
There are two more peaks.
4. Results

γ(315) and γ(895)

\[ \gamma(315) \quad \gamma(895) \]

\[ \rightarrow \text{Energy: } 315.5 \pm 0.4^{+0.6}_{-0.5} \text{ keV} \]

\[ \rightarrow \text{Energy: } 895.2 \pm 0.3^{+0.6}_{-0.5} \text{ keV} \]
At the forward reaction angle, we found two more gamma-ray peaks at 953 keV and 1267 keV.

$\gamma(953) \rightarrow E: 952.8 \pm 1.2^{+0.5}_{-0.6}$ keV

$\gamma(1267) \rightarrow E: 1265.9 \pm 1.2 \pm 0.7$ keV

$\sim 313$ keV

$\Rightarrow$ The energy difference is consistent with the $\gamma(315)$ energy.
5. Discussion
Based on theoretical calculations, the gamma rays are assigned to their gamma transitions.
Spin-Spin Interaction in \(sd\)-shell Hypernuclei

<table>
<thead>
<tr>
<th>Theoretical Calculation</th>
<th>Experiment</th>
<th>Shell-model with NSC97f model by Umeya and Motoba</th>
<th>Shell-model with (ΛΣ) spin-dependent interaction at (p)-shell hypernuclei by Millener</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ΔE(3/2^+, 1/2^+)) [keV]</td>
<td>315.5 (±0.4_{-0.2}^{+0.3})</td>
<td>419</td>
<td>305</td>
</tr>
</tbody>
</table>

→ The measured energy spacing is well represented by the spin-dependent interaction in \(p\)-shell hypernuclei. It also indicates the \(ΛΣ\) coupling effect is negligible for the energy spacing.

→ The results will be soon published in a major physics journal.
6. Summary
Summary

- A new $\gamma$-ray spectroscopy of $sd$-shell hypernucleus ($^{19}_\Lambda F$) via the $(K^-, \pi^-)$ reaction with 1.8 GeV/c beam was performed at the J-PARC K1.8 beamline.

- Several $\gamma$ rays from $^{19}_\Lambda F$ are observed. The $^{19}_\Lambda F(315)$, $^{19}_\Lambda F(895)$, $^{19}_\Lambda F(953)$, and $^{19}_\Lambda F(1267)$ are assigned to the M1($3/2^+ \rightarrow 1/2^+$), E2($5/2^+ \rightarrow 1/2^+$), E1($1/2^- \rightarrow 3/2^+$), and E1($1/2^- \rightarrow 1/2^+$) transitions, respectively.

- The measured energy spacing (315 keV) between the ground state doublet is well represented by the spin-dependent interaction at $\nu$-shell hypernuclei.

- It is meaningful to extend the $\gamma$-ray spectroscopy to medium hypernuclei, and it will be a guide for future experiments.
*Back Up
K1.8 Beamline

- K1.8 Beamline: High intensity and high purity $K^-$ beam
  - Intensity of $K^-$ beam: $\sim 350$ k/spill
  - $K^-/\pi^- = \sim 2.5$

*J-PARC Hadron facility

Proton Beam

Secondary Beam

@PTEP, 2012, 02B009
Energy calibration

Energy of $\gamma$ ray is calibrated through two steps.
1. Off-beam calibration: spill-off condition for each runs
2. In-beam calibration: spill-on condition

Off-beam calibration: Three $\gamma$ ray from $^{238}$Th source

Fit by 1$^{\text{st}}$ polynomial

Residual [keV]
In-beam calibration: 10 γ rays from normal nuclei

\[ E_{f} - E_{\text{reference}} \text{ [keV]} \]

Fit by 1\textsuperscript{st} polynomial
+ Exponential functions

\[ E_{r} \text{ [keV]} \]

\[ \text{Residual [keV]} \]
-B_Λ Distribution of $^{19}_ΛF$ with CF$_2$ Target (6.6 g/cm$^2$)

*Background from $^{12}_ΛC$ is estimated using calibration data with CH$_2$ target.*

Structure of $^{19}_ΛF$

*Reaction angle, 2<θ<12*