High-resolution $\gamma$-ray spectroscopy of hyperfragments produced by stopped K$^-$ method


$^a$Department of Physics, Kyoto University
$^b$RIKEN(The Institute of Physical and Chemical Research)
$^c$Department of Physics, Tohoku University
$^d$Brookhaven National Laboratory
$^e$Laboratory of Physics, Osaka Electro-communication University
The purpose of $\gamma$-ray spectroscopy of hypernuclei

- Precise measurement of the level structure information of spin-dependent $\Lambda N$ interaction
- Impurity nuclear physics induced by $\Lambda$ shrinkage of nuclei
- Medium effect of baryons

But, in these experiments where $(\pi^+, K^+), (K^-, \pi^-)$ reactions were used, a beam time of more than one month is necessary for each target. The systematic study of hypernuclei is difficult within a reasonable beam time.
For the systematic study of hypernuclei

stopped K⁻ method and Hyperball

- hypernuclei are produced abundantly (8%/stopped k)
- various species of hypernuclei are produced
- neutron (proton) rich hypernuclei

There is a chance to observe many γ rays from various hypernuclei in one experiment

Some difficulties

Many background → good energy resolution of germanium detector
Identify of γ ray → γ−γ coincidence method

We want to show this method is suitable for γ-ray spectroscopy, and make great progress to the γ-ray spectroscopy of hypernuclei
E509 Experiment

KEK 12GeV PS
K5 beam line
650MeV/c K^-beam
K^- ・・・ 14k/spill
π/K ・・・ 160

K beam = B1 × B2 × B3 × (LC2 + LC3)
Stop K = K beam × \text{FV}

γ-d detector ・・・ Hyperball
trigger = stop K × Σ(Ge×BGO)
Target

\[ ^7 \text{Li}, ^9 \text{Be}, ^{10} \text{B}, ^{11} \text{B}, ^{12} \text{C} \]

To see the target dependence of $\gamma$–ray yield

Target dependence? \[ \rightarrow \] \[ \gamma \text{ ray from others} \]

Yes
\[ \gamma \text{ ray from target} \]

From normal nuclei \((A \leq 12)\)?

No

Candidate of hypernuclei
Many γ rays were observed

<table>
<thead>
<tr>
<th>$E_γ$ (keV)</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1302</td>
<td>$^9$Be $^{10}$B $^{11}$B</td>
</tr>
<tr>
<td>2049</td>
<td>$^{10}$B $^{11}$B $^{12}$C</td>
</tr>
</tbody>
</table>

**γ-ray spectrum**

The γ-ray spectrum shows a variety of peaks corresponding to different energy levels. The table lists the energies of observed γ rays and their corresponding targets, highlighting the specificity of these interactions.
$^7\lambda$Li$(5/2^+ \rightarrow 1/2^+$) E2 transition

We succeeded in clear observation with stopped K- method for the first time!
$^7\text{Li}(5/2^+ \rightarrow 1/2^+)\text{E2 transition}$

$E_\gamma = 2049.4 \pm 0.3 \pm 0.5 \text{ keV}$

Peak Count = $516 \pm 74(^{10}\text{B})$

$E419$ (In-flight reaction)
Peak Count = 197
beam time = 1 month

2.5 times more statistics within 3.5 days beam time

$\gamma$-ray intensity of $^7\Lambda\text{Li}$
$\text{E2}(5/2^+ \rightarrow 1/2^+)$ transition

$0.075 \pm 0.016\% / \text{stopped } K^- (^{10}\text{B})$

production mechanism of hyperfragment
Another candidate

We observed an unknown $\gamma$ ray in $^9$Be, $^{10}$B, $^{11}$B target.

$E_\gamma=1302.9 \pm 0.6$ keV

$^8$Li or $^9$Li ??
Possibility of $\gamma-\gamma$ coincidence

Cascade of $^7\Lambda$Li($7/2^+ \rightarrow 5/2^+ \rightarrow 1/2^+$)

- This experiment
  It was impossible because of low efficiency of germanium detector caused by BGO pile-up trouble.

From the background level measured in this experiment, we conclude that $\gamma-\gamma$ coincidence becomes possible by improving the photo-peak efficiency. This improvement can be realized by adjusting beam condition. Furthermore the upgraded Hyperball having large photo peak efficiency is now under development.
Summary

- We performed an experiment to measure $\gamma$ ray from hyperfragment produced by stopped $K^-$ method at the KEK K5 beam line. We employed Hyperball as $\gamma$-ray detector.
- We clearly observed $^{\Lambda_7}\text{Li} E2(5/2 \rightarrow 1/2^-)$ transition by stopped $K^-$ method for the first time, and obtained that the $\gamma$–ray intensity is $0.075 \pm 0.016 \%$ per stopped $K^-$. 
- From the result of this pioneering experiment, we conclude $\gamma$–$\gamma$ coincidence become possible by improving photo-peak efficiency.
- This method is promising for the systematic study of $\gamma$-ray spectroscopy of hypernuclei.
**ΛN interaction**

Effective potential of ΛN interaction

\[ V_{ΛN} = V_0 + V_s(r)\vec{s}_Λ \cdot \vec{s}_N \]  

- Spin-spin interaction

\[ + V_Λ(r)\vec{L} \cdot \vec{s}_Λ \]  

- Spin(Λ) orbit force

\[ + V_N(r)\vec{L} \cdot \vec{s}_N \]  

- Spin(N) orbit force

\[ + V_T\left(\frac{3(\vec{s}_Λ \cdot \vec{r})(\vec{s}_N \cdot \vec{r})}{r^2} - \vec{s}_Λ \cdot \vec{s}_N\right) \]  

- Tensor force

**Our experiment**

- E419 (⁷ΛLi)
- E930 (⁹ΛBe)
- E930 (¹⁶ΛO)

But, in these experiments where (π⁺,K⁺),(K⁻,π⁻) reactions were used, a beam time of more than one month is necessary for each target. The systematic study of hypernuclei is difficult within a reasonable beam time.
There is a broad peak in the expected energy Region (~ 1100 keV),
we cannot recognize the target dependence.
Analysis of BGO

BGO occurred pile-up due to high intensity of beam, almost attributed $\pi^-$. We can reject such event by offline analysis.

The points to be improved

We can reject such event by offline analysis.
Estimation of stopped $K^+$ event

About 63% of $K^+$ stopped in $T_1$, carbon, and $T_2$.

Decay after the life time

By detecting the charged particle after the decay of $K^+$

$\tau = 12.9$ (nsec)
生成されるハイパーオープメントのターゲット依存性を考慮

Target

$^{7}\text{Li}, ^{9}\text{Be}, ^{10}\text{B}, ^{11}\text{B}, ^{12}\text{B}, \text{C}$
Comparison of $^{10}\text{B}$ and $^7\text{Li}$

Division of $^{10}\text{B}$ and $^7\text{Li}$

- $^{10}\text{B}$ ($414\text{keV}$)
- $^7\text{Li}$ ($477\text{keV}$)
- ?? ($472\text{keV}$)
- $^{10}\text{B}$ ($718\text{keV}$)
γ-ray spectroscopy of $\text{Li}_7^\Lambda$  

Hyperball初めての実験  
基底状態の2重項の間隔  
$\Lambda N$のスピン・スピンカ
Identification of $K^-$

used B2 ADC and LC1 ADC

There were many pile-up event of $K^-$ and $\pi^-$

We used only $K^-$ event (not pile-up) for analysis
Hyperball

- 14 set of germanium detector
- Large solid angle (15%)
- 3% photopeak efficiency for 1MeV $\gamma$ ray
- 4.2keV (FWHM) @ 717keV

BGO counter

Suppress of background from Compton scattering and $\pi^0$

Figure 4: Schematic drawings of Hyperball.