γ-Ray Spectroscopy in Λ Hypernuclei

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The present status of hypernuclear γ-ray spectroscopy with Hyperball is summarized. We observed two γ transitions of $^{16}_{Λ}O(1^{-}\rightarrow 1^{-}, 0^{-})$ and obtained the strength of the ΛN tensor force. In $^{10}_{Λ}B(K^{-}, π^{-}\gamma)$ data, we did not observe the spin-flip M1 transition of $^{10}_{Λ}B(2^{-}\rightarrow 1^{-})$, but γ rays from hyperfragments such as $^{7}_{Λ}Li(7/2^{+}\rightarrow 5/2^{+})$ and $^{9}_{Λ}Be(3/2^{+}\rightarrow 1/2^{+})$ were observed. In $^{11}_{Λ}B(π^{+}, K^{+}\gamma)$ data, we observed six γ transitions of $^{11}_{Λ}B$. We also attempted an inclusive γ-ray measurement with stopped $K^{-}$ beam.

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1. Introduction

Since 1998, our project of hypernuclear \( \gamma \) spectroscopy with a germanium (Ge) detector array, Hyperball, has brought great progress in hypernuclear physics by revealing precise structure of several light \( \Lambda \) hypernuclei with a resolution in the keV range.

Hyperball is a large-acceptance germanium (Ge) detector array dedicated to hypernuclear \( \gamma \) spectroscopy. It has a large efficiency of 2.5 \% at 1 MeV realized with fourteen large-volume Ge detectors, and is featured by special readout electronics which enables detection of \( \gamma \) rays under extremely high counting-rate conditions in hypernuclear experiments with meson beams. Details of Hyperball are described in Ref. [1,2].

One of the most important physics motivations of hypernuclear \( \gamma \) spectroscopy is the study the \( \Lambda N \) interaction. In particular, we have been investigating the strengths of the \( \Lambda N \) spin-dependent forces from precise level structure of \( p \)-shell \( \Lambda \) hypernuclei. The potential of the \( \Lambda N \) two-body effective interaction can be written as:

\[
V_{\Lambda N}^{\text{eff}}(r) = V_0(r) + V_\sigma(r)\sigma_\Lambda\sigma_N + V_\Lambda(r)\Lambda \sigma_N + V_N(r)\Lambda \sigma_N + V_T(r)[3(\sigma_\Lambda \hat{r})(\sigma_N \hat{r}) - \sigma_\Lambda \sigma_N]
\]

The four spin-dependent terms, namely, the spin-spin term \( V_\sigma \), the \( \Lambda \)-spin-dependent spin-orbit term \( V_\Lambda \), and the tensor term \( V_T \), have not been studied well by experiments of the \((K^- \pi^-)\) and \((\pi^+, K^+)\) reaction spectroscopy. The radial integrals of \( V_\sigma, V_\Lambda, V_N, \) and \( V_T \) with the \( pNs_\Lambda \) wavefunction in \( p \)-shell hypernuclei are denoted as \( \Delta, S_\Lambda, S_N, \) and \( T \), respectively. These effective-interaction parameters can be experimentally determined from low-lying level energies of \( p \)-shell hypernuclei [3,4]. However, because of a small level spacing between the spin-doublet states, high-resolution \( \gamma \)-ray spectroscopy with Ge detectors is necessary to investigate them.

1.1. Recent Experiments

Table 1 shows all the Hyperball experiments we have carried out. In 1998, we performed two experiments, KEK E419 for \( \Lambda^7 \)Li [11,12] and BNL E930(98) for \( \Lambda^9 \)Be [13], as we already reported in the HYP2000 conference. After that, we carried out the second run of BNL E930 (E930(01)) for \( ^{16} \)O and \( ^{10} \)B targets. With the \( ^{16} \)O target data, we observed \( ^{16} \Lambda^8 \)O and \( ^{1} \Lambda^5 \)N \( \gamma \) rays as described later. With the \( ^{10} \)B target data, we did not observe the \( ^{10} \Lambda^8 \)B(2\(^-\) \( \rightarrow \) 1\(^-\)) \( \gamma \) ray transition, but observed several \( \gamma \) rays from hyperfragments such as \( ^7 \)Li, \( ^9 \)Be, \( ^{11} \)B, \( ^{12} \)C(\( K_{\text{stop}}, \gamma \)) hyperfragments, and \( ^7 \)Li.

| Experiment | Year | Line | Target/Reaction | Hypernuclei studied |
|------------|------|------|-----------------|---------------------|
| KEK E419   | 1998 | K6   | \(^7 \Lambda\)Li(\( \pi^+, K^+\gamma \)) | \( ^7 \Lambda\)Li |
| BNL E930(98) | 1998 | D6   | \(^9 \Lambda\)Be(\( K^-, \pi^-\gamma \)) | \( ^9 \Lambda\)Be |
| BNL E930(01) | 2001 | D6   | \(^{16} \Lambda\)O(\( K^-, \pi^-\gamma \)) | \( ^{16} \Lambda\)O, \( ^{15} \Lambda\)N |
|            |      |      | \(^{10} \Lambda\)B(\( K^-, \pi^-\gamma \)) | \( ^{10} \Lambda\)B, \( ^9 \Lambda\)Be, \( ^7 \)Li etc. |
| KEK E509   | 2002 | K5   | \(^7 \Lambda\)Li, \(^9 \Lambda\)Be, \(^{10} \Lambda\)B, \(^{11} \Lambda\)B, \(^{12} \Lambda\)C(\( K_{\text{stop}}, \gamma \)) hyperfragments (\(^7 \)Li) | \( ^7 \Lambda\)Li |
| KEK E518   | 2002 | K6   | \(^{11} \Lambda\)B(\( \pi^+, K^+\gamma \)) | \( ^{11} \Lambda\)B |
Figure 1. Level schemes of $^7\Lambda\text{Li}$, $^9\Lambda\text{Be}$, $^{10}\Lambda\text{B}$, $^{11}\Lambda\text{B}$, and $^{16}\Lambda\text{O}$ determined from Hyperball experiments. Newly observed $\gamma$ rays, measured level energies, and assigned spins in the recent experiments (E930('01), E509, E518) are shown in thick arrows and bold letters.

as $^7\Lambda\text{Li}$ and $^9\Lambda\text{Be}$. In 2002, we moved Hyperball from BNL to KEK and performed two experiments, E509 for hyperfragments [9] and E518 for $^{11}\Lambda\text{B}$ [10].

Figure 1 shows the level schemes of $p$-shell hypernuclei determined from these Hyperball experiments. The $\gamma$ rays first observed and identified in E930('01), E509, and E518, which are shown in thick arrows, are described in detail in the following sections.

2. $^9\Lambda\text{Be}$ and the spin-orbit force

The experiment BNL E930 aims at determination of all the spin-dependent force strengths from structure of several $p$-shell hypernuclei. Using high-intensity and pure $K^-$ beam at 0.93 GeV/$c$ provided by the D6 beam line at BNL AGS, hypernuclei were produced by the $(K^-\pi^-,\pi^-)$ reaction. The momenta of incident $K^-$ and scattered $\pi^-$ were measured with magnetic spectrometers to obtain the hypernuclear excitation spectrum. $\gamma$ rays were detected with Hyperball installed around the target.

We previously reported that the $^9\Lambda\text{Be}$ target data in E930('98) exhibited the $5/2^+, 3/2^+ \rightarrow 1/2^+$ transitions and revealed a hypernuclear fine structure of $^9\Lambda\text{Be}(5/2^+, 3/2^+)$ [7]. Recently, we have applied Doppler-shift correction to this $^9\Lambda\text{Be}$ spectrum and observed clearly-
Figure 2. Doppler-shift corrected spectrum of $^9\Lambda\text{Be}$ γ rays around 3 MeV obtained in the E930(’98) experiment. The two-peak structure was well fitted by the simulated peak shape with a lifetime of $< 0.1$ ps.

Figure 3. γ-ray spectrum for the mass region slightly higher than the bound-state region of $^{10}\Lambda\text{B}$ ($-18 < -B_\Lambda < 28$ MeV). A γ-ray peak from $^9\Lambda\text{Be}$ is observed.

separated two peaks as shown in Fig. 2. This structure was well fitted by the simulated peak shape with a short lifetime ($< 0.1$ ps). The γ-ray energies were obtained to be $3024 \pm 3 \pm 1$ and $3067 \pm 3 \pm 1$ keV, and the separation energy to be $43 \pm 5$ keV. The separation energy and the lifetime have been revised from the previous values in Ref. [7].

In the $^{10}\text{B}$ target data taken in E930(’01), we observed a γ-ray peak at 3065 keV, when the mass region slightly higher than the $^{10}\Lambda\text{B}$ bound states is selected, as shown in Fig. 3. $^9\Lambda\text{Be}$ can be produced by proton emission from excited states of $^{10}\Lambda\text{B}$, and this observed γ-ray energy coincides with the energy of one of the $^9\Lambda\text{Be}$ γ rays observed in the $^9\text{Be}$ target run. Therefore, this γ ray is assigned as one of the $^9\Lambda\text{Be}$ transitions of $3/2^+ \rightarrow 1/2^+$ or $5/2^+ \rightarrow 1/2^+$. The $^{10}\Lambda\text{B}(3^-, -B_\Lambda \sim 1$ MeV) state, which is expected to have a large cross section, mostly decays into $^9\Lambda\text{Be}(3/2^+) + p$ (see Fig. 1(d)), while other $^{10}\Lambda\text{B}$ excited states decaying into $^9\Lambda\text{Be}(5/2^+) + p$ have much smaller cross sections [11]. Therefore, we assigned the observed peak as $3/2^+ \rightarrow 1/2^+$. From this spin assignment, the previous result for the Λ-spin-dependent spin-orbit force parameter of $-0.02 < S_\Lambda < 0.03$ MeV [7] was improved to $-0.02 < S_\Lambda < -0.01$ MeV. This sign of the Λ-spin-dependent spin-orbit term is consistent with the $p_{1/2} - p_{3/2}$ spin-orbit splitting in $^{13}\Lambda\text{C}$ measured with NaI counter arrays by the BNL E929 experiment [12].
3. \(^{16}\Lambda\text{O}\) and \(\Lambda N\) tensor force

The purpose of the \(^{16}\text{O}\) target run in E930('01) is to investigate the \(\Lambda N\) tensor force strength \((T)\), which has never been studied experimentally. Since the one-pion exchange is forbidden in the \(\Lambda N\) interaction, the tensor force is expected to be small, but the kaon exchange and the two-pion exchange through the \(\Sigma\)-\(\Lambda\) coupling are expected to give some contribution to the tensor force.

It was pointed out that energy spacings of the spin doublets in \(p_{1/2}\)-shell hypernuclei are sensitive to the \(\Lambda N\) tensor force strength \([3]\). According to a shell-model calculation by Millener, the spacing of the ground-state doublet \((0^- , 1^-)\) of \(^{16}\Lambda\text{O}\) is given as

\[
E(1^-) - E(0^-) = -0.382\Delta + 1.378S_\Lambda - 0.004S_N + 7.850T + \Lambda\Sigma\ \text{(MeV)},
\]

where \(\Lambda\Sigma\) denotes the effect of \(\Lambda - \Sigma\) coupling. By the \(^{16}\text{O}(K^-,\pi^-)\) reaction, we can populate the 6 MeV-excited \(^{16}\text{O}\) \([p_{3/2}]^{-1}(s_{1/2})\Lambda_1^-\) state and detect \(M1\) transitions from this state to each member of the ground-state doublet, even if the spacing is too small \((-100\ \text{keV})\) to detect the spin-flip \(M1\) transition between the doublet members (see Fig. 1 (c)). In addition, the 11 MeV-excited \(([p_{1/2}]^{-1}(p_{1/2})\Lambda)_{0^+}\) state and the 17 MeV-excited \(([p_{3/2}]^{-1}(p_{3/2})\Lambda)_{0^+}\) state of \(^{16}\Lambda\text{O}\) are expected to decay to excited states of \(^{15}\text{N}\) by proton emission with sizable branching ratios, which is followed by emission of \(^{15}\Lambda\text{N}\) \(\gamma\) rays. The ground-state doublet spacing of \(^{15}\Lambda\text{N}\), which also has a large contribution of the \(\Lambda N\) tensor force, may also be measured.

The experimental method and setup are almost identical to those in the previous E930 run for \(^9\text{Be}\) described in Ref. [7]. We used a 20 cm-thick water target and irradiated it with \(4.0 \times 10^{10}\ \text{K}^-\) in total. More description on this experiment is found in Ref. [8].

Figure 4 shows preliminary \(\gamma\)-ray spectra for \(^{16}\Lambda\text{O}\). Figure 4 (a) shows the spectrum when events in the 6 MeV-excited \(1^-\) state region of the \(^{16}\text{O}\) mass spectrum \((-21 < -B_\Lambda < 8\ \text{MeV})\) are selected. A broad bump is observed at around 6.55 MeV. After the event-by-event Doppler-shift correction was applied, the broad bump is resolved into two narrower peaks as shown in (b). This structure is not observed for the highly unbound region \((-B_\Lambda > 50\ \text{MeV})\) as shown in Fig. 4 (c), in which beam-induced \(\gamma\) rays from the \(^{16}\text{O}\) target are observed. (The 6130 keV \(^{16}\text{O}\) peak width demonstrates the resolution in this energy region.)

The structure at 6.55 MeV is thus attributed to the \(M1(1^-_2 \rightarrow 1^-_1, 0^-)\) transitions in \(^{16}\Lambda\text{O}\). The peaks in Fig. 4 (b) were fitted with the expected Doppler-corrected peak shape which was calculated from a simulation for the Doppler-shift correction. The spectrum was fitted well with two peaks as shown in Fig. 5. The energies (and the counts) of these peaks were obtained as 6534.1±1.5 keV (149±18 counts) and 6560.2±1.3 keV (226±30 counts). By comparing the ratio of the peak counts with the expected branching ratios, the 6534 keV and 6560 keV peaks were assigned as \(1^-_2 \rightarrow 1^-_1\) and \(1^-_2 \rightarrow 0^-\) transitions, respectively [8]. Then we obtained the energy spacing of the ground-state doublet:

\[
E(1^-) - E(0^-) = 26.1 \pm 2.0\ \text{keV}\ \text{(preliminary)}.
\]

It is the smallest spacing in hypernuclear fine structure observed so far. This very small spacing results from a cancellation of the spin-spin force \((\Delta\ \text{term})\) and the tensor force \((T\ \text{term})\) contributions. It gives the tensor term strength of \(T = +30\ \text{keV}\ \text{(preliminary)}\) from...
Figure 4. γ-ray spectrum of $^{16}$O (preliminary). (a) Bound-state region ($-21 < -B_{\Lambda} < 8$ MeV) is gated. (b) Same as (a) but Doppler-shift correction is applied. (c) Highly unbound region ($-B_{\Lambda} > 50$ MeV) is gated.

Figure 5. (a) Simulated peak shape for a fast γ transition after Doppler-shift correction. (b) The structure around 6.55 MeV in Fig. 4 (b) was fitted with two peaks of the simulated peak shape (preliminary).

Eq. 1 and with the $\Delta$, $S_{\Lambda}$, and $S_N$ values already determined from previous Hyperball experiments. This is the first experimental information on the $\Lambda N$ tensor force.

The meson-exchange baryon-baryon interactions models (ND, NF, NSC89, NSC97f) predict a tensor force strength of $T = 18 - 54$ keV through a G-matrix calculation [13]. They are almost consistent with the experimental value.

4. Study of $^{10}_\Lambda$B

The purpose of the $^{10}$B target run in E930(01) is to measure the energy spacing of the $^{10}_\Lambda$B ground-state doublet ($2^-, 1^-$) by observing the spin-flip M1 transition ($2^- \rightarrow 1^-$). Since the production cross section of the $2^-$ state is large enough, the M1 transition can be easily observed if the level spacing is as large as predicted ($\sim 200$ keV). On the other hand, if the spacing is smaller than $\sim 100$ keV, the γ transition is overcome by weak decay.

Figure 6 is a preliminary γ-ray spectrum when the bound-state region of $^{10}_\Lambda$B($K^-, \pi^-)$ is selected. We observed no peak structure. Considering the number of the expected γ-ray peak yield, we concluded that the $2^-$ state is higher than the $1^-$ state only by 100 keV or less, or the order of the spins in the doublet is reversed. Thus, we confirmed the old result by Chrien et al. [14] with higher statistics. The confirmed result of $E(2^-) - E(1^-) < 100$ keV seems contradictory to the $\Delta$ value (0.4 MeV) obtained from the $^7$Li ground-state
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Figure 6. Preliminary γ-ray spectrum for the bound-state region of \(^{10}_ΛB\) \((-23 < -B_Λ < 7\) MeV). No peak is observed.

doublet \((3/2^+,1/2^+)\) spacing, suggesting that more theoretical and experimental studies are necessary, particularly for the Σ-Λ coupling effect as investigated in Ref. [11].

5. Complete study of \(^7ΛLi\)

In the \(^{10}_ΛB\) target data in E930('01), we observed γ rays from \(^7ΛLi\) produced as hyperfragments from highly excited states of \(^{10}_ΛB\), presumably though the s-substitutional \(^{10}_ΛB\) \((3^+, \sim 28\) MeV excited) state decaying into \(^7ΛLi + ^3He\) as shown in Fig. II (d). Figure 7 (a) shows the γ-ray spectrum when the unbound region \((0 < -B_Λ < 40\) MeV) was selected. The \(M1(3/2^+ \rightarrow 1/2^+)\) and \(E2(5/2^+ \rightarrow 1/2^+)\) γ rays of \(^7ΛLi\) previously observed in E419 are identified. We selected the \(E2\) γ-ray events \((2042 < E_γ < 2058\) keV) and plotted a spectrum of another γ ray emitted in coincidence. As shown in Fig. 7 (b), a peak was observed at 471 keV. The probability that background fluctuation makes such a peak anywhere in the region of 0.1–1 MeV is 0.006%. This peak is assigned as the \(M1(7/2^+ \rightarrow 5/2^+)\) transition, because it is the only transition emitted in coincidence with \(E2(5/2^+ \rightarrow 1/2^+)\). This is the first successful application of the γ-γ coincidence method to hypernuclei.

The observed energy can be compared with theoretical predictions. A cluster-model calculation by Hiyama et al. predicted the \((7/2^+,5/2^+)\) spacing to be 560 keV when the Λ-spin-dependent spin-orbit force is assumed to be zero [15]. It is close to the observed value. According to the Millener’s shell-model calculation [11], the energy spacing is described as \(E(7/2^+) \rightarrow E(5/2^+) = 1.29\Delta + 2.20S_Λ + 0.02S_N - 2.39T + \LambdaΣ\). By using the already determined values of \(\Delta\), \(S_Λ\), \(S_N\), \(T\), and the theoretically calculated \(ΛΣ\) value, the equation gives 511 keV, being also close to the observation. It is found that the observed value is consistent with the already-known strengths of the spin-spin force \(\Delta\) and the very small spin-orbit force \(S_Λ\).

Together with the E419 results [11], we have clarified the complete level scheme and energies of all the bound states of \(^7ΛLi\) as shown in Fig. II (a).

6. Spectroscopy of \(^{11}_ΛB\) (E518)

In 2002, we carried out a γ spectroscopy experiment of \(^{11}_ΛB\) with the \((\pi^+, K^+)\) reaction at 1.05 GeV/c employing Hyperball and the SKS spectrometer at KEK-PS [10]. One of the purposes of this experiment is to measure the transition probability \(B(M1)\) of
the $\Lambda$ spin-flip $M1$ transition $^{11}_\Lambda$B$(3/2^+ \rightarrow 1/2^+)$ and extract information on the magnetic moment of a $\Lambda$ inside a nucleus by the method described in Ref. \cite{16}. The other purpose is to cross-check the $\Lambda N$ spin-dependent interaction parameters which have been determined from the $^7_\Lambda$Li, $^9_\Lambda$Be, and $^{16}_\Lambda$O experiments with Hyperball.

The experimental setup is almost identical to the one in E419 \cite{15}. We used a 10 cm-thick 98%-enriched $^{11}$B metal target. When the bound-state region is gated in the $^{11}$B mass spectrum, the $\gamma$-ray spectrum exhibited six peaks as shown in Fig. 8. One of them was observed in the Doppler-shift-corrected spectrum. They are attributed to transitions from $^{11}_\Lambda$B, but the assignment of all these $\gamma$ rays and the reconstruction of the level scheme are difficult because of low statistics which does not allow $\gamma\gamma$ coincidence measurement.

The prominent peak at 1482 keV is assigned as $E2(1/2^+ \rightarrow 5/2^+)$ (see Fig. 8(e)). It is likely an $E2$ transition because its narrow width indicates a lifetime of the transition longer than $\sim 10$ ps, which gives a very small $B(M1)$ value if it is an $M1$ transition. The $1/2^+ \rightarrow 5/2^+$ transition is the only $E2$ transition expected in $^{11}_\Lambda$B, and the observed largest $\gamma$-ray yield is also consistent with this assignment. It is to be noted that the shell-model prediction by Millener \cite{11} for this $E2$ energy with the experimentally determined $\Lambda N$ interaction parameters is 1020 keV, significantly lower than the observed energy.

7. Hyperfragments (E509)

In KEK-PS E509, we attempted an experiment of inclusive $\gamma$-ray measurement in the stopped $K^-$ absorption reaction, which is known to produce various hyperfragments with large production yields. See Ref. \cite{9} for details. We stopped $K^-$ from the K5 beam line on several light targets ($^7$Li, $^9$Be, $^{10}$B, $^{11}$B, and $^{12}$C) and measured $\gamma$ rays with Hyperball.
From the $^{10}\text{B}$, $^{11}\text{B}$, and $^{12}\text{C}$ targets, we observed the $^{7}\text{Li}(5/2^+ \rightarrow 1/2^+)$ transition at 2050 keV. The yield of this $\gamma$ ray for the $^{10}\text{B}$ target is very large, 500 counts in 3.5 days' beam time, suggesting the effectiveness of this method. The production rate of the $^{7}\text{Li}(5/2^+)$ state is derived to be $0.075 \pm 0.016\%$ per stopped $K^-$ on $^{10}\text{B}$ target.

This method is powerful with a larger Ge detector array, by which the $\gamma\gamma$ coincidence method allows detection of hypernuclear $\gamma$ rays and their assignments. It may open a new possibility to study various hypernuclei including neutron/proton-rich ones which cannot be produced by the direct reactions such as $(K^-,\pi^-)$ and $(\pi^+,K^+)$.  

8. Future Plans

We are now constructing Hyperball2, an upgraded version of Hyperball for near-future experiments at KEK and BNL. It has an efficiency twice as large as the present Hyperball,
realizing a $\gamma\gamma$ coincidence efficiency larger by four times. It will play an essential role in study of hypernuclei having complicated level schemes such as $^{11}_\Lambda$B.

At the 50 GeV proton accelerator facility at J-PARC, we plan to pursue various types of hypernuclear $\gamma$ spectroscopy experiments [17,18]. We have started development of faster readout techniques and faster background-suppression counters necessary for the stronger beams expected at J-PARC.

9. Summary

We have investigated various $p$-shell $\Lambda$ hypernuclei employing Hyperball. In E930(’01), we successfully observed two $\gamma$ transitions of $1^-_2 \rightarrow 1^-_1, 0^-$ at 6.55 MeV, and the ground-state doublet $(1^-_1, 0^-)$ spacing was obtained to be $E(1^-_1) - E(0^-) = 26.1 \pm 2.0$ keV. It gives the $\Lambda N$ tensor force strength of $T = 30$ keV. All the $\Lambda N$ spin-dependent force parameters have been thus determined from our $\gamma$ spectroscopy experiments. In $^{10}$B($K^-, \pi^-\gamma$) data, we observed $\gamma$ rays from hyperfragments such as $^3_\Lambda$Be($3/2^+ \rightarrow 1/2^+$) and $^7_\Lambda$Li($7/2^+ \rightarrow 5/2^+$). In the observation of the $^7_\Lambda$Li($7/2^+ \rightarrow 5/2^+$) transition, we successfully applied the $\gamma\gamma$ coincidence method to hypernuclei for the first time. On the other hand, the spin-flip M1 transition of $^{10}_\Lambda$B($2^- \rightarrow 1^-$) was not observed. At KEK, we studied $^{11}_\Lambda$B with the ($\pi^+, K^+$) reaction and observed six $\gamma$ transitions. We also performed a pioneering experiment with the ($K_{stop}$, $\gamma$) reaction (E509), and observed a $\gamma$-ray peak from $^7_\Lambda$Li hyperfragments. Hypernuclear $\gamma$ spectroscopy will be further pursued with much stronger beams at J-PARC.

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