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# γ-ray Spectroscopy of Hypernuclei: Recent KEK Results and Future Plans at J-PARC*

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**Abstract**: In this proceeding, we will first outline the experimental setup and main results of the most recent hypernuclear γ-ray spectroscopy experiment (KEK-E566) performed at KEK-PS K6 beam line. The main feature and characteristics of this type of research will be emphasised. After that, the approved experimental proposal (E13) at J-PARC facility will be introduced briefly.

**Key words**: γ-ray spectroscopy; hypernuclei
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## 1 Introduction

Hypernuclear physics provides a unique opportunity to investigate the baryon-baryon interactions by introducing hyperons into the normal nuclear system. Many new phenomena have been reported or predicted regarding to this system, for example, the hyperon glue-like effects[1]. As a specific branch in the hypernuclear research, γ-ray spectroscopy study reveals (Λ) hyperon effects on normal nuclear structure precisely. In this proceeding, we will give an introduction to the most recent hypernuclear γ-ray spectroscopy experiment at KEK as a concrete example to illustrate the main feature of this field. Then the approved experimental proposal (E13) at J-PARC facility will be outlined as our future research plan.

The KEK-E566 experiment was designed to study the spin-dependent Λ hyperon nucleon (ΛN) interactions. In this experiment the hypernuclei to be investigated can be classified as *p*-shell hypernuclei, in which the Λ hyperon locates in the *s*-orbit while the nucleons pile up to the *p*-orbit. There is

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a convenient parametrisation scheme that can be applied with analogy to the Hamada-Johnston potential in the normal nuclear system. We can explicitly write this out as[2, 3]:

$$V_{\Lambda N}(r)=V_0(r)+V_\sigma(r)\boldsymbol{s}_N\cdot\boldsymbol{s}_\Lambda+V_\Lambda(r)\boldsymbol{l}_{N\Lambda}\cdot\boldsymbol{s}_\Lambda+V_N(r)\,\boldsymbol{l}_{N\Lambda}\cdot\boldsymbol{s}_N+V_T(r)\cdot\left(\frac{3(\boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{r})(\boldsymbol{\sigma}_N\cdot\boldsymbol{r})}{r^2}-\boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\right),$$

where $r$ is the relative position between a Λ and a nucleon and $\boldsymbol{l}_{N\Lambda}$ stands for the relative orbital angular momentum. The $\boldsymbol{s}_N$ and $\boldsymbol{s}_\Lambda$ are the spin angular momentum operator of a nucleon and a Λ, respectively. To describe low-lying level energies of $p$-shell hypernuclei, the radial integrals of these five terms for $p_N\ s_\Lambda$ wave functions are introduced as parameters and denoted by $\overline{V}$ (radial interaction), Δ (spin-spin interaction), $S_\Lambda$ (Λ spin-dependent spin-orbit interaction), $S_N$ (N spin-dependent spin-orbit interaction) and $T$ (tensor interaction), respectively. The $\overline{V}$ term is usually set to fit the binding energy of the Λ hyperon inside a hypernucleus. Based on a shell model calculation, level energies of a hypernucleus can be written in a linear combination of the interaction parameters[2]. With this preparation, the spin-dependent ΛN interaction parameters are directly related to the corresponding hypernuclear energy spacings. Experimentally determined level scheme can be used to calculate the interaction parameters. Through a series of experiments in the last ten years, a complete set of parameters have been obtained[4].

One important fact of the hypernuclear γ-ray spectroscopy experiment to be noted is the small magnitude of the energy splittings due to the spin-dependent ΛN interactions. According to the previous studies, the ΛN spin-orbit interaction was found to be about one tenth of that of the NN case. Consequently, normal γ-ray detectors, such as the NaI scintillation counters, used in the nuclear spectroscopy experiments are not functional any more. To face this difficulty, our group constructed a large acceptance germanium detector array, Hyperball, and its upgraded version, Hyperball2. It is the Hyperball2 that was used in the KEK-E566 experiment. In the current phase, the next generation germanium detector array, Hyperball-J, is under construction for the upcoming J-PARC facility[5]. The proposal file can be found in http://j-parc.jp/NuclPart/Proposale.html#0801.

## 2 KEK-E566 Experiment

The KEK-E566 experiment was performed at the KEK-PS K6 beam line with $\pi^+$ beam bombarding a polyethylene ($CH_2$) target with the mass thickness of 18.6 g/cm$^2$ to generate the ${}^{12}_{\Lambda}C$ / ${}^{11}_{\Lambda}B$+p hypernuclei. The momentum of the incident $\pi^+$ was set to be 1.05 GeV/$c$ to utilize a relative large n($\pi^+$, $K^+$)Λ cross section[6]. From a pure kinematic consideration, the outgoing $K^+$ then has a momentum of 0.75 GeV/$c$ and the momentum transfer is about 350 MeV/$c$. This large momentum transfer will allow various hypernuclear states to be populated[7]. The beam intensity was set to be ~$3\times10^6$ per spill (one spill was ~1.5 s followed by a 2.5 s spill off period).

### 2.1 Experimental setup

The schematic view of the experimental setup is shown in Fig. 1.

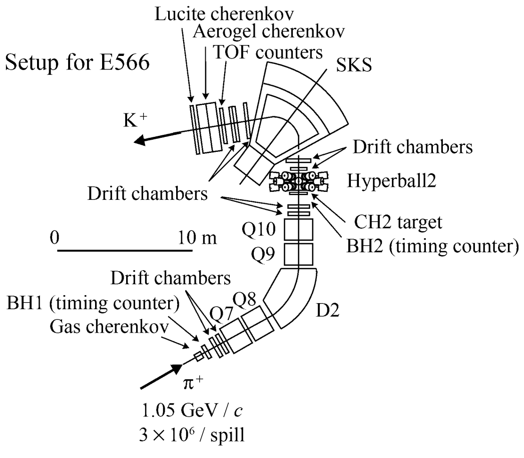

Fig. 1 Experimental setup for the KEK-E566 experiment.

The background particles contaminating in the

$\pi^+$ beam were vetoed by the trigger counters in the beam line. Four sets of drift chambers together with a magnetic spectrometer are employed to measure the momentum of the projectile $\pi^+$ with a least chisquare method[6]. The kinematic information of the scattered particles was obtained by the scattered particle spectrometer system. The major component of this system is the Superconducting Kaon Spectrometer (SKS)[8]. There were also four sets of drift chambers (SDC), one set of TOF counters, two sets of aerogel Cerenkov counters (AC1, 2) and one set of Lucite Cerenkov counters (LC) used in conjunction with the SKS magnet. The (AC1, 2) and LC were responsible for vetoing the scattered $\pi^+$ and p, respectively. The Runge-Kutta method was used to reconstruct the tracks of the scattered particles with the measured hit position by the SDC and a magnetic field map of SKS[9]. The mass of the produced hypernuclei can then be evaluated with the measured momentum of the incident $\pi^+$ and that of the outgoing $K^+$ by

$$M_{\mathrm{HY}} = \sqrt{(E_\pi + M_\Lambda - E_\mathrm{K})^2 - (p_\pi{}^2 + p_\mathrm{K}{}^2 - 2p_\pi p_\mathrm{K}\cos\theta_{\pi\mathrm{K}})}.$$

To be physically more instructive, we further express the hypernuclear mass in terms of the binding energy of $\Lambda$ hyperon as

$$B_\Lambda = M_{\mathrm{A}-1} + M_\Lambda - M_{\mathrm{HY}},$$

where $M_{\mathrm{A}-1}$ and $M_\Lambda$ are the mass of the core nucleus and a $\Lambda$ hyperon, respectively. The analysis result is shown by Fig. 2. The vertical lines in Fig. 2 are the theoretical results whose height represents the relative intensity[10].

By selecting a certain region in the $\Lambda$ binding energy spectrum, the corresponding hypernuclear level spacings can be experimentally determined with the $\gamma$-ray spectrum measured with Hyperball2 apparatus.

Hyperball2 consists of 14 single type and 6 clover type Ge detectors in total and can cover 25% of 4π solid angle. The schematic drawing of Hyperball2 is given in Fig. 3.

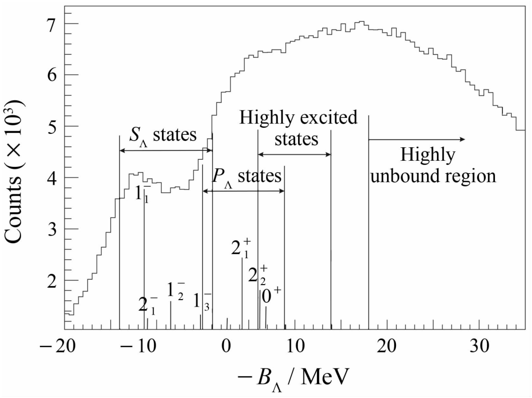

Fig. 2 Measured hypernuclear mass spectrum in the $^{12}\mathrm{C}(\pi^+, \mathrm{K}^+)^{12}_{\Lambda}\mathrm{C}$ reaction plotted in the $B_\Lambda$ scale. Vertical lines show theoretically calculated cross sections and $B_\Lambda$ for $^{12}_{\Lambda}\mathrm{C}$ states.

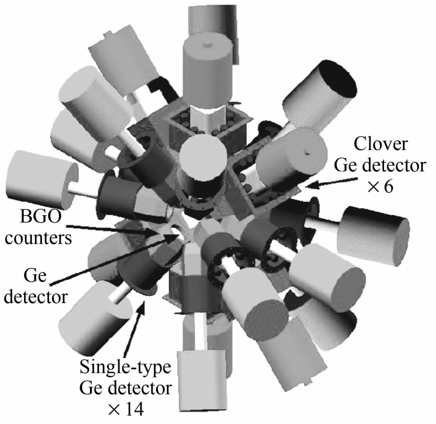

Fig. 3 Schematic view of Hyperball2.

Each of the Ge detectors was surrounded by BGO counters to suppress the background signals. The function of the BGO suppression is shown in Fig. 4, in which the identified $\gamma$-ray peaks were also indicated.

There was a $^{60}$Co source attached to each Ge detector to monitor its performance during the beam time. The $^{152}$Eu and $^{60}$Co sources were used for the low energy region calibration of the Ge detectors. The $\gamma$ rays from the excited state of $^{16}$O (6 128 keV) and $^{24}$Mg (2 754 keV), which were generated from the materials in the detector frame around the target, were used for the Ge calibration in the high energy region. As a summary, the Hyperball2 worked in a stable condition through one month beam time. The energy resolution by adding all the detectors' data was 5.3 keV for 1.33 MeV $\gamma$ rays and the photo peak efficiency was about 3.6% for 1.33 MeV $\gamma$ rays.

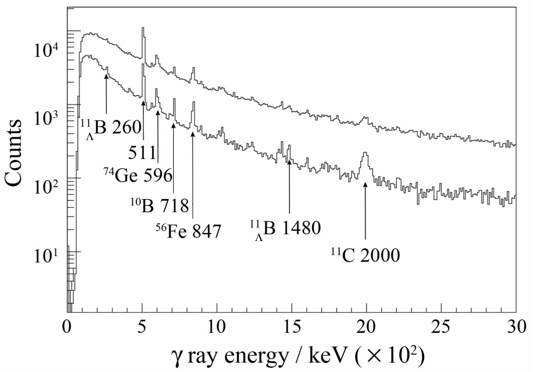

Fig. 4 The $\gamma$-ray spectrum with (lower curve) and without (upper curve) BGO suppression.

## 2.2 Results and discussion

As shown in Fig. 2, the $B_{\Lambda}$ spectrum was divided into sub-regions according to the theoretical calculation as well as taking into account the experimental energy resolution. For the ${}^{12}_{\Lambda}\mathrm{C}$ hypernucleus, if the $\Lambda$ was populated in the *p*-orbit or highly excited states, a proton emission should occur during deexcitation. The ${}^{11}_{\Lambda}\mathrm{B}$ hypernucleus was populated in this process as a hyperfragment. Thus, the possible $\gamma$-ray transitions we can observe when requesting $-5\ \mathrm{MeV} < -B_{\Lambda} < 9\ \mathrm{MeV}$ are ${}^{11}_{\Lambda}\mathrm{B}(1/2^+ \to 5/2^+)$ and the transition between the ground state doublet, ${}^{11}_{\Lambda}\mathrm{B}(7/2^+ \to 5/2^+)$, as shown in Fig. 5.

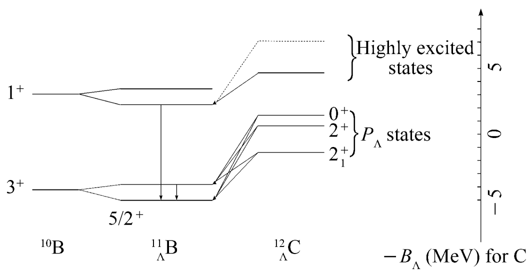

Fig. 5 The level scheme of ${}^{11}_{\Lambda}\mathrm{B}$ and its parent ${}^{12}_{\Lambda}\mathrm{C}$ hypernucleus.

The identified two $\gamma$ rays are $(1\,481.7 \pm 0.7)$ keV and $(261.6 \pm 0.24)$ keV. They were assigned to ${}^{11}_{\Lambda}\mathrm{B}(1/2^+ \to 5/2^+)$ and ${}^{11}_{\Lambda}\mathrm{B}(7/2^+ \to 5/2^+)$, respectively. In fact, the 261 keV $\gamma$ ray was first observed in a previous Hyperball experiment (KEK-E518)[11]. However, the spin assignment was not possible in that experiment.

The $\gamma$ rays from the ${}^{12}_{\Lambda}\mathrm{C}$ can be studied by setting $-14\ \mathrm{MeV} < -B_{\Lambda} < -4\ \mathrm{MeV}$ since this corresponds to the *s*-orbit $\Lambda$ state which can not decay strongly. The level scheme and possible transitions are shown in Fig. 6. The level energies mentioned are from a previous reaction spectroscopy experiment[7]; the branching ratios are provided by Millener.

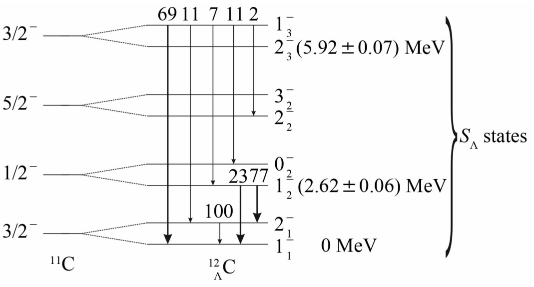

Fig. 6 The low-lying level scheme and possible transitions of ${}^{12}_{\Lambda}\mathrm{C}$ hypernucleus.

In this $B_{\Lambda}$ region, one $\gamma$-ray peak was identified at $(2667.3 \pm 2.8)$ keV after applying Doppler shift correction[9]. We assigned this peak to the transition of ${}^{12}_{\Lambda}\mathrm{C}(1^-_2 \to 2^-)$ instead of ${}^{12}_{\Lambda}\mathrm{C}(1^-_2 \to 1^-)$ by considering the branching ratio.

From these three hypernuclear $\gamma$-ray peaks, we can extract information on the interaction parameters. In the case of ${}^{11}_{\Lambda}\mathrm{B}(7/2^+ \to 5/2^+)$, the spin-spin interaction term ($\Delta$) has the main contribution to the level spacing. By assuming the numerical values of the other three terms derived from previous experiments, the $\Delta$ can be calculated to be 0.33 MeV. Similarly, the nucleon spin- dependent spin-orbit term ($S_N$) can be obtained from the ${}^{11}_{\Lambda}\mathrm{B}(1/2^+ \to 5/2^+)$ and ${}^{12}_{\Lambda}\mathrm{C}(1^-_2 \to 2^-)$ transitions. The $S_N$ was calculated to be $-0.7$—$-0.9$ MeV in this way. A previous experiment on ${}^{7}_{\Lambda}\mathrm{Li}$ hypernucleus determined $\Delta$ (0.43 MeV) and

$S_N$（$-0.4$ MeV） values[4]. This may suggest that the $\Delta$ value should be slightly smaller (0.33 MeV) in the later half of the $p$-shell than the value in the first half of the $p$-shell（${}^{7}_{\Lambda}$Li） hypernuclei. This point is also supported by the newly discovered excitation doublet in ${}^{16}_{\Lambda}$O[12]. The variation of the $S_N$ term among different species of hypernucleus is within 10% except our present data. Thus the current $S_N$ term is inconsistent with the previously established value. This may be solved by introducing a more sophisticated shell model calculation or it may be considered as a hint for other effects in the $\Lambda$N interaction. However, more experimental data is needed to draw a conclusion.

## 3 E13 at J-PARC

The upcoming J-PARC facility can provide high intensity kaon beam with various beam energies. A systematic investigation of light hypernuclei via $\gamma$-ray spectroscopy method was proposed and approved as one of the Day-1 experiments. In the proposed experiment (E13), several light hypernuclei will be studied (${}^{4}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li, ${}^{10}_{\Lambda}$B, ${}^{11}_{\Lambda}$B and ${}^{19}_{\Lambda}$F). The newly developed germanium detector array Hyperball-J will be used. The motivation to choose ${}^{10}_{\Lambda}$B and ${}^{11}_{\Lambda}$B as our target is to solve the long existing inconsistency between the theoretical prediction and experiment[13]. The ${}^{7}_{\Lambda}$Li hypernucleus shows a good opportunity to measure the $\Lambda$ hyperon magnetic momentum inside the nuclear medium because the $\mu_\Lambda$ is related to the M1 transition probability, which can be measured with Doppler shift attenuation method. The ${}^{19}_{\Lambda}$F as the simplest $d$-shell hypernucleus will reveal the radial dependence of the $\Lambda$N interaction by comparing to the previous $p$-shell hypernuclear data. The ${}^{4}_{\Lambda}$He hypernucleus will be populated on a liquid helium target. The precisely measured level spacing of the ${}^{4}_{\Lambda}$He hypernucleus is essential to check the existence of a large charge symmetry breaking in the $\Lambda$N interaction suggested by the old data.

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