Letter

Precise determination of $^{12}$C level structure by $\gamma$-ray spectroscopy

Kenji Hosomi$^{1,2,*}$, Yue Ma$^{1,b}$, Shuhei Ajimura$^{3,c}$, Kanae Aoki$^{4}$, Seishi Dairaku$^{5}$, Yuanyong Fu$^{6}$, Hiroyuki Fujioka$^{7,d}$, Kenta Futatsukawa$^{1,e}$, Wataru Imoto$^{8}$, Yutaka Kakiuch$^{g}$, Masaharu Kawai$^{1}$, Sari Kinoshita$^{1}$, Takeshi Koike$^{1}$, Nayuta Maruyama$^{1}$, Masahiro Mimori$^{1}$, Shizu Minami$^{3,f}$, Yusuke Miura$^{1}$, Koji Miwa$^{5,g}$, Yohei Miyagi$^{1}$, Tomofumi Nagae$^{4,d}$, Daisuke Nakajima$^{5,h}$, Hiroyuki Noumi$^{4,c}$, Kotaro Shirotori$^{1,c}$, Tomokazu Suzuki$^{9,c}$, Toshiyuki Takahashi$^{4}$, Tonomori N. Takahashi$^{7,c}$, Hirokazu Tamura$^{1}$, Kiyoshi Tanida$^{10,a}$, Nobuhiro Terada$^{1}$, Akihisa Toyoda$^{4}$, Kyo Tsukada$^{1,i}$, Mifuyu Ukai$^{9,g}$, and Shuhua Zhou$^{6}$

1 Department of Physics, Tohoku University, Sendai 980-8578, Japan
2 Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
3 Department of Physics, Osaka University, Toyonaka 560-0043, Japan
4 High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
5 Department of Physics, Kyoritsu University, Kyoto 606-8502, Japan
6 China Institute of Atomic Energy, Beijing 102413, China
7 Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
8 Osaka Electro-Communication University, Neyagawa 572-8530, Japan
9 Cyclotron and Radioisotope Center, Tohoku University, Sendai 980-8578, Japan
10 RIKEN, Wako 351-0198, Japan
*E-mail: hosomi@post.j-parc.jp

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The level structure of the $^{12}$C hypernucleus was precisely determined by means of $\gamma$-ray spectroscopy. We identified four $\gamma$-ray transitions via the $^{12}$C($\pi^+, K^+\gamma$) reaction using a germanium detector array, Hyperball2. The spacing of the ground-state doublet $(2^-, 1^+_1)$ was measured to be $161.5 \pm 0.3$(stat) $\pm 0.3$(syst) keV from the direct $M1$ transition. Excitation energies of the $1^-_2$ and $1^-_3$ states were measured to be $2832 \pm 3 \pm 4$ keV and $6050 \pm 8 \pm 7$ keV, respectively. The level energies obtained provide definitive references for the reaction spectroscopy of $\Lambda$ hypernuclei.

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*Present address: Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan.

**Present address: Advanced Meson Science Laboratory, RIKEN, Wako 351-0198, Japan.

†Present address: Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan.

‡Present address: Department of Physics, Kyoto University, Kyoto 606-8502, Japan.

§Present address: High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan.

¶Present address: GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany.

¥Present address: Department of Physics, Tohoku University, Sendai 980-8578, Japan.

$Present address: Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 227-8582, Japan.

**Present address: Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai 982-0826, Japan.

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1. **Introduction**  Spectroscopic studies of hypernuclei have played remarkable roles in our understanding of hyperon–nucleon (YN) and hyperon–hyperon (YY) interactions, since the short lifetimes of hyperons make YN and YY scattering experiments technically difficult, unlike the nucleon–nucleon (NN) case. For investigation of Λ hypernuclei structure, two types of spectroscopic techniques, one reaction based and the other γ-ray based, have made active progress in recent years.

Reaction spectroscopy, in which hypernuclear states are directly populated and analyzed from missing mass in the \((K^-, \pi^-), (\pi^+, K^+), \) and \((e, e' K^+)\) reactions, originated in the 1970s. The first experiment utilized the \((K^-_{\text{stopped}}, \pi^-)\) reaction at CERN [1], which was soon replaced by the in-flight \((K^-, \pi^-)\) reaction [2] with a small momentum transfer. After the 1980s, the \((\pi^+, K^+)\) reaction with a large momentum transfer was developed at BNL [3] and later at KEK [4]. At the beginning of this century, the \((e, e' K^+)\) reaction was developed at Jefferson Lab (JLab) [5], achieving a sub-MeV (FWHM) mass resolution. In addition, a new type of experiment was also performed with the \((K^-_{\text{stopped}}, \pi^-)\) reaction with an excellent resolution using low-energy \(K^-\) s from \(\phi\) meson decay at the DAΦNE facility [6]. Those reaction spectroscopy methods have their own characteristics in terms of selectivity of populating states, mass resolution, experimental yields, background, and so on. From among them one can choose the most suitable method according to the purpose of the study. Although it is necessary to cross check and/or calibrate the mass scale among different experiments using those different reactions, in general the cross check is not straightforward because the populated states are not necessarily the same between the different reactions.

High-precision γ-ray spectroscopy with ultra-high resolution (typically a few keV) employing a dedicated germanium detector array, Hyperball [7], has been available since 1998 and revealed level schemes of various \(p\)-shell hypernuclei [8] below the nucleon emission threshold. The γ-ray spectroscopy data have been used to investigate spin-dependent parts of the \(\Lambda N\) interaction. In addition, precise level schemes determined by γ-ray spectroscopy have provided excellent reference data for reaction spectroscopy.

In all of the above reaction spectroscopy, carbon \((^{12}\text{C})\) has been chosen as the first target and then used to obtain a benchmark spectrum of \(^{12}\Lambda\text{C}\) or \(^{12}\Lambda\text{B}\) for spectrometer calibration. This is because 1) its structure is rather simple, and two peaks corresponding to hypernuclear states with a \(\Lambda\) in the \(s\) and the \(p\) orbit can be clearly separated; 2) the two peaks have relatively large production cross sections; and 3) \(^{12}\text{C}\) is readily available as a target. The \((\pi^+, K^+)\) experiments at KEK-PS [9,10] revealed small peaks lying between the prominent two peaks in the \(^{12}\Lambda\text{C}\) spectrum for the first time. These were assigned as the core excited states where a \(\Lambda\) in the \(s\) orbit is coupled to the excited states \((1/2^-, 3/2^-)\) of the core nucleus \(^{11}\text{C}\) (Fig. 1). Similar peaks were also observed later in \(^{12}\Lambda\text{B}\) spectra via the \((e, e' K^+)\) reaction [11,12]. In other words, progressive improvements of mass resolution in reaction spectroscopy opened access to detailed structures of \(^{12}\Lambda\text{C}\) and \(^{12}\Lambda\text{B}\). However, the reported excitation energies, which are summarized in Table 1, show significant differences with one another, even though the global structure of the spectra agree well. Thus, precise reference data on the \(^{12}\Lambda\text{C}\) level scheme via a γ-ray spectrum are essential for all the reaction spectroscopy.

We report here the first precise measurement of the \(^{12}\Lambda\text{C}\) level structure by γ-ray spectroscopy. Preliminary results have been reported in Refs [13–15].

2. **Experiment**  The KEK-PS E566 experiment was carried out at the K6 beam line of the 12 GeV Proton Synchrotron (PS) in KEK. For hypernuclear production, we used the \((\pi^+, K^+)\) reaction at 1.05 GeV/c. A total of \(2 \times 10^{12}\) pions were irradiated on a \(^{12}\text{C}\) target of a 19.1 g cm\(^{-2}\)-thick polyethylene disk in one month beam time. A typical beam intensity at the target was \(3 \times 10^6\) particles per spill.
Fig. 1. Low-lying level structures of $^{12}_\Lambda$C with the corresponding levels for the core nucleus, $^{11}$C \cite{16}. The four $\gamma$-ray transitions observed in the present experiment (KEK-PS E566) are shown together with the three excitation energies determined.

Table 1. List of the low-lying excitation energies of $^{12}_\Lambda$C($^{12}_\Lambda$B) measured in various experiments. The spin parities of the states which are theoretically expected to be populated are given in the $J^\pi$ column based on the weak-coupling picture of a $\Lambda$ and a $^{11}$C($^{11}$B) core. “Present” shows results obtained from $\gamma$-ray spectroscopy (KEK-PS E566), and the others are measured by missing mass spectroscopy.

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$^{12}<em>\Lambda$C $E</em>{ex}$ (MeV)</th>
<th>$^{12}<em>\Lambda$B $E</em>{ex}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^-$</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.06</td>
</tr>
<tr>
<td>2$^-$</td>
<td>0.1615</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>±0.0003</td>
<td></td>
</tr>
<tr>
<td>1$^-$</td>
<td>2.832</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td>±0.003</td>
<td>±0.17</td>
</tr>
<tr>
<td>1$^-$</td>
<td>6.050</td>
<td>6.30</td>
</tr>
<tr>
<td></td>
<td>±0.010</td>
<td>±0.11</td>
</tr>
</tbody>
</table>

1The doublet spacings were derived from two-peak component fitting with some constraints. See references for details.

of 1.5 s duration in every 4 s. Trajectories and momenta of beam pions and outgoing kaons were measured by the K6 beam spectrometer and Superconducting Kaon Spectrometer (SKeS), respectively. SKS had a large acceptance (100 msr) for detecting the outgoing kaons with laboratory reaction angles of $\theta_{\pi K} = 0^\circ$–$20^\circ$. More descriptions of the spectrometer system and analysis procedures for calculating missing mass are found in Refs. [10,17]. A germanium (Ge) detector array, Hyperball2, was newly constructed and installed surrounding the target for $\gamma$-ray detection. It was an upgraded version of the Hyperball array, which was set up with fourteen Ge detectors having an N-type coaxial crystal of 60% relative efficiency (r.e.). Hyperball2 used these fourteen detectors with an addition of six clover-type Ge detectors, each of which has four smaller (20% r.e.) N-type coaxial crystals closely packed in a common cryostat. The clover-type detector achieves 120% r.e. by taking the sum of energies in the four crystals, which is known as the add-back effect \cite{18}. The total solid angle and the photo-peak efficiency of Hyperball2 were about 30% × 4$\pi$ sr and 4% for 1 MeV $\gamma$ rays, respectively. Each Ge detector was surrounded by segmented bismuth germanate (BGO) counters for suppressing
background, such as Compton scattering events inside the Ge crystals and high-energy $\gamma$ rays from $\pi^0$ decays.

3. Analysis Energy calibration of Hyperball2 was performed over the range of 0.1–6.1 MeV using a $^{152}$Eu source as well as $\gamma$ rays from surrounding materials activated by beam-induced reactions, such as $^{24}$Na($2754$ keV) from $^{27}$Al($n, \alpha$) in the detector frames and $^{10}$N($6129$ keV) from $^{16}$O($n, p$) in the BGO crystals. The systematic error in the energy calibration was estimated to be 0.3 keV for the energy region below 3 MeV and 0.6 keV for the energy region above 3 MeV. Performance of each Ge detector was continuously monitored using a $^{60}$Co source embedded in a plastic scintillation counter [7]. The in-beam live time and the energy resolution were $(59.3 \pm 0.3)$% on average and 5.4 keV (FWHM) at 1.33 MeV, respectively. The coincidence window for the Ge detectors relative to the beam timing was set to 20–200 ns as a function of energy because the time resolution of Ge detectors strongly depended on the amplitude of signals. Events were also rejected when surrounding BGO counters had a hit within 65 ns relative to the beam timing.

In the ($\pi^+, K^+$) reaction at 1.05 GeV/$c$, the hypernuclei produced have recoil velocities of $\beta = 0.028$–0.038, which lead to a typical stopping time of 2 ps in the target medium. Therefore, $M1$ transitions with an energy larger than a few hundred keV are expected to have a broadened peak shape due to the Doppler-shift effect. We applied an event-by-event correction to $\gamma$-ray energy by using recoil momenta of $^{12}_{\Lambda}$C, reaction vertices, and positions of Ge detectors with hits. It is noted that the Doppler-shift correction systematically gives a 0.1% uncertainty on the measured $\gamma$-ray energy, where the dominant component is geometrical ambiguity ($\pm$5 mm) in the positions of the Hyperball2 apparatus relative to the magnetic spectrometer system.

Figure 2 shows the missing mass spectrum for $^{12}_{\Lambda}$C plotted versus the $\Lambda$ binding energy ($B_\Lambda$). As illustrated with the dashed and the dotted curves, $^{12}_{\Lambda}$C states are decomposed into three groups corresponding to different combinations of a $^{11}$C core and a $\Lambda$ hyperon orbit. The dashed curve on the left side represents the $^{12}_{\Lambda}$C ground state. The other curves are mixtures of several states, of which cross sections and excitation energies measured in KEK-E369 [10] are referred. We simulated a response function of a single state in our missing mass spectrum by taking account of the measured performance of the spectrometer system and the effect of target thickness. As a result, the missing mass resolution was 6 MeV (FWHM). The absolute mass scale was adjusted so that the ground state has $B_\Lambda = 10.76$ MeV [19]. The region of $-10$ MeV $< -B_\Lambda < -2$ MeV was set for a tight event selection of the core-excited $s_\Lambda$ states that are supposed to $\gamma$ decay.

4. $\gamma$-ray assignment Figure 3 shows $\gamma$-ray energy spectra. Figures 3(a) and 3(c) are the spectra without the Doppler shift correction when the unbound region ($-B_\Lambda > -2$ MeV) of $^{12}_{\Lambda}$C is selected. The $e^+e^-$ annihilation peak and several $\gamma$ rays from ordinary nuclei such as $^{10}$B, $^{11}$C, $^{12}$C, $^{56}$Fe, and $^{74}$Ge are presented in the spectrum. Two peaks at 264 keV and 1483 keV are consistent with the known energies of transitions in $^{11}_{\Lambda}$B, which were previously measured with Hyperball in the $^{11}$B($\pi^+, K^+$) reaction [20]. In the present experiment, $^{11}_{\Lambda}$B was formed through one proton emission from the unbound states of $^{12}_{\Lambda}$C. Figures 3(b) and 3(d) are the spectra without the Doppler shift correction for the “core-excited $s_\Lambda$ region,” where peaks appear more prominently at 162 keV and at 2671 keV. After the event-by-event Doppler shift correction, the 2671 keV peak becomes sharp and then enhanced as shown in Fig. 3(e). Additionally, two more peaks at 2838 keV and 6048 keV are observed with a statistical significance of about 3 $\sigma$ in Fig. 3(e). The fact that the peaks are observed only in Fig. 3(b) and in Fig. 3(e) clearly demonstrates their origin in $^{12}_{\Lambda}$C. 
Fig. 2. $^{12}$C excitation spectrum obtained in the $^{12}$C($\pi^+$, $K^+$) reaction with the missing mass resolution of 6 MeV (FWHM). The dashed and the dotted curves show decomposition of $^{12}$C states based on a simulation (see text). The “core-excited region” is defined as $-10 \text{ MeV} < -B_\Lambda < -2 \text{ MeV}$ and is used for $\gamma$-ray analysis.

Fig. 3. $\gamma$-ray energy spectra measured by Hyperball2 in coincidence with the $^{12}$C($\pi^+$, $K^+$) reaction. Missing mass selections are applied to the unbound region ($-B_\Lambda > -2 \text{ MeV}$) for (a) and (c), and to the core-excited $s_\Lambda$ region ($-10 \text{ MeV} < -B_\Lambda < -2 \text{ MeV}$) for (b), (d), and (e). The peak at 162 keV in (b) is assigned as the direct $M1$ transition between the ground-state doublet ($2\frac{1}{2}^- \rightarrow 1\frac{1}{2}^- \rightarrow 1\frac{1}{2}^-$). The spectrum (e) is obtained by applying an event-by-event Doppler shift correction to the same data set of (d). Three peaks are observed in (e): two peaks at around 2.8 MeV are attributed to the $M1(1\frac{1}{2}^- \rightarrow 2\frac{1}{2}^- \rightarrow 1\frac{1}{2}^-)$ transitions, and the peak at 6 MeV to the $M1(1\frac{1}{2}^- \rightarrow 2\frac{1}{2}^- \rightarrow 1\frac{1}{2}^-)$ transition.

The two peaks at 2671 keV and 2838 keV are assigned to transitions from the upper $1\frac{1}{2}^-$ state to the ground-state doublet, by comparing their energies from the high-resolution ($\pi^+$, $K^+$) $^{12}$C spectrum with a thin target [10]. In the weak-coupling picture, both transitions are of $M1$ character induced by the transition of the core nucleus itself, $^{11}$C : $M1(1/2^- \rightarrow 3/2^-)$. It is consistent with the fact that the peaks are enhanced by the Doppler-shift correction. As results of the peak fitting to the Doppler-shift corrected spectrum, the $\gamma$-ray energies and the yields are $2671 \pm 3 \text{(stat)} \pm 3 \text{(syst)}$ keV and $56 \pm 10$ counts for the lower peak, and $2838 \pm 4 \pm 3 \text{keV and } 24 \pm 7 \text{ counts for the upper peak}$, respectively.

Since the transition ratio of ($1\frac{1}{2}^- \rightarrow 1\frac{1}{2}^-) / (1\frac{1}{2}^- \rightarrow 2\frac{1}{2}^-)$ is calculated to be 0.33 in the weak-coupling limit, the observed yield ratio $N(2838) / N(2671) = 0.43 \pm 0.15$ supports a spin $1^-$ assignment to the ground state. The effective efficiencies of Hyperball2 are different for the two transitions.
when we take into account the angular correlations [21] between the outgoing $K^+$s and $\gamma$ rays. Each effective efficiency was calculated by a simulation and the ratio $\epsilon(1_2^- \rightarrow 1_1^-)/\epsilon(1_2^- \rightarrow 2_1^-) = 0.88 \pm 0.02\text{(syst)}$ was obtained. In the simulation, we assumed the strongest $\theta_{K\gamma}$ correlation case at $\theta_{\pi K} = 0^\circ$, though the correlations are smeared at non-zero $\theta_{\pi K}$. The observed yield ratio $N(2838)/N(2671)$ is modified to $0.49 \pm 0.17$ by considering the $\theta_{K\gamma}$ correlation. It is found that the $\theta_{K\gamma}$ correlation effect does not change the spin $1^-$ assignment to the ground state. This spin assignment is further evidenced by a $\gamma$-ray yield for the direct $M1$ transition between the ground-state doublet as mentioned below.

The energy difference $(167 \pm 5 \text{ keV})$ between the $2671 \text{ keV}$ and $2838 \text{ keV}$ transitions overlaps with the $162 \text{ keV}$ peak energy. Thus, the $162 \text{ keV}$ $\gamma$ ray is assigned as the $M1$ transition between the ground-state doublet ($2_1^- \rightarrow 1_1^-)$, where the essential process is the spin flip of a $\Lambda$ hyperon. A simple Gaussian fitting gives the transition energy of $161.5 \pm 0.3 \pm 0.3 \text{ keV}$ and the yield of $172 \pm 25$ counts. The $2_1^-$ state is excited by the spin-flip interaction in the $(\pi^+, K^+)$ reaction with a small cross section relative to the spin-non-flip $1_1^-$ state (about 10% at $\theta_{\pi K} = 15^\circ$) according to theoretical prediction [22]. The observed $162 \text{ keV}$ yield (172 counts) is consistent with the expected yield for the $2_1^- \rightarrow 1_1^-$ transition via the direct spin-flip production of the $2_1^-$ state and the cascade feedings from the upper excited states, as discussed in detail later.

The $6 \text{ MeV}$ $\gamma$ peak observed in the Doppler-shift-corrected spectrum is attributed to the $M1(1_3^- \rightarrow 1_1^-)$ transition. The $\gamma$-ray energy and yield of $6048 \pm 8 \pm 7 \text{ keV}$ and $21 \pm 7$ counts, respectively, are obtained by fitting with a simulated response function. The observed peak width agrees with that for a full Doppler broadening. Although it is difficult to identify population of the $1_3^-$ state in our missing mass spectrum, the $1_3^-$ state of $^{12}_\Lambda\text{C}(^{11}\text{B})$ has been confirmed around $6 \text{ MeV}$ excitation energy in other experiments with much better missing mass resolutions (see Table 1). The $M1(1_3^- \rightarrow 1_1^-)$ yield is expected to be $24 \pm 6$ counts based on the $1_3^-$ state cross section measured in KEK-E369, theoretical $\gamma$-ray branching ratios [23], and detector efficiencies in the present experiment. The obtained yield of the $6 \text{ MeV}$ $\gamma$ ray supports the assignment of $M1(1_3^- \rightarrow 1_1^-)$ to the transition.

The excitation energies of the $^{12}_\Lambda\text{C}$ states were determined by applying a nuclear recoil correction to the observed $\gamma$-ray energies. They are summarized in Table 1 with comparable results of other experiments. For the $2.8 \text{ MeV}$ excitation energy, we took an energy sum of the cascading transitions ($1_2^- \rightarrow 2_1^- \rightarrow 1_1^-)$ because of poor statistics for the ($1_2^- \rightarrow 1_1^-)$ transition. The measured energy spacing of the $(2_1^-, 1_1^-)$ doublet implies that weak decay competes with the $M1$ transition for the $2_1^-$ state. This poses a question in weak decay measurements of $\Lambda N$ interaction. Low-lying levels of $p$-shell hypernuclei have been studied with a phenomenological approach, where strengths of the spin-dependent $\Lambda N$ interactions are parametrized in four terms [26,27]. A recent shell model calculation [28] predicts a comparable doublet spacing of $153 \text{ keV}$ by using the already known $\Lambda N$ interaction parameters and an additional term for the $\Lambda - \Sigma$ coupling effect. More detailed discussion on the $\Lambda N$ interaction will be given in another paper to be published later together with $^{11}_\Lambda\text{B} \gamma$-ray results.

5. Reaction angle dependence of $\gamma$-ray intensities Figure 4 shows relative intensities of $\gamma$-ray transitions plotted against the $(\pi^+, K^+)$ reaction angle with an interval of $3^\circ$ in the laboratory frame. The relative intensities were calculated from the measured $\gamma$-ray counts with a correction for the spectrometer acceptance and with a normalization for the $\gamma$-ray efficiency at...
162 keV. A wide missing mass region (−15 MeV < −B_L < 5 MeV) was selected for the γ-ray counting. We compared the obtained angular distributions with a calculation [29] in terms of the spin-flip and the spin-non-flip production components. The (1−2 → 1−1) intensities are understood from the calculation for the 1− spin-non-flip state. On the other hand, the (2−1 → 1−1) intensities show an enhancement at around θπK = 10°, at which the calculation for the 2− spin-flip state also has the maximum amplitude. This enhancement indicates a contribution of the direct 2− population in addition to the feeding process from the upper excited states.

With an assumption that the 2−1 state is populated by two processes, namely the direct production and the feeding from the 1−2 state, the production ratio of 2−1/1−1 was estimated to be (8 ± 3)% at θπK = 2°–20° from the yields of the cascading (1−2 → 2−1 → 1−1) transitions, the cross sections of (1−1, 1−2) in KEK-E369, and an estimated weak decay branching ratio of the 2−1 state (ΓM1 : Γweak = 0.32 : 0.68). For the estimation of the weak decay branching ratio, the calculated M1 transition width [21] and the measured weak decay width [30] for the ground state were used. We also referenced the magnetic moments in Ref. [16] for a 11C nucleus and in Ref. [31] for a Λ hyperon. More elaborate analysis gave the 2−1/1−1 ratio of (5 ± 3)% with a consideration of feeding populations from possible excited states. We estimated that the effect of angular correlations between the outgoing K+ and γ rays is negligible in this discussion by comparing with the statistical error of γ-ray yields. The aforementioned theoretical calculation predicts 6% for the 2−1/1−1 ratio in the region of θπK = 2°–20° and agrees with the present result.

6. Summary
In summary, the KEK-PS E566 experiment successfully identified four γ-ray transitions from 12ΛC produced by the 12C(π+, K+) reaction. Low-lying 12ΛC levels were deduced. The obtained (2−1, 1−1) doublet spacing is consistent with other p-shell results in terms of strengths of the spin-dependent ΛN interactions. Our precise γ-ray data provide a solid reference to benchmark spectra for Λ hypernuclear spectroscopy experiments with various reactions, in which the 12ΛC (12ΛB) excitation spectra play particularly important roles for the purpose of spectrometer calibration as well as to investigate the reaction mechanism and weak decay properties of Λ hypernuclei.

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References