Measurement of the $B(E2)$ of ${}^{7}_{\Lambda}$Li and Shrinkage of the Hypernuclear Size

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We report on the first measurement of a hypernuclear γ-transition probability. γ rays emitted in the $E2(5/2^+ \to 1/2^+)$ transition of ${}^{7}_{\Lambda}$Li were detected by a large-acceptance germanium detector array (Hyperball), and the lifetime of the parent state $(5/2^+)$ was determined by the Doppler shift attenuation method. The obtained result, $5.8^{+0.9}_{-0.7} \pm 0.7$ ps, was then converted into the reduced transition probability $[B(E2)]$ to be $B(E2; 5/2^+ \to 1/2^+) = 3.6 \pm 0.5^{+0.5}_{-0.4}\ e^2\,\mathrm{fm}^4$. Compared with the $B(E2)$ of the corresponding $E2(3^+ \to 1^+)$ transition in the ^{6}Li nucleus, our result gives evidence that the size of the ^{6}Li core in ${}^{7}_{\Lambda}$Li is smaller than the ^{6}Li nucleus in the free space.

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Change of matter properties under the presence of impurities is an important subject in condensed matter physics. Similarly, bulk properties of nuclei, such as size, shape, collective motion, and so on might be changed by the presence of hyperons as impurities, although no experimental evidence has been found yet. In particular, significant reduction of nuclear size could be expected when a Λ hyperon is added to loosely bound light nuclei such as ^{6}Li [1–3]. Since a Λ particle does not suffer from Pauli blocking, it can locate at the center of a nucleus; then the Λ attracts surrounding nucleons and makes the nucleus shrink.

In order to obtain information on such a possible size contraction experimentally, we used the $E2(5/2^+ \to 1/2^+)$ transition in ${}^{7}_{\Lambda}$Li (see Fig. 1). The reduced transition probability $[B(E2)]$ is very sensitive to size contraction as it is approximately proportional to fourth power of the nuclear size. In the weak coupling limit, since the $E2(5/2^+ \to 1/2^+)$ transition in ${}^{7}_{\Lambda}$Li is due to the $E2(3^+ \to 1^+)$ transition in ^{6}Li core, we introduce a factor S which naively represents degree of size change of ^{6}Li core [3] by

$$S = \left[\frac{9}{7} \frac{B(E2; {}^{7}_{\Lambda}\mathrm{Li} 5/2^+ \to 1/2^+)}{B(E2; {}^{6}\mathrm{Li} 3^+ \to 1^+)} \right]^{1/4}, \quad (1)$$

where the factor $9/7$ comes from the fact that the $B(E2)$ of the core transition $(3^+ \to 1^+)$ is distributed to the two $E2$ transitions in ${}^{7}_{\Lambda}$Li as $B(E2; {}^{7}_{\Lambda}\mathrm{Li}5/2^+ \to 1/2^+) : B(E2; {}^{7}_{\Lambda}\mathrm{Li}5/2^+ \to 3/2^+) = 7 : 2$ in this limit [4]. If the ^{6}Li core in ${}^{7}_{\Lambda}$Li is the same as the ^{6}Li nucleus in the free space, this size factor equals unity. As we know the $B(E2; {}^6\mathrm{Li}3^+ \to 1^+)$ to be $10.9 \pm 0.9\ e^2\,\mathrm{fm}^4$ [5] or $9.3 \pm 2.1\ e^2\,\mathrm{fm}^4$ [6], we can extract hypernuclear size information from $B(E2; 5/2^+ \to 1/2^+)$.

The experiment (E419) was performed at the K6 beam line of the 12 GeV Proton Synchrotron (PS) in the High Energy Accelerator Research Organization (KEK) as the first experiment using the germanium (Ge) detector array recently constructed for hypernuclear γ-ray spectroscopy (Hyperball). We have already reported in Ref. [7] on the energies and assignments of the four γ transitions in ${}^{7}_{\Lambda}$Li observed in the experiment. In this paper, we report on the measurement of the $B(E2)$ value of the $E2(5/2^+ \to 1/2^+)$ transition. Taking advantage of high resolution of Ge detectors, we successfully measured the lifetime of the $5/2^+$ state by the Doppler shift attenuation method and then converted it into the $B(E2; 5/2^+ \to 1/2^+)$ value.

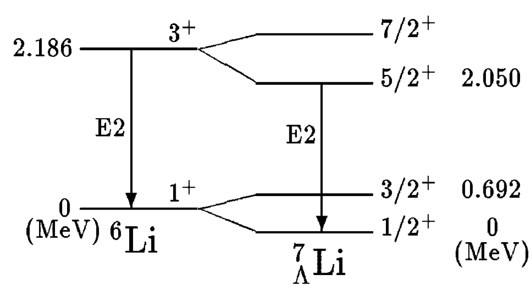

FIG. 1. Low-lying states of ${}^{7}_{\Lambda}$Li. Excitation energies are taken from Ref. [7]. Corresponding levels of ^{6}Li are also shown.

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In E419, we used the ^{7}Li(π^+, K^+) reaction at incident pion momentum of 1.05 GeV/c to produce $^7_\Lambda$Li, and detected γ rays in coincidence. The large momentum transfer of the (π^+, K^+) reaction ($\sim$350 MeV/c) enables us to utilize the Doppler shift attenuation method, as the stopping time of the recoiling $^7_\Lambda$Li ($\sim$13 ps) is of the same order as the expected lifetime (3–10 ps) [1,2,4] of the $5/2^+$ state. Momenta and trajectories of beam pions and outgoing kaons were measured by the beam line spectrometer and the Superconducting Kaon Spectrometer (SKS). From the measured momenta, we reconstructed missing mass of $^7_\Lambda$Li and selected the production events of the bound states of $^7_\Lambda$Li. More descriptions of the K6 beam line and SKS are found in Refs. [8,9]. A typical intensity of the pion beam was 1.8×10^6 per 3 second cycle. We irradiated a 98% enriched ^{7}Li target of 25 cm long with about 1.0×10^{12} pions in the beam time of about 25 days.

For γ-ray detection, we used Hyperball, which consisted of fourteen coaxial type Ge detectors having a crystal size of about 70 mmϕ $\times$ 70 mm. The Ge detectors were placed 15 cm away from the beam line and the total solid angle and the photopeak efficiency were about 15% $\times$ 4π sr and 2.5% for 1 MeV γ rays, respectively. Each Ge detector was surrounded by six bismuth germanate (BGO) counters, which provided veto signals for Compton scattering and electromagnetic shower of high-energy γ rays from π^0 decay. It is noted that we did not use the Ge detectors or the BGO counters for triggering, so that the inclusive ^{7}Li(π^+, K^+) spectrum could be taken.

Energy calibration of the Ge detectors was performed in the energy range of 0.1–1.8 MeV using a standard mixed source containing ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{51}Cr, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{60}Co, and ^{88}Y. Those calibration γ rays were also used to obtain response functions of the Ge detectors, which play an important role in the lifetime analysis described below. It is noted that slight deterioration of the response functions, especially in their tail parts, induced by radiation damage was observed during the beam time. The in-beam performance of each Ge detector was monitored simultaneously with the data taking through the whole beam time by using triggered γ rays from a weak (1 kBq) ^{60}Co source embedded in a plastic scintillator and installed behind each Ge detector. With the beam on, slight broadening (typically 10%–20%) of peak width due to the high-counting rate of the Ge detectors (20–60 kHz) was observed, while the tail shape was found to be the same. More experimental details are given in Ref. [7].

Figure 2 shows the excitation spectrum of $^7_\Lambda$Li plotted in the scale of Λ binding energy (B_Λ). See Ref. [9,10] for the analysis procedure to obtain the excitation spectrum. We decomposed the bound region of the observed spectrum into four Gaussian peaks, as described in Ref. [7]. The absolute energy scale was adjusted to reproduce the known B_Λ of the $^7_\Lambda$Li ground state. We set the gate for the "bound region" at $-10 < -B_\Lambda < 2$ MeV, as shown in the figure.

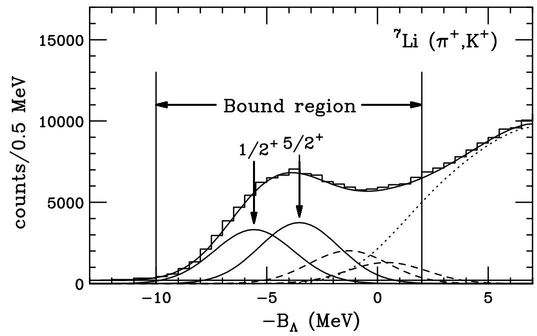

FIG. 2. Hypernuclear mass spectrum of $^7_\Lambda$Li (plotted versus the Λ binding energy, B_Λ) taken in the (π^+, K^+) reaction with a 25 cm thick ^{7}Li target. See Ref. [7] for the decomposition and assignments of states. The "bound region" is defined as shown.

Figure 3 shows the γ-ray energy spectra summed up for all the fourteen Ge detectors after the energy calibration. Figure 3(a) is the spectrum for the bound region of $^7_\Lambda$Li, and Fig. 3(b) is for the unbound region ($-B_\Lambda > 2$ MeV). See Ref. [7] for the assignment of the peaks observed in the spectra. The peak due to the $E2(5/2^+ \rightarrow 1/2^+)$ transition is the one at 2050 keV in spectrum 3(a).

Figure 4 is a magnification of Fig. 3(a) around the $E2(5/2^+ \rightarrow 1/2^+)$ peak. The high resolution of Ge detectors reveals that the peak has two components, namely, the sharp part and the broad tails; this fact indicates that the γ-ray energy is partly Doppler broadened. The γ-ray energy was determined to be 2050.1 $\pm$ 0.4 $\pm$ 0.7 keV from the position of the narrow peak as described in Ref. [7].

The lifetime of the parent state ($5/2^+$) was examined by analyzing the peak shape. First, in order to obtain the lifetime dependence of the peak shape, we performed Monte Carlo simulations. Then the lifetime was derived

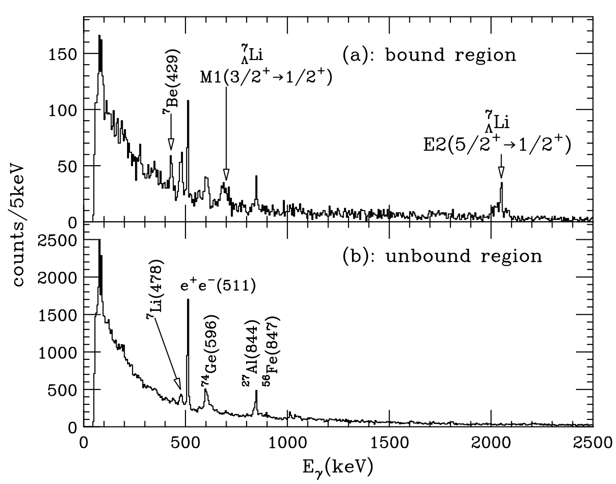

FIG. 3. γ-ray energy spectra measured in coincidence with the ^{7}Li(π^+, K^+) reaction. (a) For the bound region, and (b) for the unbound region ($-B_\Lambda > 2$ MeV). See Ref. [7] for the assignment of the peaks.

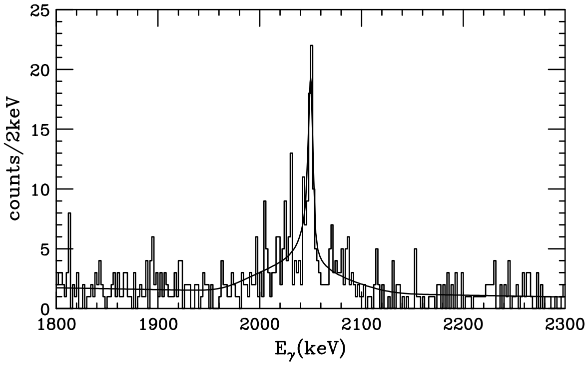

FIG. 4. γ-ray energy spectrum around the $E2$ peak. The result of the fitting to simulated spectra (see text) is shown with the solid line.

by fitting the simulated spectra with a background to the observed spectrum. Here we assumed a linear shape for the background, and there was no significant change of the lifetime when we used quadratic or exponential shapes.

The Monte Carlo simulations were performed in the following way. First, for each of the measured (π^+, K^+) events, we generated γ rays at the reaction point, which was determined by taking the vertex of the measured trajectories of beam π^+ and outgoing K^+ projected onto the horizontal (xz) plane. The rms spatial resolutions of the reaction point thus determined were 1, 5, and $1.2/|\theta_{\mathrm{horizontal}}|$ mm, for the x, y, and z coordinates, respectively, where $\theta_{\mathrm{horizontal}}$ is the horizontal scattering angle measured in radian. In order to obtain good z-vertex resolution, we rejected events with $|\theta_{\mathrm{horizontal}}| < 10$ mrad. The effect of this finite resolution together with that of a systematic position uncertainty of 5 mm was considered in estimating the systematic error of the lifetime and was found to be negligible. We also performed a simulation where we used a vertex position uniformly distributed in the target volume instead of the measured one, and obtained the same lifetime.

The energy of the generated γ ray was fixed to be 2050.1 keV in the rest frame of $^{7}_{\Lambda}$Li; even if we changed the γ-ray energy by ± 0.4 keV, no significant change of obtained lifetime was found. The angular distribution of the γ rays was assumed to be uniform in the rest frame of $^{7}_{\Lambda}$Li, since we could not obtain it reliably due to the limited statistics. Because of a possible spin alignment effect of $^{7}_{\Lambda}$Li, this assumption may not be correct. In order to estimate the systematic error due to this assumption, we also performed a simulation in which the spin of $^{7}_{\Lambda}$Li was aligned to $|j_{z'}| = 5/2$ where the z' direction is normal to the reaction plane.

Second, for a given lifetime, the γ-decay timings were determined to follow exponential distributions. The Doppler shift of the γ-ray energy was calculated from the velocity of $^{7}_{\Lambda}$Li at the time of the decay, which was derived from the recoil momentum of $^{7}_{\Lambda}$Li by taking into account the slowing down process in the target. The initial recoil momentum was calculated by subtracting the measured K^+ momentum vector from that of π^+ with a correction for the momentum loss in the target. The resolution of the recoil momentum was estimated to be 6 MeV$/c$ (FWHM) from the $^{7}_{\Lambda}$Li mass resolution. The absolute value was calibrated by using the position of the ground state in the $^{7}_{\Lambda}$Li mass spectrum (see Fig. 2) with a systematic error of ± 1 MeV$/c$ coming from the uncertainty of central beam momentum (± 4 MeV$/c$). The systematic error and the resolution of the recoil momentum were found to have negligible effects on the lifetime analysis.

Slowing down of $^{7}_{\Lambda}$Li in the lithium target was simulated by the SRIM code [11] which is based on experimental data and is commonly used for calculating the stopping powers of ions in matter. We estimated the overall uncertainty of the stopping power given by the code to be $\pm 5\%$ from the errors of the calculated stopping powers of various ions in helium and beryllium [12] and that of protons in lithium [13].

Last, when a γ ray hits a Ge detector, the γ-ray energy, after convolution with the response function of the Ge detectors, was booked into a histogram. The response function was derived from the calibration data of the 1.836 MeV γ rays from ^{88}Y, averaged over all the Ge detectors and the calibration runs throughout the beam time. Here the peak width and tail width were extrapolated to 2.05 MeV by assuming that they were proportional to $\sqrt{E_\gamma}$ and E_γ, respectively. We also used response functions at the beginning and at the end of the beam time to estimate the systematic error. It is noted that the in-beam peak broadening of about 20% was taken into account in the simulations and was found to have negligible effect on the obtained lifetime.

The results of the simulations are shown in Fig. 5 for the lifetimes of 5.8 ps (best fit value), 4.4 ps (best fit -2σ), and 7.6 ps (best fit $+2\sigma$). It is noted that the simulation well reproduced the peak shape of the $M1(3/2^+ \rightarrow 1/2^+)$ transition at 692 keV by assuming a very short lifetime ($<$1 ps) for the $3/2^+$ state [7].

The fitting result is shown with the solid line in Fig. 4. The reduced χ^2 of the fit was 0.78 at the best-fit point given

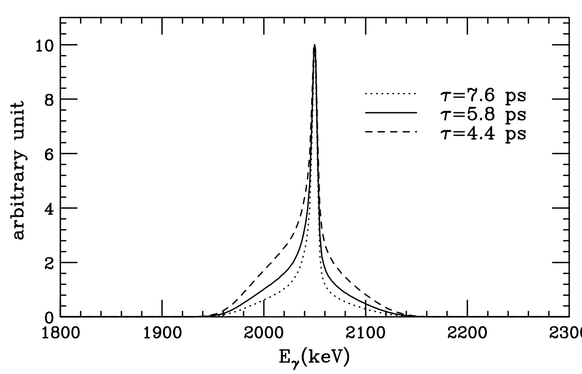

FIG. 5. Simulated γ-ray energy spectra of the $E2(5/2^+ \rightarrow 1/2^+)$ γ rays for $5/2^+$ lifetimes of 4.4 ps (dashed line), 5.8 ps (solid line), and 7.6 ps (dotted line). Peak heights are normalized.

by the maximum likelihood method. The lifetime of the $5/2^+$ state obtained by the fitting is $5.8^{+0.9}_{-0.7} \pm 0.7$ ps. Here the main sources of the systematic errors are uncertainties in the distribution of γ-ray direction (± 0.4 ps), in the Ge response function (± 0.4 ps), and in the stopping power (± 0.3 ps).

We then converted the lifetime thus obtained into the $B(E2)$ value. To do this, we need the branching ratio of the $E2(5/2^+ \rightarrow 1/2^+)$ transition, which was derived by subtracting estimated branching ratios of the other possible decay modes, namely, the $5/2^+ \rightarrow 3/2^+$ transition and the weak decay. We took the weak coupling limit value (3.6%) as the branching ratio of the $5/2^+ \rightarrow 3/2^+$ transition; this value is consistent with the calculation of Hiyama *et al.* (3.8%) [3] and our nonobservation of the transition, whose branching ratio was found to be smaller than 4.3% at 68% confidence level. The branching ratio of the weak decay was estimated to be $2.6 \pm 0.4\%$, assuming the partial decay rate to be $(230 \pm 40\ \text{ps})^{-1}$ from the lifetime data of $A = 4, 5, 11, 12$ hypernuclei [14–17]. Thus the branching ratio of the $E2(5/2^+ \rightarrow 1/2^+)$ transition was obtained to be $93.8^{+3.6}_{-0.8}\%$.

Using this branching ratio, the $B(E2; 5/2^+ \rightarrow 1/2^+)$ was calculated to be $3.6 \pm 0.5^{+0.5}_{-0.4}\ e^2\,\text{fm}^4$. Then the size factor in Eq. (1) is $S = 0.81 \pm 0.04$ [for $B(E2; {}^6\text{Li}) = 10.9 \pm 0.9\ e^2\,\text{fm}^4$: use of $B(E2; {}^6\text{Li}) = 9.3 \pm 2.1\ e^2\,\text{fm}^4$ gives 0.84 ± 0.06], and is significantly smaller than unity expected if the ^{6}Li core in $^7_\Lambda$Li is the same as the ^{6}Li in the free space. This fact gives strong evidence for the shrinkage of ^{6}Li core in $^7_\Lambda$Li.

In cluster models, the reduction of the $B(E2)$ value can be interpreted as due to shrinkages of intercluster distances. For example, in a simple $\alpha(^5_\Lambda\text{He})$-$d$ cluster model for $^6\text{Li}(^7_\Lambda\text{Li})$, $S = 0.81$ means the rms distance between $^5_\Lambda$He and d in $^7_\Lambda$Li is by 19% shorter than that of α and d in ^{6}Li. This interpretation remains valid in a more elaborate $\alpha(^5_\Lambda\text{He})$-$p$-$n$ model calculation [2,3] where the contraction occurs along the distance between the (np) center of mass and the $\alpha(^5_\Lambda\text{He})$ cluster with the n-p internal motion hardly changed. The $B(E2)$ values themselves are calculated by Motoba *et al.* [α-d-(Λ) model] [1] and by Hiyama *et al.* [$\alpha(^5_\Lambda\text{He})$-$p$-$n$ model] [3], and they predicted $S = 0.84$ and $S = 0.75$, respectively. As for the latter calculation, Hiyama *et al.* recently updated it by using a four-body α-p-n-Λ model for $^7_\Lambda$Li [18] and gave $S = 0.78$. These calculated values are consistent with the present result. Thus the present result can be understood within the frameworks of those cluster models.

In summary, we obtained the reduced transition probability of the $E2(5/2^+ \rightarrow 1/2^+)$ transition in $^7_\Lambda$Li by measuring the lifetime of the $5/2^+$ state using the Doppler shift attenuation method. This is the first determination of a γ-transition probability in hypernuclei. The obtained result, $3.6 \pm 0.5^{+0.5}_{-0.4}\ e^2\,\text{fm}^4$, is about one-third of the $B(E2)$ of the corresponding $E2(3^+ \rightarrow 1^+)$ transition in ^{6}Li, and is evidence for the shrinkage of the ^{6}Li core in the $^7_\Lambda$Li hypernucleus.

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