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Observation of the 7 MeV excited spin-flip and non–spin-flip partners in $^{16}_{\Lambda}$O by γ-ray spectroscopy

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Abstract. We have observed three γ-ray transitions in $^{16}_{\Lambda}$O from both 7 MeV excited spin-flip and non–spin-flip partners $(2^-, 1^-_2)$ to the ground-state doublet $(1^-_1, 0^-)$ via the ^{16}O(K^-, π^-) reaction. The 7 MeV excitation energies of the spin-doublet members $(2^-, 1^-_2)$ were determined to be $6784 \pm 4 \pm 4$ keV and $6562 \pm 1 \pm 2$ keV, respectively, and thus the spacing was obtained to be $222 \pm 4 \pm 5$ keV. This is the first observation of the spin-flip state directly populated by the (K^-, π^-) reaction. Moreover, such directly populated spin-flip and non–spin-flip partners were resolved for the first time.

PACS. 21.80.+a Hypernuclei – 23.20.Lv γ transitions and level energies – 13.75.Ev Hyperon-nucleon interactions

1 Introduction

We have performed a series of hypernuclear γ-ray spectroscopy experiments using the germanium detector array, Hyperball [1]. Information on the ΛN spin-dependent interactions can be obtained from the precise measurements of hypernuclear level structures [2]. The effective ΛN interaction has four spin-dependent components, the spin-spin, the Λ-spin-dependent spin-orbit, the N-spin-dependent spin-orbit and the tensor interactions, whose strengths in p-shell hypernuclei are given by the parameters denoted as Δ, S_Λ, S_N and T, respectively. All the low-lying level spacings in p-shell hypernuclei are given by their linear combinations through shell-model calculations.

In the Hyperball experiments, all of the four parameters were determined from specific level spacings of hypernuclei, Δ from $^{7}_{\Lambda}$Li $(3/2^+, 1/2^+)$ [3], S_Λ from $^{9}_{\Lambda}$Be $(3/2^+, 5/2^+)$ [4], S_N from $^{7}_{\Lambda}$Li $(5/2^+, 1/2^+)$ [3] and T from $^{16}_{\Lambda}$O $(0^-, 1^-)$ [5], respectively. Since each parameter was determined almost independently from one particular level spacing, it is necessary to verify that these four parameters can consistently explain all other spacings of p-shell hypernuclei. Thus accumulation of other p-shell hypernuclear data is an important subject.

In many cases, in hypernuclear spin-doublet states, the upper member of the doublet is a spin-flip state. The spin-flip amplitude is much smaller than the non-spin flip amplitude in ordinary used reactions such as (π^+, K^+) at $p_\pi \sim 1$ GeV$/c$ and (K^-, π^-) at $p_K < 1$ GeV$/c$. If there

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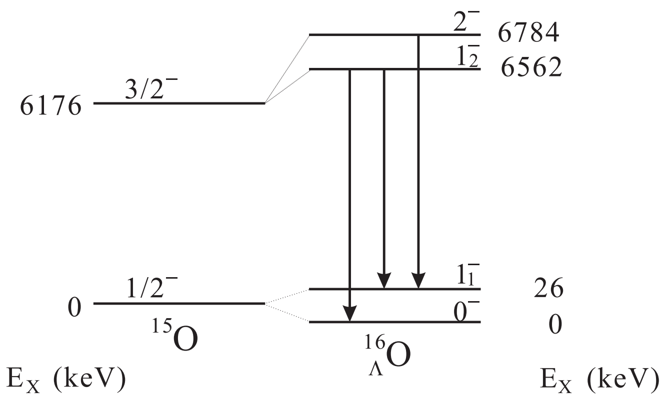

Fig. 1. Experimentally determined level scheme of $^{16}_{\Lambda}$O and observed γ-ray transitions in the present experiment. The corresponding level scheme of ^{15}O is also shown. Both 1^- states of $^{16}_{\Lambda}$O are populated via the 0.93 GeV/c (K^-,π^-) with the $\Delta L = 1$ and $\Delta S = 0$ reaction and the 2^- state was found to be also populated via the $\Delta L = 1$ and $\Delta S = 1$ reaction.

are higher-energy bound states which can de-excite to the doublet states, the doublet spacing can be measured from the energy difference between γ-ray transitions to both doublet members (*e.g.*, $^{16}_{\Lambda}$O$(1_2^- \to 1_1^-, 0^-)$ [5]). In alternative way it can be resolved from the direct measurement of the spin-flip $M1$ transition between the doublet (*e.g.*, $^{7}_{\Lambda}$Li$(1/2^+; T = 1 \to 3/2^+, 3/2^+ \to 1/2^+)$ [3])[1]. If particle unbound states of a primary hypernucleus produced by a direct reaction can decay to a secondary hypernucleus, spin-flip states in the secondary hypernucleus can be also populated (*e.g.*, $^{10}_{\Lambda}$B$^* \to {}^{7}_{\Lambda}$Li $(7/2^+) + {}^{3}$He [6]). However, such methods cannot always be applied to produce the spin-flip states. In order to produce various hypernuclear spin-flip states, a new Hyperball experiment exploiting the (K^-,π^-) reaction at $p_K = 1.5$ GeV/c [7] was proposed. This experiment was approved as one of the Day-1 experiments at a new facility, J-PARC [8].

Nevertheless, it is pointed out that there is a small but non-zero spin-flip amplitude in the (K^-,π^-) reaction at $p_K = 0.9$ GeV/c [9,10], which was the momentum value of the beam used during the previous Hyperball experiment at BNL (E930) [4–6]. One of the hypernuclei investigated in E930('01) was $^{16}_{\Lambda}$O. Figure 1 shows the level scheme of the bound states in $^{16}_{\Lambda}$O. In this reaction, the 1_2^- and the 1_1^- states are mainly produced via the $\Delta L = 1$ and $\Delta S = 0$ transition. In addition, the 2^- and the 0^- states were expected to be also produced via the $\Delta L = 1$ and $\Delta S = 1$ transition with smaller production cross-sections. The 1_2^- state can decay to both ground-state doublet members $(1_1^-, 0^-)$ while the 2^- state can only decay to the 1_1^- state via $M1$ transitions. In this paper we report on the observation of the $2^- \to 1^-$ transition from a recent reanalysis of the data.

[1] Among the five bound states in $^{7}_{\Lambda}$Li, the non–spin-flip states are $1/2^+; T = 1$, $5/2^+$ and $1/2^+$, and the spin-flip states are $7/2^+$ and $3/2^+$.

2 Experiment

The γ-ray spectroscopy experiment on $^{16}_{\Lambda}$O, E930('01), was performed at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS). Bound states of $^{16}_{\Lambda}$O were produced by the ^{16}O(K^-,π^-) reaction employing a 0.93 GeV/c kaon beam at the D6 beam line [11]. This experiment was aimed to measure the ground-state spin doublet spacing to determine the ΛN tensor interaction parameter, T. Some results was reported in ref. [5].

A high-purity K^- beam with a K^-/π^- ratio of 3 was delivered every 4.6 s, to the target, with a typical intensity of 2×10^5 per spill of 1.5 s duration. We irradiated a 20 g/cm^2 H_2O target with 4×10^{10} K^-. The spectrometer accepted particles scattered by $-8°$ to $+8°$ in the horizontal direction and by $0°$ to $16°$ in the vertical direction. Incident and outgoing particles were momentum analyzed with magnetic spectrometers and the bound states production events were selected by the reconstructed $^{16}_{\Lambda}$O mass.

γ-rays were detected using Hyperball installed around the target. Hyperball consisted of 14 Ge detectors, each surrounded by six bismuth germanate (BGO) counters used to suppress background events such as Compton scattering and π^0 decay. Each Ge detector had an N-type coaxial crystal of about 200 cc in volume and their relative efficiency to a $3'' \times 3''$ NaI counter was 60%. The total photo-peak efficiency for the beam-on period was measured to be (1.5 ± 0.3)% for 2.3 MeV γ-ray and (4.2 ± 1.0)% for 0.7 MeV γ-ray including electronics dead time as well as analysis efficiencies. The efficiency curve as a function of the γ-ray energy was simulated by the GEANT code and the absolute efficiency scale was adjusted to fit the measured efficiencies.

Detailed experimental method and the apparatus are described in ref. [5].

3 Analysis

The $^{16}_{\Lambda}$O mass was calculated as missing mass in the ^{16}O (K^-,π^-) reaction. The absolute mass scale was calibrated using the π^0 mass reconstructed in the $K^- \to \pi^-\pi^0$ decay. The energy loss of the incident K^- and outgoing π^- in the target medium was corrected for every event. Due to the straggling on the energy loss in the thick target and the original beam momentum width, the K^- momentum at the reaction point peaked at around 0.91 GeV/c with a width of 0.06 GeV/c (FWHM). The mass resolution of hypernuclear state was found to be 15 MeV (FWHM).

Since the 1_2^- state mass was measured to be $-B_\Lambda = -7$ MeV [12–14], the mass region corresponding to the excited doublet states $(2^-, 1_2^-)$ was set as $-17 < -B_\Lambda < 3$ MeV. Here, B_Λ is the Λ-binding energy defined by $B_\Lambda = M_{^{16}\mathrm{O}} + M_\Lambda - M_{^{16}_{\Lambda}\mathrm{O}}$.

Events were selected in which a Ge detector has a hit in the 20 ns time gate for over 5 MeV energy without any

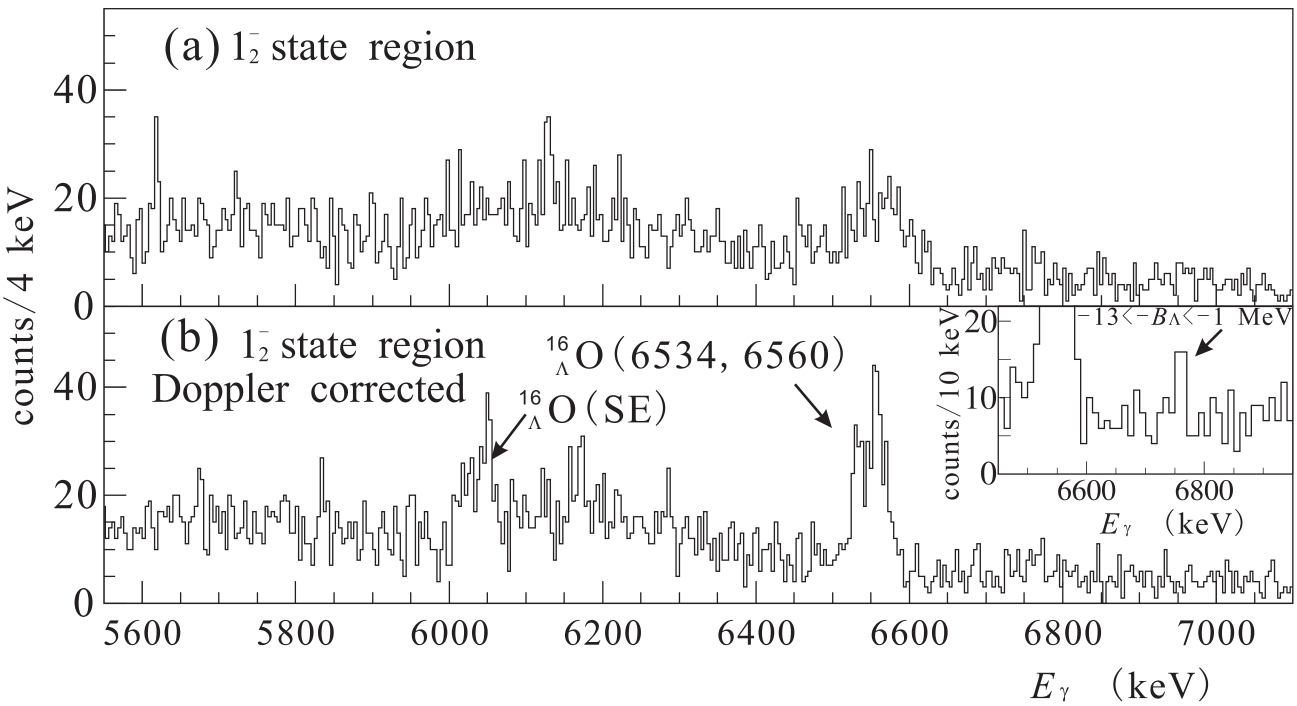

Fig. 2. Mass-gated γ-ray spectra measured in the ^{16}O(K^-, π^-) reaction for the 1_2^- state region ($-17 < -B_\Lambda < 3$ MeV). (b) is the same spectrum as (a) but with event-by-event Doppler-shift correction applied. The two peaks which appear at 6534 and 6560 keV are assigned to the $1_2^- \to 1_1^-$ and the $1_2^- \to 0^-$ transitions, respectively [5]. The inset in (b) shows the spectrum for $-13 < -B_\Lambda < -1$ MeV. Gathering of events appears at $6758 \pm 4 \pm 4$ keV was found to be a peak with a statistical significance 3 σ from background. The narrower mass gate, $-13 < -B_\Lambda < -1$ MeV, was chosen to maximize the signal to noise ration, S^2/N, of the γ-ray peaks from the 1_2^- state (6534 and 6560 keV γ-rays).

hits in the corresponding BGO detectors in the 50 ns coincidence gate. The energy calibration curve of Ge detectors was successfully obtained up to 7.1 MeV using the γ-ray peaks from the sources and activities originating from the beam; in particular, we used γ-ray peaks from ^{16}N $\to$ ^{16}O + β^- at 6129 and 7115 keV. These γ-rays from ^{16}N were observed in the Ge-self-trigger data taken during the beam-off period of the synchrotron cycle.

The response function of the γ-ray peak shape after summing up the 14 Ge detectors well fitted by a Gaussian function. The beam-on energy resolution in FWHM was obtained to be 5.7 keV for 2 MeV γ-ray and 8.6 keV for 6.5 MeV γ-ray.

The 1_2^- and 2^- states at ~ 7 MeV excitation are expected to decay by $M1$ transitions and the lifetimes of these states would be less than 1 fs on the basis of a single-particle estimation. On the other hand, the stopping time of the produced ${}^{16}_{\Lambda}$O with 0.1–0.2 GeV/c recoil momentum in the target medium was estimated to be of the order of 1 ps. Therefore, the γ-ray peak shape should be fully Doppler broadened to a width of over 100 keV. However, the shifted energy can be corrected event by event using the reconstructed recoil momentum of ${}^{16}_{\Lambda}$O, reaction vertex point and the position of a Ge crystal with the hit. The peak shape after the Doppler-shift correction was determined from the setup geometry, kinematical condition, reaction vertex point, Ge crystal volume and the original response function.

4 Result

Figure 2(a) shows the mass-gated γ-ray spectrum for the 1_2^- state region ($-17 < -B_\Lambda < 3$ MeV). The same spectrum after the event by event Doppler shift correction is reported in fig. 2(b). Two peaks which appear at 6533.9 ± 1.2 (stat.) $\pm$ 1.7 (syst.) keV and $6560.3 \pm 1.1 \pm 1.7$ keV in the Doppler-shift–corrected spectrum are assigned to the $1_2^- \to 1_1^-$ and the $1_2^- \to 0^-$ transitions, respectively. Since the $1^- \to 0^-$ transition is calculated to have a larger branching ratio than the $1^- \to 1^-$ transition, the spin-ordering of the doublet was obtained from the γ-ray yield ratio $N(6534)/N(6560) = 0.69 \pm 0.11 \pm 0.05$ [5].

To observe the γ-ray transition from the weaker spin-flip state, background level should be reduced. Therefore, we set a narrower mass gate ($-13 < -B_\Lambda < -1$ MeV) which was chosen to maximize the signal-to-noise ratio, S^2/N, of the 6534 and 6560 keV γ-ray peaks, because the mass difference between the $(2^-, 1_2^-)$ doublet states is expected to be much smaller than the mass resolution. As a result we found a peak in the Doppler-shift–corrected spectrum with a statistical significance of 3.0 σ ($21.0^{+7.2}_{-6.5}$ counts) at an energy of $6758 \pm 4 \pm 4$ keV, as shown in the inset of fig. 2(b). The peak width was found to be consistent with the simulated Doppler-shift–corrected peak shape. Since no states other than the ground and 7 MeV excited doublet members, namely $(1_1^-, 0^-)$ and $(2^-, 1_2^-)$, are expected to be produced by this reaction, this γ-ray transition is attributed to the $2^- \to 1^-$ transition. This results is the first experimental evidence of direct production of the spin-flip state in hypernuclei via the (K^-, π^-) reaction.

Applying after the recoil energy correction, the excitation energy of the 2^- state was obtained to be $6786 \pm 4 \pm 4$ keV. The level scheme of $^{16}_{\Lambda}$O was thus obtained as shown in fig. 1, where the corresponding level scheme of the core ^{15}O and the observed transitions are also shown.

For the narrower gate, the sum of the 6534 and the 6560 keV γ-ray yield was obtained to be 262 ± 24 counts. The γ-ray intensity ratio taking into account the γ-ray efficiencies was found to be

$$\frac{I_\gamma(6758)}{I_\gamma(6534) + I_\gamma(6560)} = 0.08 \pm 0.03. \quad (1)$$

This result suggests that the spin-flip cross-section is 10–20 times smaller than the non-spin-flip cross-section in the same doublet. Since the angular $(\theta_{K\pi})$ distribution of the production cross-section is expected to be different between the $\Delta S = 0$ and $\Delta S = 1$ reactions, the acceptance of the spectrometer may not be the same. This effect has to be corrected for to finalize the ratio of the $\Delta S = 1/\Delta S = 0$ cross-sections.

As shown in fig. 1, the 7 MeV excited spin-doublet $(2^-, 1^-_2)$ spacing was obtained to be $222 \pm 4 \pm 5$ keV. This spacing is mainly determined by the ΛN spin-spin interaction. According to the Millener's shell model calculation [15], this spacing can be well reproduced using $\Delta = 0.33$ MeV rather than $\Delta = 0.43$ MeV which was determined from the $^{7}_{\Lambda}$Li data [3]. This smaller Δ value was also suggested by another hypernuclear spin-doublet spacing, $^{11}_{\Lambda}$B$(7/2^+, 5/2^+)$ [16,17] (the ground-state doublet of $^{11}_{\Lambda}$B). To confirm the ΛN spin-dependent interaction strengths, further experimental data are strongly required.

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