Hypernuclear Fine Structure in ${}^{9}_{\Lambda}$Be

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With a germanium detector array (Hyperball), we observed two γ-ray peaks corresponding to the two transitions ($5/2^+ \to 1/2^+$ and $3/2^+ \to 1/2^+$) in the ${}^{9}_{\Lambda}$Be hypernucleus which was produced by the ^{9}Be(K^-, π^-) reaction. The energies of the γ rays are $3029 \pm 2 \pm 1$ keV and $3060 \pm 2 \pm 1$ keV. The energy difference was measured to be $31.4^{+2.5}_{-3.6}$ keV, which indicates a very small Λ-spin-dependent spin-orbit force between a Λ and a nucleon. This is the smallest level splitting by far ever measured in a hypernucleus.

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Spectroscopy of hypernuclei with keV resolution has been long awaited for the purpose of studying hypernuclear structure and hyperon-nucleon interactions. Recently, γ rays from ${}^{7}_{\Lambda}$Li were successfully observed [1,2] with a few keV resolution by using the germanium (Ge) detector array (Hyperball). The γ-ray spectroscopy is expected to reveal "fine structure" in Λ hypernuclei, namely, level splittings due to the spin-dependent ΛN interactions between a Λ and a core nucleus. It is expected that many such energy splittings are small, of the order of 100 keV or less, due to probably small spin-dependent ΛN interactions [3].

The effective two-body ΛN interaction in Λ hypernuclei can be expressed with five terms as [3,4]

$$\begin{aligned} V_{\Lambda N}(r) = {} & V_0(r) + V_\sigma(r)\boldsymbol{s}_N\boldsymbol{s}_\Lambda + V_\Lambda(r)\boldsymbol{l}_{N\Lambda}\boldsymbol{s}_\Lambda \\ & + V_N(r)\boldsymbol{l}_{N\Lambda}\boldsymbol{s}_N \\ & + V_T(r)[3(\boldsymbol{\sigma}_N\hat{\boldsymbol{r}})(\boldsymbol{\sigma}_\Lambda\hat{\boldsymbol{r}}) - \boldsymbol{\sigma}_N\boldsymbol{\sigma}_\Lambda]. \end{aligned}$$

As for the four spin-dependent terms, the radial integrals for $s_\Lambda p_N$ wave functions in p-shell hypernuclei, which are denoted as Δ, S_Λ, S_N, and T, can be determined phenomenologically so as to fit low-lying level energies of various p-shell hypernuclei [3–5]. The sensitivity to each term depends on the structure of the state to be measured.

Study of the spin-orbit components of hyperon-nucleon interactions is important to investigate the nature of the short-range baryon-baryon interaction. In particular, the characteristics of the ΛN spin-orbit interactions vary significantly in different models of the baryon-baryon interaction. One boson exchange (OBE) models [6] and quark models [7,8] predict similar magnitudes for the symmetric spin-orbit (SLS) force [$\propto \boldsymbol{l}_{N\Lambda}(\boldsymbol{s}_\Lambda + \boldsymbol{s}_N)$], whereas quark models predict much stronger antisymmetric spin-orbit (ALS) force [$\propto \boldsymbol{l}_{N\Lambda}(\boldsymbol{s}_\Lambda - \boldsymbol{s}_N)$] [7] than OBE models. In quark models, cancellation between the SLS and ALS forces results in a very small Λ-spin-dependent spin-orbit force [$V_\Lambda(r)\boldsymbol{l}_{N\Lambda}\boldsymbol{s}_\Lambda$ term] and, consequently, a very small spin-orbit splitting of Λ single-particle states.

The first indication of a small Λ spin-orbit force was given by an ^{16}O$(K^-, \pi^-){}^{16}_{\Lambda}$O experiment at CERN [9]. The energy difference between the $[(p_{1/2})_n^{-1}, (p_{1/2})_\Lambda]0^+$ and the $[(p_{3/2})_n^{-1}, (p_{3/2})_\Lambda]0^+$ states in ${}^{16}_{\Lambda}$O is almost the same as the difference between the $p_{1/2}$ and the $p_{3/2}$ hole states in ^{15}O, which corresponds to a spin-orbit splitting for the $p_{1/2}$ and $p_{3/2}$ Λ orbits of less than 0.3 MeV neglecting residual interactions. A small $p_{1/2}$-$p_{3/2}$ spin-orbit splitting of 0.36 ± 0.3 MeV was also obtained by studying the ^{13}C$(K^-, \pi^-){}^{13}_{\Lambda}$C reaction [10]. On the other hand, some recent data suggest larger splittings. A recent analysis of old emulsion data on ${}^{16}_{\Lambda}$O obtained a large $p_{1/2}$-$p_{3/2}$ spin-orbit splitting about 1 MeV [11]. In the ^{89}Y(π^+, K^+) spectroscopy experiment at KEK [12], double-peak structures were observed for the Λ single-particle states in ${}^{89}_{\Lambda}$Y. If the double-peak structures are interpreted as due to the spin-orbit splitting, a large spin-orbit force similar to the one suggested by the ${}^{16}_{\Lambda}$O emulsion data is implied.

It has been pointed out that ${}^{9}_{\Lambda}$Be is one of the best hypernuclei to study the ΛN spin-orbit interaction [4]. The first excited state (2^+) of the ^{8}Be core nucleus has an almost pure $L = 2$, $S = 0$ structure. When a Λ particle in the 0s orbit in ${}^{9}_{\Lambda}$Be is coupled to ^{8}Be(2^+), the state splits into a $5/2^+$ and $3/2^+$ doublet due to the Λ-spin-dependent spin-orbit force, $V_\Lambda(r)\boldsymbol{l}_{N\Lambda}\boldsymbol{s}_\Lambda$ (see Fig. 1). The other spin-dependent terms are expected to give small contributions to this level spacing. Therefore, the magnitude of the Λ-spin-dependent spin-orbit force can be obtained by measuring the energy spacing between the two excited states of $^9_\Lambda$Be.

The γ rays from the excited states ($5/2^+$, $3/2^+$) to the ground state ($1/2^+$) of $^9_\Lambda$Be were first observed using sodium iodide (NaI) counters in 1982 [14]. This experiment observed only one peak at 3079 ± 40 keV. Since the cross sections to populate the $5/2^+$ and $3/2^+$ states are calculated to be almost equal [4,15], it was concluded that the two transitions were not separately observed because of the limited energy resolution of the NaI counters ($\sim$160 keV), and an upper limit of 100 keV was set on the energy spacing of the ($5/2^+, 3/2^+$) doublet. However, another interpretation that the Λ spin-orbit force is so strong as to make the upper state of the doublet unbound is not excluded. In the present experiment, we measured γ rays from $^9_\Lambda$Be again but with Ge detectors, having much better energy resolution than NaI counters.

The experiment (E930) was performed at the Brookhaven National Laboratory (BNL) alternating gradient synchrotron (BNL AGS). Bound states of $^9_\Lambda$Be were produced by the ^{9}Be(K^-, π^-) reaction with a 0.93 GeV/c K^- beam at the D6 beam line, and γ rays were detected with Hyperball. Except for Hyperball, the setup was almost the same as in the previous experiments [16,17] at the D6 beam line. An 18.5-g/cm^2 ^{9}Be target was irradiated with 1.9×10^{10} K^- during the beam time of about 30 days.

A typical K^- intensity was 8×10^4 per spill of 1.4 s duration occurring every 4 s. The K^-/π^- ratio of the beam was typically 6. The incident K^- was identified with aerogel and total-reflection-type quartz Čerenkov counters at the trigger level and by the time-of-flight (TOF) method in the off-line analysis. Particle misidentification was negligible. For each event, the momentum of the K^- was analyzed by the beam-line spectrometer. A more detailed description of the D6 beam line can be found in Ref. [18].

The outgoing π^- was identified with two aerogel Čerenkov counters at the trigger level and momentum analyzed with a dipole magnetic spectrometer. The spectrometer is equipped with three drift chambers located upstream of the magnet, two drift chambers downstream of the magnet, and TOF counters downstream of them. After off-line analysis, contamination of other particles was negligible except for μ^- from K^- decay. Details of the elements of the spectrometer are described in Ref. [16]

Hyperball consists of fourteen Ge detectors having crystals of about 7 cm (diameter) $\times$ 7 cm (height). The Ge detectors were placed at 10 cm from the beam axis and arranged in barrellike form. They covered a solid angle of about 20% $\times$ 4π sr in total and their photopeak efficiency was 3.7% at 1000 keV and 1.5% at 3000 keV. Each Ge detector was surrounded by six bismuth germanate (BGO) counters which were used to suppress backgrounds from Compton scattering and γ rays from π^0 decays. Hits in more than one Ge detector within a 1 μs time gate in coincidence with the ^{9}Be(K^-, π^-) reaction were required for data acquisition. A more complete description of Hyperball can be found in Refs. [1,19].

Hyperball was calibrated in the range of 500–6000 keV. For the energy region below 2000 keV, we used e^+e^- annihilation and ^{60}Co and ^{88}Y sources. For the higher energy region, we used 6129 keV ^{16}O γ rays, which are emitted from a ^{244}Cm-^{13}C source via the ^{13}C(α, n)^{16}O* reaction, and their single and double escape peaks at 5618 and 5107 keV. We also used 2754 keV γ rays from ^{24}Na produced by a beam-induced reaction on aluminum [^{27}Al(n, α)^{24}Na*]. The energy resolution during beam-on conditions was measured using four peaks, 511 keV e^+e^- annihilation, 1173/1333 keV ^{60}Co γ rays, and 2313 keV ^{14}N γ rays from room background. By extrapolation, the energy resolution of Hyperball was estimated to be 7.6 keV FWHM at 3000 keV which is the energy region of our interest. The performance of each Ge detector was monitored with a ^{60}Co source embedded in a plastic scintillator behind each Ge detector. No change was found in the gain and the resolution between in-beam and off-beam periods.

Figure 2 shows a reconstructed missing mass spectrum for the ^{9}Be(K^-, π^-) reaction, plotted against the Λ binding energy (B_Λ), for events accompanied by 2000–4000 keV γ rays. The absolute mass scale was calibrated to reproduce π^0 and $\bar{\nu}$ masses from K^- decay events. The missing mass resolution was estimated to be 20 MeV FWHM from π^0 and $\bar{\nu}$ peak widths for K^- decay events. Although ^{9}Be(K^-, π^-) events include K^- decay backgrounds, the backgrounds are almost completely eliminated by requiring hits in more than one Ge detector within the time gates (typically 35 ns) and BGO timing veto (25 ns). Figure 2 is plotted after the Ge and BGO timing cuts are applied. We set the mass gate for the bound region of $^9_\Lambda$Be at -21 MeV $< -B_\Lambda <$ 4 MeV, as shown in Fig. 2. This gate was determined to maximize the figure of merit for the $5/2^+$ and $3/2^+$ excited states of $^9_\Lambda$Be. The figure of merit was defined as $S^2/(S + N)$,

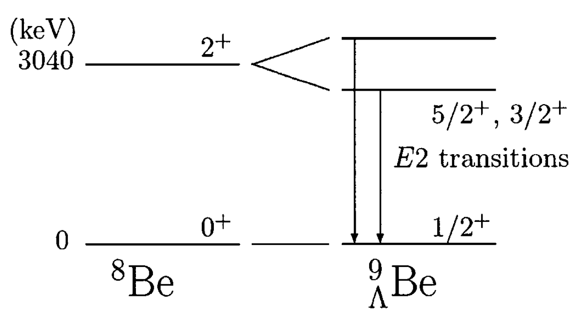

FIG. 1. Level scheme of ^{8}Be and $^9_\Lambda$Be. The excitation energy of ^{8}Be is taken from Ref. [13].

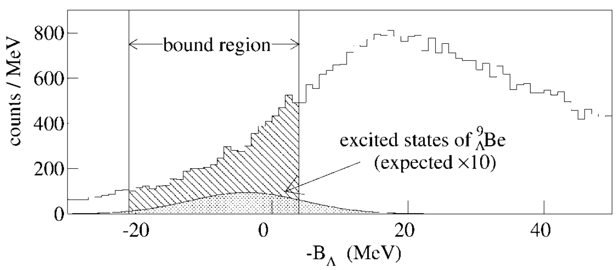

FIG. 2. Reconstructed missing mass spectrum of the ^{9}Be(K^-,π^-) reaction, plotted against Λ binding energy B_Λ, for events accompanied by 2000–4000 keV γ rays. The shaded spectrum shows the expected distribution multiplied by 10 for the $5/2^+$ and $3/2^+$ states of $^{9}_{\Lambda}$Be. The hatched region shows the "bound" region (-21 MeV $< -B_\Lambda <$ 4 MeV), which was determined to maximize the figure of merit for the excited states of $^{9}_{\Lambda}$Be (see text).

where S is the expected number of events of the $5/2^+$ and $3/2^+$ states of $^{9}_{\Lambda}$Be within the gate in the missing mass spectrum, and $(S + N)$ is the number of all the measured ^{9}Be(K^-,π^-) events within the same gate which are accompanied by 2000–4000 keV γ rays. Here, B_Λ of the ground state of $^{9}_{\Lambda}$Be was taken as 6.71 MeV [20], and the normalization of the expected distribution of the excited states of $^{9}_{\Lambda}$Be, shown in Fig. 2, was made using the cross sections calculated by Motoba [15].

Figure 3 shows γ-ray energy spectra summed up for all the Ge detectors. Figure 3(a) is the spectrum for the bound region (-21 MeV $< -B_\Lambda <$ 4 MeV) of $^{9}_{\Lambda}$Be and 3(b) is for the unbound region ($-B_\Lambda >$ 4 MeV). A twin-peak structure is observed at around 3045 keV only in the spectrum 3(a). The two peaks are assigned to the two $E2$ transitions ($5/2^+ \to 1/2^+$ and $3/2^+ \to 1/2^+$). The mean energy of the two peaks (3045 keV) is consistent with the peak energy observed in the past NaI experiment (3079 ± 40 keV) [14].

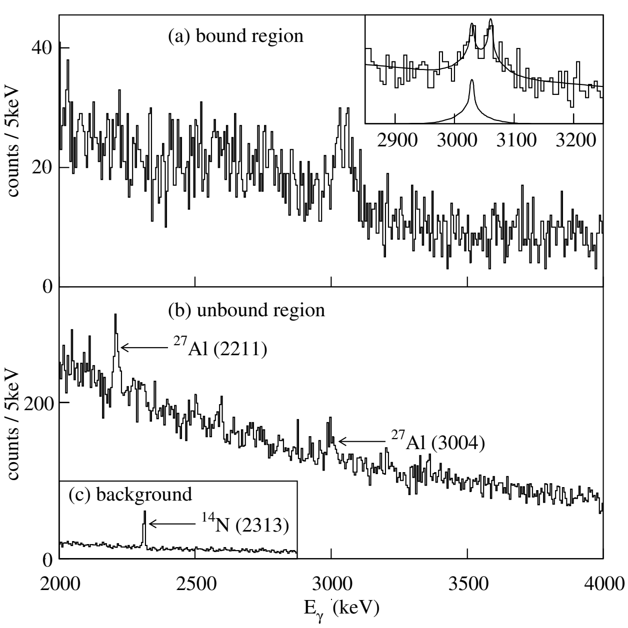

FIG. 3. γ-ray energy spectra measured in the ^{9}Be(K^-,π^-) $^{9}_{\Lambda}$Be reaction; (a) for the bound region (see Fig. 2), and (b) for the unbound region. A structure at around 3045 keV is observed only in (a). The inset of (a) shows the simulated peak shape for a single γ-ray peak (for 0.51 ps lifetime) and the fitting result with two γ-ray peaks. Inset (c) shows 2313 keV ^{14}N room background peak indicating the in-beam energy resolution.

To determine the energies of the two peaks, we made a fit with simulated peak shapes, taking into account the estimated energy resolution of Hyperball and the Doppler broadening calculated for various lifetimes of the γ-decaying states. The slowing-down process of the recoiling $^{9}_{\Lambda}$Be was simulated with the SRIM code [21]. It is noted that the lifetimes of the two states were assumed to be the same in the fit, while the numbers of counts for the two γ-ray peaks were independently taken as fitting parameters. As a result, the γ-ray energies were found to be 3029 ± 2(stat) ± 1(syst) keV and 3060 ± 2(stat) ± 1(syst) keV, where systematic errors come from the energy calibration error. The energy difference between them is $31.4^{+2.5}_{-3.6}$ keV. The lifetime of the states was derived to be $0.51^{+0.28}_{-0.14}$ ps. In the fitting, two types of background shapes were tested, a single linear function and two linear functions having different slopes for the upper side and the lower side of the peak structure. The errors in the energy spacing and in the lifetime include statistical errors and the influence of the different background types.

To investigate the possibility of interpreting the observed structure as a single broad peak rather than twin peaks, we made another γ-ray spectrum to which event-by-event Doppler shift corrections were applied assuming that the γ rays are emitted before the slowing down of the recoiling hypernucleus. If the structure is a Doppler-broadened peak originating from only one state, the Doppler shift correction should make the structure a single narrow peak. However, the Doppler-shift-corrected spectrum exhibited a broad structure. We simulated the Doppler-corrected peak shapes for various lifetimes of the decaying state. Then we fitted the Doppler-corrected peak shape and the uncorrected peak shape to the Doppler-corrected spectrum and the uncorrected spectrum, respectively. Here, the fit was performed synchronously with the common parameters, assuming the structure is composed of a single peak. As a result, the single broad peak interpretation is rejected at 95% confidence level.

The obtained lifetime converts to a reduced transition probability of $B(E2) = 5.7^{+2.1}_{-2.0}\ e^2\,\mathrm{fm}^4$. It is close to the value of 11.3 $e^2\,\mathrm{fm}^4$ predicted by Motoba *et al.* [15]. The number of observed γ rays in the peaks (181^{+46}_{-42} counts in total) was also in a reasonable agreement with the expected yield of the $E2$ transitions considering the detector and analysis efficiencies. The ratio of the counts for the two peaks (upper peak/lower peak) was 1.2 ± 0.3, which is also consistent with the calculated cross sections being almost equal for the $5/2^+$ and $3/2^+$ states of $^{9}_{\Lambda}$Be.

In a recent phenomenological shell-model approach [22], the energy spacing of the $(5/2^+, 3/2^+)$ doublet of $^{9}_{\Lambda}$Be is expressed as

$$\Delta E = E(3/2^+) - E(5/2^+) \\ = -0.036\Delta - 2.463 S_\Lambda - 0.002 S_N + 0.985 T\,.$$

In the present experiment, we cannot distinguish between $5/2^+$ and $3/2^+$ states. If the energy of the $5/2^+$ state is lower than the $3/2^+$ state, we have $-2.463S_\Lambda + 0.985T = 55$ keV, after using $\Delta = 619$ keV and $S_N = -549$ keV taken from Ref. [22]. These parameter values result after corrections for nuclear size and binding energy effects to the values which fit the energy spectrum of $^{7}_{\Lambda}$Li [1]. Thus, we obtain $S_\Lambda = -22$ keV for $T = 0$, or $-14 < S_\Lambda < -2$ keV for a typical value of $20 < T < 60$ keV [23] predicted by OBE model interactions via G-matrix calculations. If the energy of the $5/2^+$ state is higher than the $3/2^+$ state, we also obtain an S_Λ value close to zero, $3 < S_\Lambda < 27$ keV for $0 < T < 60$ keV. The derived S_Λ values are numerically much smaller than the predictions from the OBE models, $-180 < S_\Lambda < -130$ keV [23].

A similar conclusion is also derived when our observed splitting is compared with calculated ones by Hiyama *et al.* [24]. They predicted a spacing of $\Delta E = 80$–200 keV from a cluster-model calculation using ΛN interactions from the Nijmegen OBE models (NSC97a–f, Nijmegen D, and Nijmegen F). On the other hand, they obtained a much smaller spacing of 35–40 keV using the form of the spin-orbit force of the Nijmegen models together with the relative strength of the quark-model-based SLS and ALS forces (which give a very small value for S_Λ). Our result of a very small spin-orbit force seems to be consistent with the recent observation of the splitting of $152 \pm 54 \pm 36$ keV for $(p_{1/2})_\Lambda$-$(p_{3/2})_\Lambda$ states in $^{13}_{\Lambda}$C [17], which is also much smaller than the calculated value of 390–960 keV based on the OBE models [24].

Because S_N ($\propto \boldsymbol{l}_{N\Lambda} \boldsymbol{s}_N$) is rather well determined [22] to have a much larger numerical value than S_Λ, we conclude that the SLS and ALS components of the ΛN effective interactions are comparable in strength and are individually appreciable. Since the energy spacing is small, a contribution of the tensor interaction is not negligible compared to the spin-orbit force contribution as discussed above. In order to isolate the spin-orbit force contribution, an independent measurement of the strength of the tensor interaction is desirable. The objective of the next running period for E930 is to measure the ground-state doublet splittings of $^{15}_{\Lambda}$N and $^{16}_{\Lambda}$O which are very sensitive to T [3].

In summary, we measured γ rays from $^{9}_{\Lambda}$Be produced by the ^{9}Be(K^-, π^-) reaction and observed two γ ray peaks corresponding to the $5/2^+ \rightarrow 1/2^+$ and $3/2^+ \rightarrow 1/2^+$ transitions. The energies of the γ rays are $3029 \pm 2 \pm 1$ keV and $3060 \pm 2 \pm 1$ keV, and their energy spacing is $31.4^{+2.5}_{-3.6}$ keV. The lifetime of the γ-decaying states is $0.51^{+0.28}_{-0.14}$ ps which converts to a reduced transition probability of $B(E2) = 5.7^{+2.1}_{-2.0}\ e^2\,\mathrm{fm}^4$. Our result of a small spacing gives a very small Λ-spin-dependent ΛN spin-orbit force, which cannot be explained by the existing OBE models.

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[1] H. Tamura *et al.,* Phys. Rev. Lett. **84**, 5963 (2000).
[2] K. Tanida *et al.,* Phys. Rev. Lett. **86**, 1982 (2001).
[3] D. J. Millener *et al.,* Phys. Rev. C **31**, 499 (1985).
[4] R. H. Dalitz and A. Gal, Ann. Phys. (N.Y.) **116**, 167 (1978).
[5] N. Fetisov *et al.,* Z. Phys. A **339**, 399 (1991).
[6] Th. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C **59**, 21 (1999), and references therein.
[7] O. Morimatsu *et al.,* Nucl. Phys. **A420**, 573 (1984).
[8] Y. Fujiwara, C. Nakamoto, and Y. Suzuki, Phys. Rev. Lett. **76**, 2242 (1996).
[9] W. Brückner *et al.,* Phys. Lett. **79B**, 157 (1978).
[10] M. May *et al.,* Phys. Rev. Lett. **47**, 1106 (1981).
[11] R. H. Dalitz *et al.,* Nucl. Phys. **A625**, 71 (1997).
[12] H. Hotchi *et al.,* Phys. Rev. C **64**, 044302 (2001).
[13] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988).
[14] M. May *et al.,* Phys. Rev. Lett. **51**, 2085 (1983).
[15] T. Motoba, H. Bando, and K. Ikeda, Prog. Theor. Phys. **70**, 189 (1983).
[16] P. Khaustov *et al.,* Phys. Rev. C **61**, 054603 (2000).
[17] S. Ajimura *et al.,* Phys. Rev. Lett. **86**, 4255 (2001).
[18] P. H. Pile *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **321**, 48 (1992).
[19] K. Tanida, Ph.D. thesis, University of Tokyo, 2000.
[20] M. Jurič *et al.,* Nucl. Phys. **B52**, 1 (1973).
[21] J. F. Ziegler, The Stopping and Range of Ions in Matter, http://www.srim.org.
[22] D. J. Millener, Nucl. Phys. **A691**, 93c (2001).
[23] D. J. Millener, in *Proceedings of the Workshop on Hypernuclear Physics with Electromagnetic Probes,* edited by L. Tang and O. Hashimoto (Hampton University, Hampton, VA, 2001), p. 79.
[24] E. Hiyama *et al.,* Phys. Rev. Lett. **85**, 270 (2000).