Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda$He

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The energy spacing between the spin-doublet bound state of $^4_\Lambda\mathrm{He}(1^+, 0^+)$ was determined to be $1406 \pm 2 \pm 2$ keV, by measuring γ rays for the $1^+ \to 0^+$ transition with a high efficiency germanium detector array in coincidence with the $^4\mathrm{He}(K^-, \pi^-)^4_\Lambda\mathrm{He}$ reaction at J-PARC. In comparison to the corresponding energy spacing in the mirror hypernucleus $^4_\Lambda$H, the present result clearly indicates the existence of charge symmetry breaking (CSB) in ΛN interaction. By combining the energy spacings with the known ground-state binding energies, it is also found that the CSB effect is large in the 0^+ ground state but is vanishingly small in the 1^+ excited state, demonstrating that the ΛN CSB interaction has spin dependence.

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Charge symmetry is a basic concept in nuclear physics which holds almost exactly for atomic nuclei. It should also hold in the ΛN interaction and Λ hypernuclei; the Λp and Λn interactions and the Λ binding energies (B_Λ) between a pair of mirror Λ hypernuclei such as $^4_\Lambda$H and $^4_\Lambda$He should be identical under this symmetry.

In the NN interaction and ordinary nuclei, effects of charge symmetry breaking (CSB) have been observed, for example, in the ^{3}H and ^{3}He binding-energy difference of 70 keV and the nn and pp scattering length difference of $a_{nn} - a_{pp} = -1.5 \pm 0.5$ fm (both corrected for large Coulomb effects). In meson-exchange models, those effects are suggested to be explained by $\rho^0 - \omega$ mixing (see Ref. [1], for example).

On the other hand, there has been a long-standing puzzle in CSB for the ΛN interaction; the reported CSB effects are relatively large, having yet to be theoretically explained. Old experiments using emulsion techniques reported B_Λ of the ground states of $^4_\Lambda\mathrm{H}(0^+)$ and $^4_\Lambda\mathrm{He}(0^+)$ to be 2.04 ± 0.04 MeV and 2.39 ± 0.03 MeV, respectively [2], giving a B_Λ difference $\Delta B_\Lambda(0^+) = B_\Lambda(^4_\Lambda\mathrm{He}(0^+)) - B_\Lambda(^4_\Lambda\mathrm{H}(0^+)) = 0.35 \pm 0.05$ MeV. Theoretical efforts have been made since the 1960s [3] to account for the $\Delta B_\Lambda(0^+)$ value, but contemporary quantitative studies fail to give a $\Delta B_\Lambda(0^+)$ value larger than 100 keV; for example, a four-body $YNNN$ coupled-channel calculation with $Y = \Lambda$ and Σ using the widely accepted baryon-baryon interaction model (NSC97e) gives $\Delta B_\Lambda(0^+) \sim 70$ keV [4].

To resolve this problem, confirmation and improvement of experimental data on CSB are also necessary. Since systematic errors are not well evaluated in the old emulsion data for B_Λ, new data, ideally also gathered by different experimental methods, have been awaited. Recently, the π^- momentum in the ${}^4_\Lambda\mathrm{H} \to {}^4\mathrm{He} + \pi^-$ weak decay was precisely measured at MAMI-C [5], and the obtained value of $B_\Lambda({}^4_\Lambda\mathrm{H}(0^+)) = 2.12 \pm 0.01(\mathrm{stat}) \pm 0.09(\mathrm{syst})$ MeV is consistent with the emulsion value.

The B_Λ difference for the excited 1^+ states provides additional important information on the spin dependent CSB effect from which the origin of CSB can be studied. The B_Λ values for the 1^+ state are obtained via the $1^+ \to 0^+$ γ-ray transition energies. The ${}^4_\Lambda\mathrm{H}$ γ ray was measured three times, and the ${}^4_\Lambda\mathrm{H}(1^+, 0^+)$ energy spacing was determined to be 1.09 ± 0.02 MeV as the weighted average of these three measurements (1.09 ± 0.03 MeV [6], 1.04 ± 0.04 MeV [7], and 1.114 ± 0.030 MeV [8]), as shown in Fig. 1 (on the left). On the other hand, observation of the ${}^4_\Lambda\mathrm{He}$ γ ray was reported only once by an experiment with stopped K^- absorption on a ${}^7\mathrm{Li}$ target, which claimed the (1^+, 0^+) energy spacing to be 1.15 ± 0.04 MeV [7]. This result suggests a significantly large CSB effect also in the 1^+ state with $\Delta B_\Lambda(1^+) = 0.29 \pm 0.06$ MeV. However, this ${}^4_\Lambda\mathrm{He}$ γ-ray spectrum is statistically insufficient, and identification of the ${}^4_\Lambda\mathrm{He}$ hyperfragment through high energy γ rays attributed to the ${}^4_\Lambda\mathrm{He} \to {}^4\mathrm{He} + \pi^0$ weak decay seems to be ambiguous.

In order to clarify this situation, we performed a γ-ray spectroscopic experiment for ${}^4_\Lambda\mathrm{He}$ at J-PARC [9], in which the 1^+ excited state of ${}^4_\Lambda\mathrm{He}$ was directly produced via the ${}^4\mathrm{He}(K^-, \pi^-)$ reaction with a 1.5 GeV/c K^- beam, and γ rays were measured using germanium (Ge) detectors with an energy resolution one order of magnitude better than that of the NaI counters used in all of the previous ${}^4_\Lambda\mathrm{H}$ and ${}^4_\Lambda\mathrm{He}$ γ-ray experiments. In this Letter, we present the result which clearly supersedes the previously claimed γ-ray transition energy and firmly establishes the level scheme of ${}^4_\Lambda\mathrm{He}$, as shown in Fig. 1 (on the right).

The J-PARC E13 experiment was carried out at the K1.8 beam line in the J-PARC Hadron Experimental Facility [10]. The ${}^4\mathrm{He}(K^-, \pi^-)$ reaction was used to produce ${}^4_\Lambda\mathrm{He}(1^+)$, which was populated via the spin-flip amplitude of the $K^- + n \to \Lambda + \pi^-$ process. A beam momentum of 1.5 GeV/c was chosen considering the elementary cross section of the spin-flip Λ production and the available beam intensity. A 2.8 g/cm^2-thick liquid ${}^4\mathrm{He}$ target was irradiated with a total of 2.3×10^{10} kaons. A K^- beam ($K^-/\pi^- = 2 \sim 3$) was delivered to the target with a typical intensity of 3×10^5 over a 2.1 s duration of the beam spill occurring every 6 s. Incident K^- and outgoing π^- mesons were particle identified and momentum analyzed by the beam line spectrometer and the Superconducting Kaon Spectrometer (SKS) [11], respectively. In addition, γ rays were detected by a Ge detector array (Hyperball-J) surrounding the target. Through a coincidence measurement between these spectrometer systems and Hyperball-J, γ rays from hypernuclei were measured. The detector system surrounding the target is shown in Fig. 2.

The detector setting in SKS was configured for γ-ray spectroscopic experiments via the (K^-, π^-) reaction (SksMinus). SksMinus had a large acceptance (~100 msr) for detecting the outgoing pions in the laboratory scattering angle range of $\theta_{K\pi} = 0°$–$20°$. The

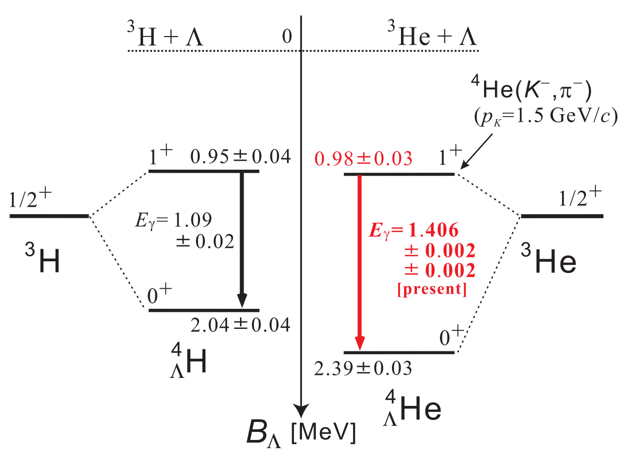

FIG. 1 (color online). Level schemes of the mirror hypernuclei, ${}^4_\Lambda\mathrm{H}$ and ${}^4_\Lambda\mathrm{He}$. Λ binding energies (B_Λ) of ${}^4_\Lambda\mathrm{H}(0^+)$ and ${}^4_\Lambda\mathrm{He}(0^+)$ are taken from past emulsion experiments [2]. $B_\Lambda({}^4_\Lambda\mathrm{He}(1^+))$ and $B_\Lambda({}^4_\Lambda\mathrm{H}(1^+))$ are obtained using the present data and past γ-ray data [6–8], respectively. Recently, $B_\Lambda({}^4_\Lambda\mathrm{H}(0^+)) = 2.12 \pm 0.01(\mathrm{stat}) \pm 0.09(\mathrm{syst})$ MeV was obtained with an independent technique [5].

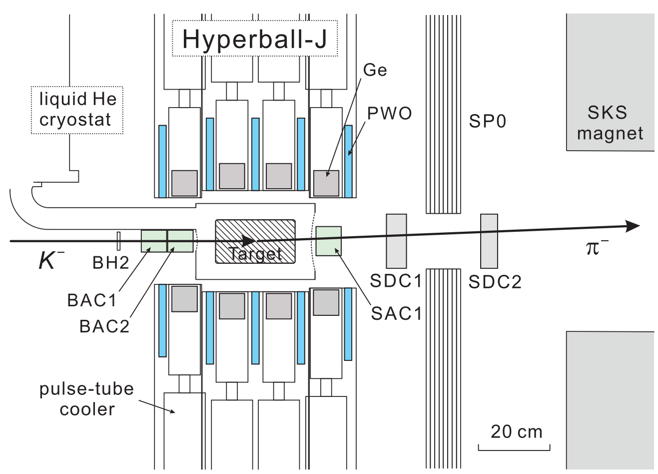

FIG. 2 (color online). A schematic view of the experimental setup around the liquid ${}^4\mathrm{He}$ target (side view). SKS is a superconducting dipole magnet (2.5 T); BH2 is a plastic scintillation counter hodoscope; BAC1,2 and SAC1 are aerogel Čerenkov counters with $n = 1.03$; SDC1,2 are drift chambers. SP0 is an electromagnetic shower counter to tag high energy photons from π^0 decay. Hyperball-J consists of 27 Ge detectors, each surrounded by PWO counters for background suppression.

(K^-, π^-) reaction events were identified with threshold-type aerogel Čerenkov counters at the trigger level and by time of flight in the off-line analysis. The ${}^4_\Lambda$He mass was calculated as the missing mass of the ^{4}He(K^-, π^-) reaction. A detailed description of the spectrometer system and of the analysis procedure for calculating missing mass will be reported elsewhere.

Hyperball-J is a newly developed Ge detector array for hypernuclear γ-ray spectroscopy [12]. The array can be used in high intensity hadron beam conditions by introducing mechanical cooling of the Ge detectors [13]. The array consisted of 27 Ge detectors in total, equipped with $PbWO_4$ (PWO) counters surrounding each Ge crystal to suppress background events such as Compton scattering and high energy photons from π^0 decay. The Ge detectors were of the coaxial type with a 60% relative efficiency. The Ge crystals covered a solid angle of $0.24 \times 4\pi$ sr in total, with the source point at the center. The total absolute photopeak efficiency was ~4% for 1 MeV γ rays when taking account of self-absorption in the target material. Energy calibration was performed over the 0.6–2.6 MeV range, by using data taken with Thorium-series γ rays in the period without the beam spill. The systematic error in the energy calibration was estimated to be 0.5 keV for that energy region. The energy resolution was 5 keV (FWHM) at 1.4 MeV after summing up data for all the detectors. The resolution was slightly worse during the beam spill period.

The selected events were those in which a Ge detector was hit within a typical time gate of 50 ns, and corresponding PWO counters had no hit during the 50 ns coincidence period. In the (K^-, π^-) reaction at 1.5 GeV/c, produced hypernuclei have recoil velocities (β) of 0.03–0.10, which lead to a stopping time longer than 20 ps in the target material. The ${}^4_\Lambda$He$(1^+ \to 0^+)$ $M1$ transition with an energy of ~1 MeV is estimated to have a lifetime of ~0.1 ps, assuming weak coupling between the core nucleus and the Λ [14]. Therefore, the γ-ray peak shape is expected to be Doppler broadened. We applied an event-by-event correction to the γ-ray energy by using the measured recoil momentum of ${}^4_\Lambda$He, the reaction vertex position, and the position of the Ge detector. It is noted that the Doppler-shift correction leaves 0.1% uncertainty in the measured γ-ray energy, where the dominant contribution comes from uncertainties (±5 mm) associated with positions of the Hyperball-J apparatus with respect to the magnetic spectrometer systems. Details of the analysis procedures are almost the same as the previous hypernuclear γ-ray spectroscopic experiments [15].

Figure 3 shows the missing mass spectrum for ${}^4_\Lambda$He as a function of the excitation energy, E_{ex}. Events with scattering angles ($\theta_{K\pi}$) larger than 3.5° were selected to reduce the background due to beam $K^- \to \pi^- + \pi^0$ events which kinematically overlap with hypernuclear production events at $\theta_{K\pi} = 0°$–3°. The background spectrum associated with materials other than liquid helium, as well as with K^- beam decay events, was obtained with the empty target vessel, as shown together in Fig. 3; it is evident that the observed peak originates from the ^{4}He(K^-, π^-) reaction. According to a theoretical calculation, the ${}^4_\Lambda$He(0^+) ground state is predicted to be predominantly populated, while the ${}^4_\Lambda$He(1^+) excited state is produced at a lower rate [~1/4 of ${}^4_\Lambda$He(0^+)] [16]. Therefore, the obtained peak is composed of ${}^4_\Lambda$He(0^+) with a small contribution from ${}^4_\Lambda$He(1^+), and the peak width of 5 MeV (FWHM) approximately corresponds to the missing mass resolution. The energy region for bound ${}^4_\Lambda$He is $E_{ex} = 0$–2.39 MeV (see Fig. 1). Thus, the region of $-4 < E_{ex} < +6$ MeV was chosen for event selection of the ${}^4_\Lambda$He bound state that is allowed for γ decay.

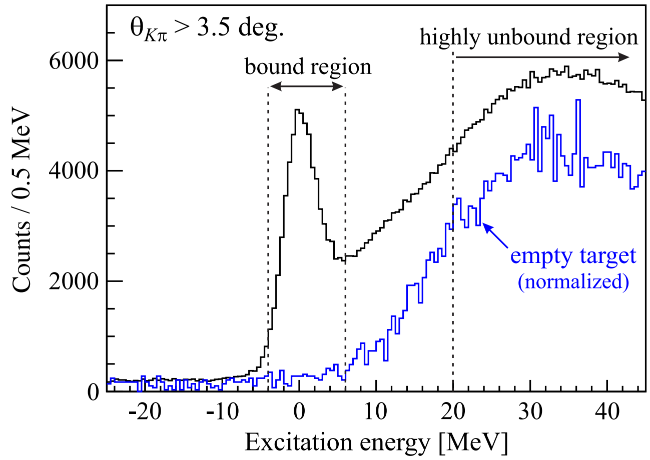

FIG. 3 (color online). The missing mass spectrum for the ^{4}He$(K^-, \pi^-){}^4_\Lambda$He kinematics plotted as a function of the excitation energy, E_{ex}, where events with scattering angles ($\theta_{K\pi}$) larger than 3.5° are selected. Black and blue lines show a spectrum with and without liquid helium, respectively.

Figure 4 shows mass-gated γ-ray energy spectra. Figures 4(a) and 4(b) are the spectra without and with the Doppler-shift correction, respectively, when the highly unbound region ($E_{ex} > +20$ MeV) of ${}^4_\Lambda$He is selected. Figure 4(c) is the spectrum without the Doppler-shift correction for the ${}^4_\Lambda$He bound region. Only after the event-by-event Doppler-shift correction, the 1406-keV peak is clearly visible, as shown in Fig. 4(d). The peak at 1406 keV is assigned to the spin-flip $M1$ transition between the spin-doublet states, ${}^4_\Lambda$He$(1^+ \to 0^+)$, because no other state which emits γ rays is expected to be populated in the selected excitation energy region. This assignment is also consistent with the fact that the peak appears after the Doppler-shift correction.

Figure 5(a) shows simulated γ-ray peak shapes. The thin black line is for a γ ray emitted at rest, the dotted red line for a γ ray emitted immediately after the reaction where ${}^4_\Lambda$He has a maximum β before slowing down in the target material, and the thick blue line for a γ ray with Doppler-shift correction applied to the dotted red line. The observed peak shape shown in Fig. 5(b) agrees with a simulated one to which the Doppler correction was applied, reflecting

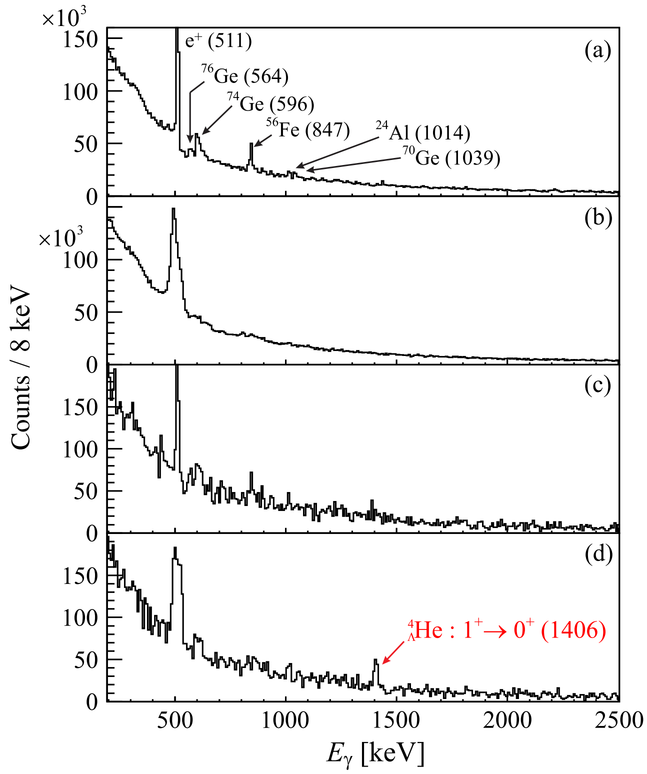

FIG. 4 (color online). γ-ray energy spectra measured by Hyperball-J in coincidence with the $^4\mathrm{He}(K^-, \pi^-)$ reaction. Missing mass selections are applied to the highly unbound region ($E_{\mathrm{ex}} > +20$ MeV) for (a) and (b), and to the ${}^4_\Lambda\mathrm{He}$ bound region ($-4 < E_{\mathrm{ex}} < +6$ MeV) for (c) and (d). An event-by-event Doppler correction is applied for (b) and (d). A single peak is observed in (d) attributed to the $M1(1^+ \to 0^+)$ transition.

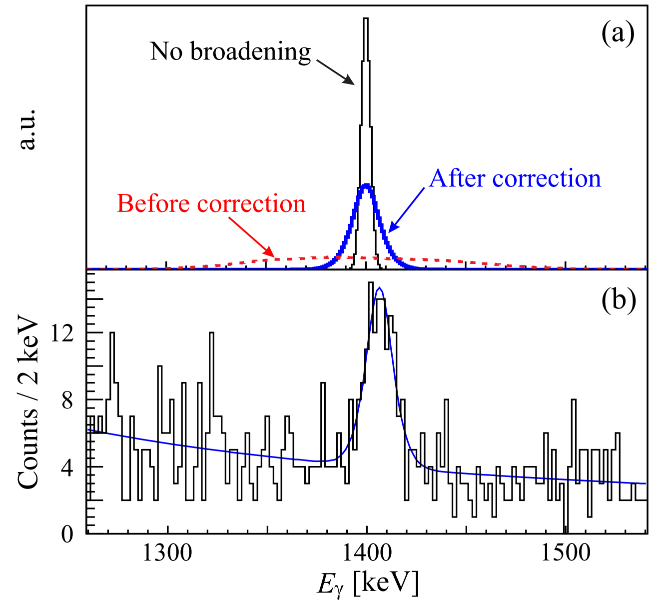

FIG. 5 (color online). (a) Simulated shapes of a 1.4 MeV γ-ray peak: the thin black line corresponds to a γ ray emitted at rest, the dotted red line to a γ ray emitted by the recoiling ${}^4_\Lambda\mathrm{He}$. The thick blue line is the result of the Doppler-shift correction applied to the dotted one. (b) The fit of the simulated peak shape to the present data.

ambiguities in the reconstructed vertex point and in the Ge detector positions. The peak fitting result for the Doppler-shift-corrected spectrum is presented in Fig. 5(b). The γ-ray energy and yield were extracted to be $1406 \pm 2(\mathrm{stat}) \pm 2(\mathrm{syst})$ keV and 95 ± 13 counts, respectively, with a peak significance of 7.4σ and a reduced χ^2 of 1.2. A dominant source of the systematic error comes from position inaccuracy of the reaction vertex and of the Ge detectors for correcting the Doppler shift. The peak energy varies less than 1 keV with different background functions used in the fitting. The obtained yield is consistent with an expected value based on a distorted-wave impulse approximation calculation [16] within a factor of 3.

In the present work, the γ-ray transition of ${}^4_\Lambda\mathrm{He}(1^+ \to 0^+)$ was unambiguously observed, and the excitation energy of the ${}^4_\Lambda\mathrm{He}(1^+)$ state was precisely determined to be $1.406 \pm 0.002 \pm 0.002$ MeV, by adding a nuclear recoil correction of 0.2 keV. By comparing it to the previously measured spacing of ${}^4_\Lambda\mathrm{H}$ (1.09 ± 0.02 MeV), the existence of CSB in the ΛN interaction has been definitively confirmed. It is to be mentioned that two old experiments using stopped K^- on $^6\mathrm{Li}$ and $^7\mathrm{Li}$ targets had reported hints of unassigned γ-ray peaks at 1.42 ± 0.02 MeV [17] and 1.45 ± 0.05 MeV [6], respectively. It is presumed that those γ rays came from ${}^4_\Lambda\mathrm{He}$ produced as a hyperfragment. By combining the emulsion data of $B_\Lambda({}^4_\Lambda\mathrm{He}(0^+))$, the present result gives $B_\Lambda({}^4_\Lambda\mathrm{He}(1^+)) = 0.98 \pm 0.03$ MeV, as shown in Fig. 1. By comparing it to $B_\Lambda({}^4_\Lambda\mathrm{H}(1^+)) = 0.95 \pm 0.04$ MeV, obtained from the emulsion data of $B_\Lambda({}^4_\Lambda\mathrm{H}(0^+))$ and the ${}^4_\Lambda\mathrm{H}$ γ-ray data, the present result leads to $\Delta B_\Lambda(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}(1^+)) - B_\Lambda({}^4_\Lambda\mathrm{H}(1^+)) = 0.03 \pm 0.05$ MeV. Therefore, the CSB effect is strongly spin dependent, being at least one order of magnitude smaller in the 1^+ state than in the 0^+ state. This demonstrates that the underlying ΛN CSB interaction has spin dependence. Our finding suggests that Σ mixing in Λ hypernuclei is responsible for the CSB effect since the 1^+ state in ${}^4_\Lambda\mathrm{H}/{}^4_\Lambda\mathrm{He}$ receives a one order of magnitude smaller energy shift due to Λ-Σ mixing than the 0^+ state [18,19], which is caused by strong ΛN-ΣN interaction in the two-body spin-triplet channel.

Recently, Gal estimated the CSB effect [20] using a central-force ΛN-ΣN interaction (the D2 potential in Ref. [18]), in contrast to the widely used tensor-force dominated ΛN-ΣN interaction in the Nijmegen one-boson exchange models. His $\Delta B_\Lambda(1^+)$ values are in agreement with the present observation. Further theoretical studies may reveal not only the origin of the CSB effect but also the properties of Λ-Σ mixing in hypernuclei.

In summary, the J-PARC E13 experiment clearly identified a γ-ray transition from ${}^4_\Lambda\mathrm{He}$ produced by the $^4\mathrm{He}(K^-, \pi^-)$ reaction and determined the energy spacing between the spin-doublet states $(1^+, 0^+)$ to be $1406 \pm 2(\text{stat}) \pm 2(\text{syst})$ keV, which is apparently different from the ${}^4_\Lambda$H spacing of 1.09 ± 0.02 MeV. Therefore, the existence of CSB in the ΛN interaction has been confirmed via γ-ray spectroscopy alone. Combined with the emulsion data of $B_\Lambda(0^+)$, the present result indicates a large spin dependence in the CSB effect, pronounced in the 0^+ state while vanishingly small in the 1^+ state. We believe that the present finding provides crucial information for understanding the ΛN-ΣN interaction and eventually baryon-baryon interactions.

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