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

T. O. Yamamoto, 1 M. Agnello, 2 Y. Akazawa, 1 N. Amano, 4 K. Aoki, 5 E. Bottà, 3, 6 N. Chiga, 1 H. Ekawa, 7 P. Evtouchkivich, 8 A. Feliciello, 3 M. Fujita, 9 T. Gogami, 7 S. Hasegawa, 9 S. H. Hayakawa, 10 T. Hayakawa, 10 R. Honda, 10 K. Hosomi, 9 S. H. Hwang, 9 N. Ichige, 1 Y. Ichikawa, 9 M. Ikeda, 1 K. Imai, 9 S. Ishimoto, 5 S. Kunatsuki, 7 M. H. Kim, 11 S. H. Kim, 11 S. Kinbara, 12 T. Koike, 1 J. Y. Lee, 13 S. Marcello, 3, 6 K. Miwa, 1 T. Moon, 13 T. Nagae, 7 S. Nagao, 1 Y. Nakada, 10 M. Nakagawa, 10 Y. Ogura, 1 A. Sakaguchi, 10 H. Sako, 9 Y. Sasaki, 1 S. Sato, 9 T. Shiozaki, 1 K. Shirotori, 14 H. Sugimura, 9 S. Suto, 1 S. Suzuki, 5 T. Takahashi, 5 H. Tamura, 1 K. Tanabe, 4 K. Tanida, 9 Z. Tsamalaidze, 8 M. Ukai, 1 Y. Yamamoto, 1 and S. B. Yang 13

(J-PARC E13-1st Collaboration)

1 Department of Physics, Tohoku University, Sendai 980-8578, Japan
2 Dipartimento di Scienze Applicate e Tecnologica, Politecnico di Torino, Corso Duca degli Abruzzi, 10129 Torino, Italy
3 INFN, Sezione di Torino, via P. Giuria 1, 10125 Torino, Italy
4 Department of Physics, Kyoto University, Kyoto 606-8502, Japan
5 Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
6 Dipartimento di Fisica, Universit di Torino, Via P. Giuria 1, 10125 Torino, Italy
7 Department of Physics, Kyoto University, Kyoto 606-8502, Japan
8 Joint Institute for Nuclear Research, Dubna, Moscow Region 141980, Russia
9 Advanced Science Research Center (ASRC), Japan Atomic Agency (JAEA), Tokai, Ibaraki 319-1195, Japan
10 Department of Physics, Osaka University, Toyonaka 560-0043, Japan
11 Department of Physics, Korea University, Seoul 136-713, Korea
12 Faculty of Education, Gifu University, Gifu 501-1193, Japan
13 Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea
14 Research Center of Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

(Dated: August 4, 2015)

The energy spacing between the ground-state spin doublet of $^4\Lambda$He($1^+, 0^+$) was determined to be $1406 \pm 2 \pm 2$ keV, by measuring γ rays for the $1^+ \rightarrow 0^+$ transition with a high efficiency germanium detector array in coincidence with the $^4\Lambda$He($K^-, \pi^-)$ $^4\Lambda$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. It is also found that the CSB effect is large in the $0^+$ ground state but is by one order of magnitude smaller in the $1^+$ excited state, demonstrating that the ΛN CSB interaction has spin dependence.

PACS numbers: 21.80.-a, 13.75.Ev, 23.20.Lv, 25.80.Nv

Charge symmetry is a basic symmetry in nuclear physics which governs properties and structures of atomic nuclei. It should also hold in ΛN interaction and Λ hypernuclei; Np and Λn interactions and the Λ binding energies ($B_\Lambda$) between a pair of mirror Λ hypernuclei such as $^4\Lambda$H and $^4\Lambda$He are expected to be identical under this symmetry.

In NN interaction and ordinary nuclei, effects of charge symmetry breaking (CSB) have been observed, for example, in the $^4\Lambda$H and $^4\Lambda$He mass 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 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 ΛN interaction. Old experiments using emulation technique reported $B_\Lambda$ of the ground states of $^4\Lambda$H($0^+$) and $^4\Lambda$He($0^+$) to be $2.04 \pm 0.04$ MeV and $2.39 \pm 0.03$ MeV, respectively [2], giving a $B_\Lambda$ difference $\Delta B_\Lambda(0^+) = B_\Lambda(^4\Lambda$H($0^+)) - B_\Lambda(^4\Lambda$He($0^+)) = 0.35 \pm 0.05$ MeV. Theoretical efforts have been made since 1960s [3] to explain the $\Delta B_\Lambda(0^+)$ value, but any quantitative studies fail to give a $\Delta B_\Lambda(0^+)$ value larger than 100 keV; for example, a 4-body YNNN coupled-channel calculation with $Y = \Lambda$ and $\Sigma$ using the widely-accepted baryon-baryon interaction model (NSC97e) gives $\Delta B_\Lambda(0^+) \sim 70$ keV [4].

To approach this problem, confirmation and improvement of experimental data on CSB are also necessary. Systematic errors are not shown in the old emulsion data for $B_\Lambda$, and thus new data, hopefully by different experimental methods, have been awaited. Recently, the $\pi^-$ momentum in the $^4\Lambda$H $\rightarrow ^4$He + $\pi^-$ weak decay was precisely measured at MAMI-C [2], and the obtained value of $B_\Lambda(^4\Lambda$H($0^+)) = 2.12 \pm 0.01$ (stat.) $\pm 0.09$ (syst.) MeV is consistent with the emulsion value.

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

In order to clarify this situation, we performed a $\gamma$-ray spectroscopy experiment of $^4$He at J-PARC [2], in which the 1$^+$ excited state of $^4$He and the directly produced via the $^4$He($K^-, \pi^-$) reaction with a 1.5 GeV/c $K^-$ beam, and $\gamma$ rays were measured using germanium (Ge) detectors with an energy resolution by one order of magnitude better than NaI counters used in all the previous $^4$H and $^4$He $\gamma$-ray experiments. In this letter, we present the result which clearly supersedes the previously claimed $\gamma$-ray transition energy and firmly establishes the level scheme of $^4$He as shown in Fig. 1 (right).

The J-PARC E13-1$^{st}$ experiment was carried out at the K1.8 beam line in the J-PARC Hadron Experimental Facility [10]. The $^4$He($K^-, \pi^-$) reaction was used to produce $^4$He(1$^+$), which was populated via the spin-flip amplitude of the $K^- + n \rightarrow \Lambda + \pi^0$ process. A beam momentum of 1.5 GeV/c was chosen considering the elementary cross section of the spin-flip $\Lambda$ production and the available beam intensity. A 2.7 g/cm$^2$-thick liquid $^4$He target was irradiated with a total of $2.3 \times 10^{10}$ kaons. A high purity $K^-$ beam with a $K^-/\pi^+$ ratio of $\sim 2$ was delivered to the target with a typical intensity of $3 \times 10^5$ over a 2.1 s duration of the beam spill occurring every 6 s. Incident $K^-$ and outgoing $\pi^-$ mesons were particle-identified and momentum-analyzed by the beam line spectrometer and the Superconducting Kaon Spectrometer (SKS) [11], respectively. On the other hand, $\gamma$ rays are detected by a Ge detector array (Hyperball-J) surrounding the target. Through coincidence measurement between these spectrometer systems and Hyperball-J, $\gamma$ rays from hypernuclei were measured. The detector system surrounding the target is shown in Fig. 2.

In SKS, detector setting was configured for $\gamma$-ray spectroscopy experiments via the $(K^-, \pi^-)$ reaction (SksMinus). SksMinus had a large acceptance for detecting the outgoing pions in the laboratory scattering angle range of $\theta_{K\pi} = 0^\circ$-$20^\circ$. The $(K^-, \pi^-)$ 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 $^4$He mass was calculated as the missing mass of the $^4$He($K^-, \pi^-$) reaction. 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 $\gamma$-ray spectroscopy [12]. The array can be used in a high intensity hadron beam condition by introducing mechanical cooling of Ge detectors [13]. The array consisted of 27 Ge detectors in total, equipped with PWO counters surrounding each Ge crystal to suppress
The analysis procedures are almost the same as the previous, with respect to the magnetic spectrometer systems. Details of the contribution come from uncertainties in the measured recoil momentum of a 4.1 MeV (FWHM) at 1.4 MeV after summing up data for all the detectors. The resolution was slightly worse in the period on the beam spill.

Selected events were those in which a Ge detector has a hit in a typical time gate of 50 ns and without any hits in the corresponding PWO counters in the 50 ns coincidence gate. In the \( K^-, \pi^- \) reaction at 1.5 GeV/$c$, produced hypernuclei have recoil velocities of \( 0.03-0.10 \), which lead to a stopping time longer than 20 ps in the target material. The \( ^{4}\text{He}(1^+ \rightarrow 0^+) \text{M1 transition} \) with an energy of \( \sim 1 \text{ MeV} \) is estimated to have a lifetime of \( \sim 0.1 \text{ ps} \) assuming weak coupling between the core nucleus and the \( \Lambda \) \cite{14}. Therefore, the \( \gamma \)-ray peak shape is expected to be Doppler broadened. We applied an event-by-event correction to the \( \gamma \)-ray energy by using the measured recoil momentum of \( ^{4}\text{He} \), 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 \( \gamma \)-ray energy, where the dominant contribution comes from uncertainties (\( \pm 5 \text{ mm} \)) 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 \( \gamma \)-ray spectroscopy experiments \cite{15}.

Figure 3 shows the missing mass spectrum for \( ^{4}\text{He} \) in coincidence with the \( ^{3}\text{He}(K^-, \pi^-) \) reaction. Missing mass selections are applied to the highly unbound region \( (E_{\text{ex}} > +20 \text{ MeV}) \) for (a) and (b), and to \( ^{4}\text{He} \) bound region \( (-4 < E_{\text{ex}} < +6 \text{ MeV}) \) for (c) and (d). An event-by-event Doppler correction is applied for (b) and (d). Single peak is observed in (d) attributed to the \( M1(1^+ \rightarrow 0^+) \text{ transition} \).

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 is originated from the \( ^{4}\text{He}(K^-, \pi^-) \) reaction. According to a theoretical calculation, the \( ^{3}\text{He}(0^+) \text{ ground state} \) is predicted to be predominantly populated, while the \( ^{3}\text{He}(1^+) \text{ excited state} \) at a lower rate \( (\sim 1/4 \text{ of } ^{3}\text{He}(0^+)) \) \cite{16}. Therefore, the obtained peak is composed of \( ^{3}\text{He}(0^+) \) with a small contribution from \( ^{3}\text{He}(1^+) \). The peak width of 5 MeV (FWHM) corresponds to the missing mass resolution. The energy region for bound \( ^{3}\text{He} \) is \( E_{\text{ex}} = 0 - 2.39 \text{ MeV} \) (see Fig. 1). Thus, the region of \( -4 < E_{\text{ex}} < +6 \text{ MeV} \) was chosen for event selection of the \( ^{3}\text{He} \) bound state that is allowed for \( \gamma \) decay.

![Figure 3](image3.png)

**FIG. 3.** (color online). The missing mass spectrum for the \( ^{4}\text{He}(K^-, \pi^-) ^{3}\text{He} \) kinematics plotted as a function of the excitation energy, \( E_{\text{ex}} \), 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](image4.png)

**FIG. 4.** (color online). \( \gamma \)-ray energy spectra measured by Hyperball-J in coincidence with the \( ^{4}\text{He}(K^-, \pi^-) \) reaction. Missing mass selections are applied to the highly unbound region \( (E_{\text{ex}} > +20 \text{ MeV}) \) for (a) and (b), and to \( ^{3}\text{He} \) bound region \( (-4 < E_{\text{ex}} < +6 \text{ MeV}) \) for (c) and (d). Single peak is observed in (d) attributed to the \( M1(1^+ \rightarrow 0^+) \text{ transition} \).
The obtained yield is consistent with an expected value based on a DWIA calculation of Ref. 16 within a factor of 3.

In the present work, the γ-ray transition of $^4\Lambda$He(1$^+ \rightarrow 0^+$) was unambiguously observed, and the excitation energy of $^4\Lambda$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 $^1\Lambda$H (1.09 ± 0.02 MeV), the existence of CSB in $\Lambda N$ interaction has been definitively confirmed. It is to be mentioned that two old experiments using stopped $K^-$ on $^6\text{Li}$ and $^7\text{Li}$ targets had reported hints of unassigned γ-ray peaks at 1.42 ± 0.02 MeV 17 and 1.45 ± 0.05 MeV 16, respectively. It is presumed that those γ rays came from $^4\Lambda$He produced as a hyperfragment. By combining the emulsion data of $B_{\Lambda}(^4\Lambda\text{He}(0^+))$, the present result gives $B_{\Lambda}(^4\Lambda\text{He}(1^+))=0.98 \pm 0.03$ MeV as shown in Fig. 1. By comparing it to $B_{\Lambda}(^4\Lambda\text{He}(0^+))$ and the $^4\Lambda$ γ-ray data, the present result leads to $\Delta B_{\Lambda}(1^+)=B_{\Lambda}(^4\Lambda\text{He}(1^+))-B_{\Lambda}(^4\Lambda\text{He}(0^+))=0.03 \pm 0.05$ MeV. Therefore, the CSB effect is strongly spin dependent, being by one order of magnitude smaller in the $1^+$ state than in the $0^+$ state. This demonstrates that the underlying $\Lambda N$ CSB interaction has spin dependence. Our finding suggests that $\Sigma$ mixing in $\Lambda$ hypernuclei is responsible for the CSB effect since the $1^+$ state in $^4\Lambda\text{H}/^4\Lambda\text{He}$ receives by one order of magnitude smaller an energy shift due to $\Lambda-\Sigma$ mixing than the $0^+$ state 18 19, which is caused by strong $\Lambda N-\Sigma N$ interaction in the two-body spin-triplet channel.

Recently, Gal 20 estimated the CSB effect using a central-force $\Lambda N-\Sigma N$ interaction (D2 potential in Ref. 18), in contrast to the widely-used tensor-force dominated $\Lambda N-\Sigma N$ interaction in the Nijmegen OBE models. Obtained $\Delta B_{\Lambda}(1^+)$ 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 $\Lambda-\Sigma$ mixing in hypernuclei.

In summary, the J-PARC E13-1st experiment clearly identified a γ-ray transition from $^4\Lambda$He produced by the $^4\text{He}(K^-, \pi^-)$ reaction and determined the energy spacing between the spin-doublet states (1$^+$, 0$^+$) to be 1406 ± 2 (stat.) ± 2 (syst.) keV. The apparent difference from the $^1\Lambda$H spacing of 1.09 ± 0.02 MeV and thus the existence of CSB in $\Lambda N$ interaction have been confirmed only via the γ-ray measurement. Combined with the emulsion data of $B_{\Lambda}(0^+)$, the present result indicates a large spin dependence in the CSB effect, by one order of magnitude larger in the $0^+$ state energy than in the $1^+$ state energy, providing crucial information toward understanding $\Lambda N-\Sigma N$ interaction and eventually baryon-baryon interactions.

We acknowledge experimental support from the J-PARC accelerator and hadron experimental facility staff. We thank SEIKO EG&G and Fuji electric Co. Ltd. for support of our Ge detector system. We thank Prof. T. Harada for theoretical inputs in designing the experiment. This work is partially supported...

---

**Figure 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 $^4\Lambda$He. The thick blue line is the result of the Doppler-shift correction applied to the dotted one. (b) shows the fit of the simulated peak shape to the present data based on the simulated peak shape.
by Grant-in-Aid Nos. 17070001, 21684011, 23244043, 24105003 and 24740138 for Scientific Research from the Ministry of Education Japan, and a Grant-in-Aid No. 22·3038 for JSPS Fellows, and Basic Research (Young Researcher) No. 2010-0004752 from the National Research Foundation in Korea. We acknowledge support from National Research Foundation, WCU program of the Ministry of Education, Science and Technology (Korea), and Center for Korean J-PARC Users (Grant No. 2013K1A3A7A060565). we also thank KEKCC and SINET4.

[1] G. A. Miller, A. K. Opper, and E. J. Stephenson, Ann. Rev. Nucl. Part. Sci. 56, 253 (2006).
[2] M. Jurić et al., Nucl. Phys. B 52, 1 (1973).
[3] R. H. Dalitz and F. Von Hippel, Phys. Lett. 10, 153 (1964).
[4] A. Nogga, H. Kamada, and W. Glöckle, Phys. Rev. Lett. 88, 172501 (2002), and references therein.
[5] A. Esser et al., Phys. Rev. Lett. 114, 232501 (2015).
[6] M. Bedjedian et al., Phys. Lett. B 62, 467 (1976).
[7] M. Bedjidian et al., Phys. Lett. B 83, 252 (1979).
[8] A. Kawachi, Doctoral Thesis, University of Tokyo (1997), unpublished.
[9] H. Tamura, M. Ukai, T.O. Yamamoto, and T. Koike, Nucl. Phys. A 881, 310 (2012).
[10] K. Agari et al., Prog. Theor. Exp. Phys. 2012, 02B009 (2012).
[11] T. Takahashi et al., Prog. Theor. Exp. Phys. 2012, 02B010 (2012).
[12] T. Koike et al., Proc. 9th Int. Conf. on Hypernuclear and Strange Particle Physics (HYP2006), October 10-14, 2006, Mainz, Ed. by J. Pochodzalla and Th. Walcher, Springer, 25 (2007).
[13] T. Koike et al., Nucl. Instrum. Methods A 770, 1 (2014).
[14] R. Dalitz and A. Gal, Annals Phys. 116, 167 (1978).
[15] M. Ukai et al., Phys. Rev. C 77, 054315 (2008).
[16] T. Harada, Private communication (2006).
[17] A. Bamberger et al., Nucl. Phys. B 60, 1 (1973).
[18] Y. Akaishi, T. Harada, S. Shinmura, and K. S. Myint, Phys. Rev. Lett. 84, 3539 (2000).
[19] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, and Y. Yamamoto, Phys. Rev. C 65, 011301 (2002).
[20] A. Gal, Phys. Lett. B 744, 352 (2015).