*Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)*
JPS Conf. Proc. **26**, 023015 (2019)
https://doi.org/10.7566/JPSCP.26.023015

# First $\gamma$-Ray Spectroscopy of an *sd*-Shell Hypernucleus, $^{19}_{\Lambda}$F

Seongbae YANG[1], Jung Keun AHN[1], Yuya AKAZAWA[2], Kanae AOKI[3], Nobuyuki CHIGA[2], Hiroyuki EKAWA[4], Petr EVTOUKHOVITCH[5], Alessandro FELICIELLO[6], Manami FUJITA[2], Shoichi HASEGAWA[7], Shuhei HAYAKAWA[8], Tomonari HAYAKAWA[8], Ryotaro HONDA[2], Kenji HOSOMI[7], Sanghoon HWANG[9], Natsumi ICHIGE[2], Yudai ICHIKAWA[7], Michihiko IKEDA[2], Ken'ichi IMAI[7], Shigeru ISHIMOTO[3], Shunsuke KANATSUKI[4], Shin Hyung KIM[1], Shinji KINBARA[10], Kazuya KOBAYASHI[8], Takeshi KOIKE[2], Jaeyong LEE[11], Koji MIWA[2], Taejin MOON[11], Tomofumi NAGAE[4], Yoshiyuki NAKADA[8], Manami NAKAGAWA[8], Yu OGURA[2], Atsushi SAKAGUCHI[8], Hiroyuki SAKO[7], Yuki SASAKI[2], Susumu SATO[7], Kotaro SHIROTORI[12], Hitoshi SUGIMURA[6], Sadami SUTO[2], Shoji SUZUKI[3], Toshiyuki TAKAHASHI[3], Hirokazu TAMURA[2], Kiyoshi TANIDA[7], Yuichi TOGAWA[2], Zviadi TSAMALAIDZE[5], Mifuyu UKAI[3], Taofeng WANG[13], and Takeshi O. YAMAMOTO[7]
(The J-PARC E13 Collaboration)

[1]*Department of Physics, Korea University, Seoul 02841, Korea*
[2]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[3]*Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[4]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[5]*Joint Institute for Nuclear Research, Dubna, Moscow Region 141980, Russia*
[6]*INFN, Sezione di Torino, via P. Giuria 1, 10125 Torino, Italy*
[7]*Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan*
[8]*Department of Physics, Osaka University, Toyonaka 560-0043, Japan*
[9]*Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, Korea*
[10]*Faculty of Education, Gifu University, Gifu 501-1193, Japan*
[11]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[12]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan*
[13]*Research Center of Nuclear Science and Technology (RCNST) and School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*

*E-mail: sbyang@korea.ac.kr*

(Received February 13, 2019)

We performed a gamma-ray spectroscopy of $^{19}_{\Lambda}$F at J-PARC Hadron Experimental Facility in 2015. It is the first measurement of $\gamma$ rays emitted from *sd*-shell hypernuclei. In this experiment, we determined the energy spacing between the ground state spin doublet, $3/2^+$ and $1/2^+$ states, as 316 keV. The excitation energies of $5/2^+$ and $1/2^+$ states are also determined to be 895 keV and 1266 keV, respectively. The energy spacing is found to be well reproduced by shell-model calculations which describe *s*- and *p*-shell $\Lambda$ hypernuclei well. The results show that the present theories of the $\Lambda N$ interaction describe not only the light hypernuclei but also a heavier hypernucleus.

**KEYWORDS:** J-PARC, $\Lambda$ hypernucleus, $\Lambda N$ interaction, Hyperball-J, Germanium detector, $\gamma$-ray spectroscopy

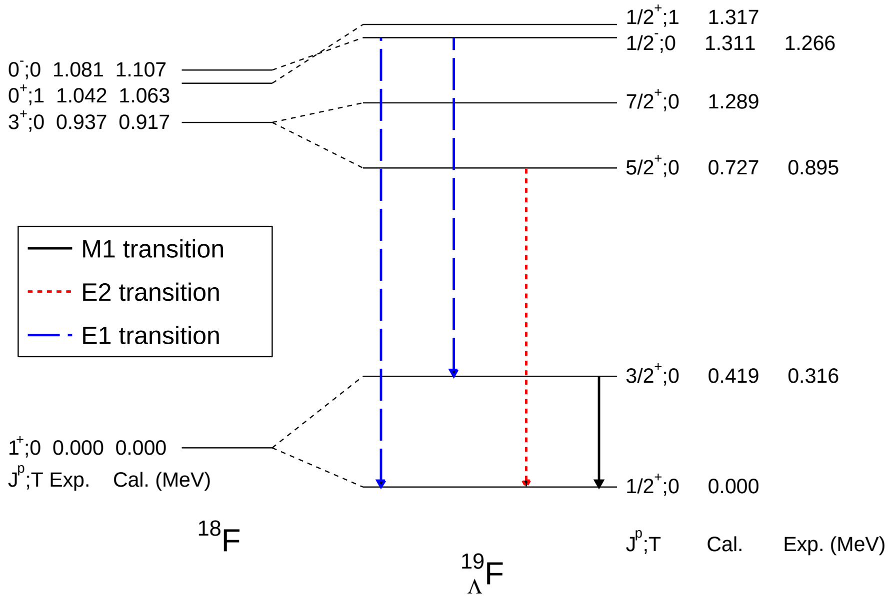


**Fig. 1.** Low-lying energy level scheme of ${}^{19}_{\Lambda}$F. The arrows represent the $\gamma$ transitions measured at this time. The "Exp." of ${}^{19}_{\Lambda}$F means the measured value in this experiment and the "Calc." of ${}^{19}_{\Lambda}$F is the calculated value by Umeya and Motoba [10].

## 1. Introduction

In the nuclear physics world, the $\Lambda$ hypernucleus consisting of nucleons and a $\Lambda$ has played an important role in extending our knowledge of the nucleus. In particular, energy level structures obtained through $\gamma$-ray spectroscopy of $\Lambda$ hypernuclei extracted information on the spin-dependent $\Lambda N$ interaction [1–8]. However, the experimental data of $\gamma$-ray measurement has been limited to light hypernuclei only due to the limited experimental environment such as low intensity of $K^-$ beam. It is a very interesting question whether our knowledge of the $\Lambda N$ interaction can be also applied to heavier hypernuclei.

The $\gamma$-ray spectroscopy experiment of ${}^{19}_{\Lambda}$F (J-PARC E13 [9]) is the first attempt to determine the fine structure of an *sd*-shell hypernucleus. We chose ${}^{19}_{\Lambda}$F as the first target of heavier hypernuclei beyond *s*- and *p*-shell hypernuclei because it is suitable to study the effective spin-spin $\Lambda N$ interaction. As shown in Fig. 1, the ground state of ${}^{18}$F ($J^p = 1^+$) is split by the spin of the added $\Lambda$, and the energy spacing is dominantly determined by the effective spin-spin $\Lambda N$ interaction. Because ${}^{19}_{\Lambda}$F has a structure similar to already well-known ${}^{7}_{\Lambda}$Li, we can know how the effective spin-spin interaction changes in the *sd*-shell hypernuclei by directly comparing the energy spacing with those which were already measured in *s*- and *p*-shell hypernuclei.

## 2. Experiment

We performed J-PARC E13 at the K1.8 beamline in the J-PARC Hadron Experimental Facility. It was $\gamma$-ray spectroscopy of ${}^{4}_{\Lambda}$He as well as ${}^{19}_{\Lambda}$F, and both results have already been reported [11,12]. The ${}^{19}_{\Lambda}$F hypernuclei were produced through the $(K^-, \pi^-)$ reaction with a beam momentum of 1.8 GeV/$c$ and a 20 g/cm$^2$ thick liquid $CF_4$ target. The momenta of the $K^-$ beam and scattered $\pi^-$ were measured by the beam line spectrometer and Superconducting Kaon Spectrometer (SKS) [13], respectively. At the same time, $\gamma$ rays emitted from the ${}^{19}_{\Lambda}$F were detected by using a new array of Germanium (Ge) detectors, Hyperball-J [14]. Detailed experimental methods and analysis procedures can be found in Refs. [11, 12, 15].

## 3. Results

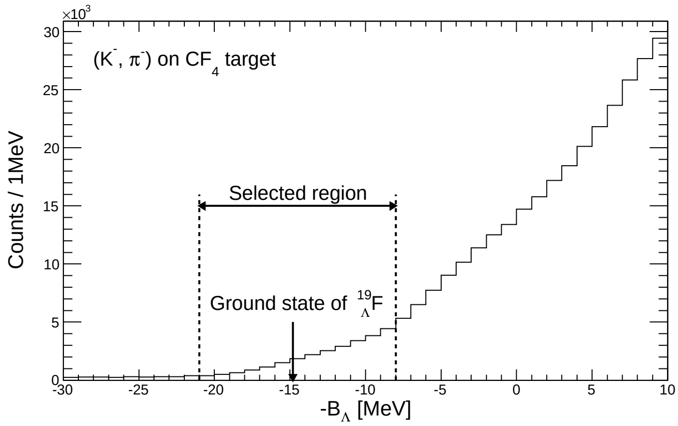


**Fig. 2.** $\Lambda$-binding energy distribution. At least one hit in the Ge detectors was required. The marked "selected region" indicates the low-lying states region of ${}^{19}_{\Lambda}$F chosen for seeing a $\gamma$-ray spectrum of ${}^{19}_{\Lambda}$F.

The $\Lambda$-binding energy ($B_\Lambda$) of ${}^{19}_{\Lambda}$F was calculated by a missing mass technique. In Fig. 2, we could not see any peaks corresponding to energy states of ${}^{19}_{\Lambda}$F due to insufficient missing mass resolution. However, there are enough events around the ground state to measure $\gamma$ rays from low-lying states of ${}^{19}_{\Lambda}$F. We selected a reaction angle ($\theta$) range from 2° to 12° to avoid high background from $K^-$ beam decays and low production cross-section of ${}^{19}_{\Lambda}$F.

As shown in Fig. 3(a), several $\gamma$-ray peaks from normal nuclei inside of the target and other materials are seen regardless of $B_\Lambda$ range. After selecting the $-B_\Lambda$ range from −21 to −8 MeV, four $\gamma$-ray peaks of ${}^{19}_{\Lambda}$F appear at 316 keV, 895 keV, 953 keV, and 1266 keV. The $\gamma$-ray peak of 316 keV is assigned to the $M1(3/2^+ \rightarrow 1/2^+)$ transition in Fig. 1 because the expected yields of the $M1$ transition are more than 10 times larger than the other transitions in the energy range from 100 keV to 500 keV [10, 16]. The 895 keV $\gamma$ ray can be attributed to the $E2(5/2^+ \rightarrow 1/2^+)$ transition. The $E1(1/2^- \rightarrow 3/2^+)$ transition is possible in this energy range, but the $E1$ transition is rejected because a $\gamma$-ray peak from another $E1(1/2^- \rightarrow 1/2^+)$ transition is not seen at 1.21 MeV. The remaining 953 keV and 1266 keV peaks appear clearer at the forward reaction angle, 2° − 6°, as shown in Fig. 3(c). This is because the two $\gamma$-ray peaks are the $E1(1/2^- \rightarrow 3/2^+)$ and $E1(1/2^- \rightarrow 1/2^+)$ transitions and the $1/2^-$ state has a large cross-section at the forward reaction angle [10]. The energy difference between these two $E1$ transitions is 312 keV, which is consistent with the $M1$ transition energy.

## 4. Discussion and Conclusion

The measured energy spacing, 316 keV, of the ground state doublet ($3/2^+$ and $1/2^+$) are consistent with the phenomenological calculation result, 305 keV, based on *s*- and *p*-shell hypernuclei data [17]. When we consider that the $\Lambda\Sigma$ coupling effect was not included in this calculation, it can be

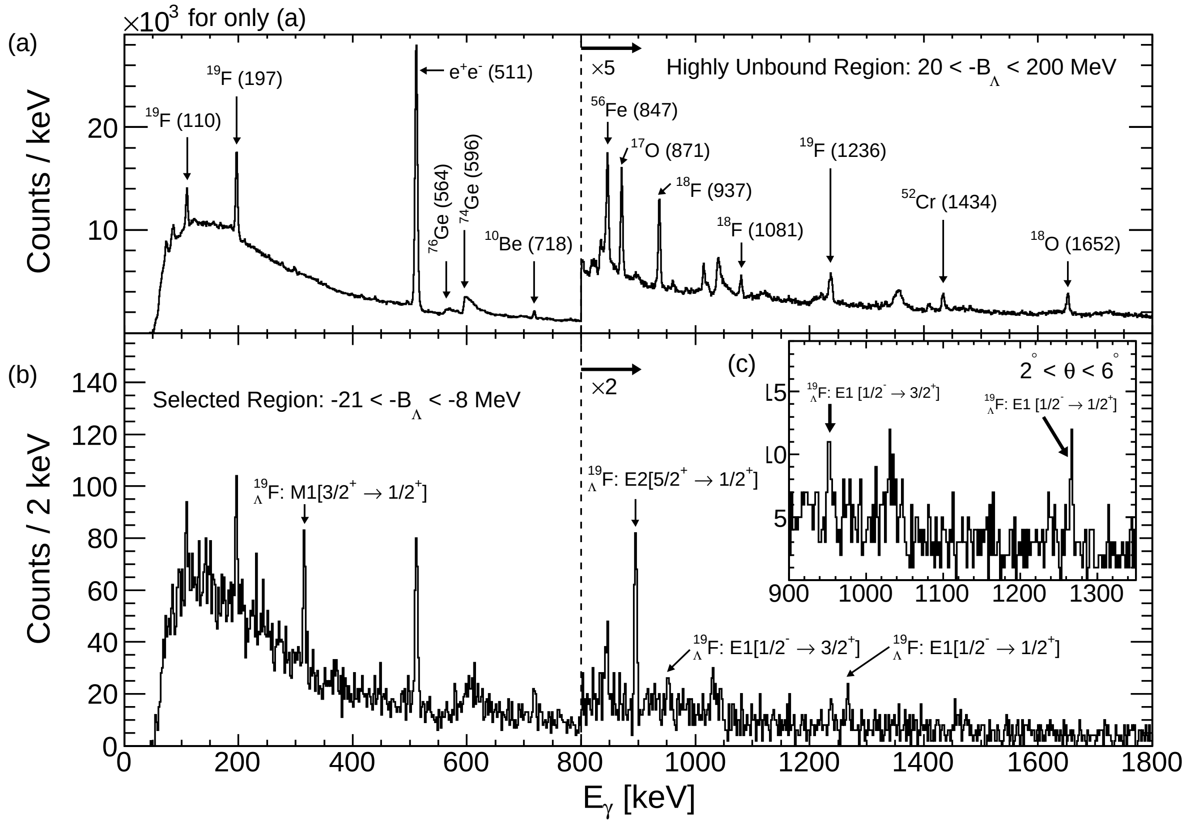


**Fig. 3.** $\gamma$-ray energy spectra according to $B_\Lambda$ energy region: (a) highly unbound region ($20 < -B_\Lambda < 200$ MeV) and (b) selected region ($-21 < -B_\Lambda < -8$ MeV). (c) is the reaction angle range changed to $2° < \theta < 6°$ in (b).

seen that this $\Lambda\Sigma$ coupling effect is negligible in the spin-spin doublet spacing of the *sd*-shell hypernuclei. On the other hand, the theoretical values based on the $\Lambda N$ interaction of Nijmegen SC97e and SC97f models are 245 keV [16] and 419 keV [10], respectively. It is also consistent with the tendency that the ground-state doublet spacing of ${}^{7}_{\Lambda}$Li (0.692 MeV [1]) is calculated as 0.348 MeV (SC97e) and 0.942 (SC97f) [16] from the Nijmegen models. Therefore, we can confirm that the theoretical frame describing *s*- and *p*-shell hypernuclei is well applied to *sd*-shell hypernuclei.

## References

[1] H. Tamura *et al.*, Phys. Rev. Lett. **84** (2000) 5963.
[2] K. Tanida *et al.*, Phys. Rev. Lett. **86** (2001) 1982.
[3] H. Akikawa *et al.*, Phys. Rev. Lett. **88** (2002) 082501.
[4] M. Ukai *et al.*, Phys. Rev. Lett. **93** (2004) 232501.
[5] H. Tamura *et al.*, Nucl. Phys. A **754** (2005) 58c.
[6] Y. Miura *et al.*, Nucl. Phys. A **754** (2005) 75c.
[7] M. Ukai *et al.*, Phys. Rev. C **73** (2006) 012501.
[8] H. Tamura *et al.*, Nucl. Phys. A **881** (2012) 310.
[9] H. Tamura *et al.*, J-PARC E13 Proposal.
[10] A. Umeya and T. Motoba, Nucl. Phys. **A954** (2016) 242.
[11] T.O. Yamamoto *et al.*, Phys. Rev. Lett. **115** (2015) 222501.
[12] S.B. Yang *et al.*, Phys. Rev. Lett. **120** (2018) 132505.
[13] T. Takahashi *et al.*, Prog. Theor. Exp. Phys. (2012) 02B010.

[14] T. Koike *et al.*, in Proceedings of the IX International Conference on Hypernuclear and Strange Particle Physics, SIF and Springer-Verlag Berlin Heidelberg, 2007, ed. J. Pochodzalla and Th. Walcher, p. 25.
[15] S.B Yang *et al.*, JPS Conf. Proc. **1** (2014) 013076.
[16] A. Umeya and T. Motoba, private communication.
[17] D.J. Millener, Nucl. Phys. **A914** (2013) 109.