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(HKS (JLab E05-115) Collaboration) Gogami, T.; Chen, C.; Kawama, D.; Achenbach, P.; Ahmidouch, A.; Albayrak, I.; Androić, Darko; Asaturyan, A.; Asaturyan, R.; Ates, O.; ...

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Letter

Spectroscopy of $A = 9$ hyperlithium with the $(e, e'K^+)$ reaction

T. Gogami,[1,2] C. Chen,[3] D. Kawama,[2] P. Achenbach,[4] A. Ahmidouch,[5] I. Albayrak,[3] D. Androic,[6] A. Asaturyan,[7] R. Asaturyan,[7,*] O. Ates,[3] P. Baturin,[8] R. Badui,[8] W. Boeglin,[8] J. Bono,[8] E. Brash,[9] P. Carter,[9] A. Chiba,[2] E. Christy,[3] S. Danagoulian,[5] R. De Leo,[10] D. Doi,[2] M. Elaasar,[11] R. Ent,[12] Y. Fujii,[2] M. Fujita,[2] M. Furic,[6] M. Gabrielyan,[8] L. Gan,[13] F. Garibaldi,[14] D. Gaskell,[12] A. Gasparian,[5] Y. Han,[3] O. Hashimoto,[2,*] T. Horn,[12] B. Hu,[15] Ed. V. Hungerford,[16] M. Jones,[12] H. Kanda,[2] M. Kaneta,[2] S. Kato,[17] M. Kawai,[2] H. Khanal,[8] M. Kohl,[3] A. Liyanage,[3] W. Luo,[15] K. Maeda,[2] A. Margaryan,[7] P. Markowitz,[8] T. Maruta,[2] A. Matsumura,[2] V. Maxwell,[8] D. Meekins,[12] A. Mkrtchyan,[7] H. Mkrtchyan,[7] S. Nagao,[2] S. N. Nakamura,[2] A. Narayan,[18] C. Neville,[8] G. Niculescu,[19] M. I. Niculescu,[19] A. Nunez,[8] Nuruzzaman,[18] Y. Okayasu,[2] T. Petkovic,[6] J. Pochodzalla,[4] X. Qiu,[15] J. Reinhold,[8] V. M. Rodriguez,[20] C. Samanta,[21] B. Sawatzky,[12] T. Seva,[6] A. Shichijo,[2] V. Tadevosyan,[7] L. Tang,[3,12] N. Taniya,[2] K. Tsukada,[2] M. Veilleux,[9] W. Vulcan,[12] F. R. Wesselmann,[22] S. A. Wood,[12] T. Yamamoto,[2] L. Ya,[3] Z. Ye,[3] K. Yokota,[2] L. Yuan,[3] S. Zhamkochyan,[7] and L. Zhu[3]

(HKS (JLab E05-115) Collaboration)

[1]*Graduate School of Science, Kyoto University, Kyoto, Kyoto 606-8502, Japan*

[2]*Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan*

[3]*Department of Physics, Hampton University, Hampton, Virginia 23668, USA*

[4]*Institute for Nuclear Physics, Johannes Gutenberg-University, D-55099 Mainz, Germany*

[5]*Department of Physics, North Carolina A&T State University, Greensboro, North Carolina 27411, USA*

[6]*Department of Physics, University of Zagreb, HR-10000 Zagreb, Croatia and Department of Applied Physics, University of Zagreb, HR-10000 Zagreb, Croatia*

[7]*A. I. Alikhanyan National Science Laboratory, Yerevan 0036, Armenia*

[8]*Department of Physics, Florida International University, Miami, Florida 27411, USA*

[9]*Department of Physics, Computer Science and Engineering, Christopher Newport University, Newport News, Virginia 23606, USA*

[10]*Istituto Nazionale di Fisica Nucleare, Sezione di Bari, University of Bari, I-70126 Bari, Italy*

[11]*Department of Physics, Southern University at New Orleans, New Orleans, Louisiana 70126, USA*

[12]*Thomas Jefferson National Accelerator Facility (JLab), Newport News, Virginia 23606, USA*

[13]*Department of Physics, University of North Carolina at Wilmington, Wilmington, North Carolina 28403, USA*

[14]*INFN, Sezione Sanità, Istituto Superiore di Sanità, 00161 Rome, Italy*

[15]*Nuclear Physics Institute, Lanzhou University, Gansu 730000, China*

[16]*Department of Physics, University of Houston, Houston, Texas 77204, USA*

[17]*Department of Physics, Yamagata University, Yamagata, 990-8560, Japan*

[18]*Mississippi State University, Mississippi State, Mississippi 39762, USA*

[19]*Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia 22807, USA*

[20]*División de Ciencias y Tecnología, Universidad Ana G. Méndez, Recinto de Cupey, San Juan 00926, Puerto Rico*

[21]*Department of Physics and Astronomy, Virginia Military Institute, Lexington, Virginia 24450, USA*

[22]*Department of Physics, Xavier University of Louisiana, New Orleans, Louisiana 70125, USA*

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Missing mass spectroscopy with the $(e, e'K^+)$ reaction was performed at Jefferson Laboratory's Hall C for the neutron-rich Λ hypernucleus ${}^{9}_{\Lambda}\mathrm{Li}$. The ground-state (g.s.) energy was obtained to be $B_{\Lambda}^{\mathrm{g.s.}} = 8.84 \pm 0.17^{\mathrm{stat.}} \pm 0.15^{\mathrm{sys.}}$ MeV by using shell-model calculations of a cross-section ratio and an energy separation of the spin doublet states ($3/2_1^+$ and $5/2_1^+$). In addition, peaks that are considered to be states of $[{}^{8}\mathrm{Li}(3^+) \otimes s_{\Lambda} = 3/2_2^+, 1/2^+]$ and $[{}^{8}\mathrm{Li}(1^+) \otimes s_{\Lambda} = 5/2_2^+, 7/2^+]$ were observed at $E_{\Lambda}(\mathrm{no.}\ 2) = 1.74 \pm 0.27^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$ and $E_{\Lambda}(\mathrm{no.}\ 3) = 3.30 \pm 0.24^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$ MeV, respectively. The $E_{\Lambda}(\mathrm{no.}\ 3)$ is larger than shell-model predictions by a few hundred keV, and the difference would indicate that a ${}^{5}\mathrm{He} + t$ structure is more developed for the 3^+ state than those for the 2^+ and 1^+ states in a core nucleus ${}^{8}\mathrm{Li}$ as a cluster model calculation suggests.

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The nucleon-nucleon interaction (NN) is well understood thanks to the rich data set from scattering and nuclear spectroscopy experiments. On the other hand, hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions are less understood because experimental data for the strangeness sector are scarce. Scattering experiments are difficult for hyperons due to their short lifetimes. Data from hyperon scattering

*Deceased.

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experiments are still limited [1], although a Σ-proton scattering experiment was recently carried out at J-PARC [2]. Therefore, hypernuclear spectroscopy plays a vital role in investigations of YN and YY interactions.

The ΛN-ΣN coupling is one of the important effects in the ΛN interaction. The energy difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He is firm evidence of the charge symmetry breaking (CSB) in the ΛN interaction [3–5], and the ΛN-ΣN coupling is considered to be key to solving the ΛN CSB issue [6–8]. A neutron-rich system is a good environment in which to investigate the ΛN-ΣN coupling because it is predicted that the Σ mixing probability in a neutron-rich system is rather higher and that the energy structure is more affected by the coupling compared to so-called normal Λ hypernuclei [9]. However, there are few data on neutron-rich Λ hypernuclei. For example, superheavy hyperhydrogen ${}^{6}_{\Lambda}$H and superheavy hyperlithium ${}^{10}_{\Lambda}$Li were investigated via double charge-exchange reactions using hadron beams. The FINUDA Collaboration identified three events that are interpreted as ${}^{6}_{\Lambda}$H [10]. Experiments at J-PARC and KEK, on the other hand, were not able to determine the Λ-binding energies of ${}^{6}_{\Lambda}$H [11,12] and ${}^{10}_{\Lambda}$Li [13] due to either low statistics or insufficient energy resolution. In this Letter, we report new spectroscopic data of a neutron-rich Λ hypernucleus ${}^{9}_{\Lambda}$Li for which we performed missing mass spectroscopy with the $(e, e'K^+)$ reaction at Jefferson Laboratory's (JLab) experimental Hall C.

A difference of Λ-binding energies between mirror hypernuclei is a benchmark of CSB in the ΛN interaction. ΛN CSB was discussed in s-shell hypernuclei [5,14–16], and the interest is extended to CSB in p-shell hypernuclear systems [17–19]. We present new binding energy data for ${}^{9}_{\Lambda}$Li which are compared with that of the mirror hypernucleus ${}^{9}_{\Lambda}$B.

We performed a series of Λ-binding energy measurements for several p-shell hypernuclei with a new magnetic spectrometer system HKS-HES (Experiment JLab E05-115) [20], and results for ${}^{7}_{\Lambda}$He [21], ${}^{10}_{\Lambda}$Be [22], and ${}^{12}_{\Lambda}$B [23] were published. We also took data with a ^{9}Be target to produce ${}^{9}_{\Lambda}$Li. A continuous $E_e = 2.344$-GeV electron beam was impinged on a 188-mg/cm^2 ^{9}Be target. The beam had a typical intensity on target of about 38 μA with a beam bunch cycle of 2 ns. A total of 5.3 C ($=3.3 \times 10^{19}$ electrons) was delivered to the target. The scattered electron and K^+ with central momenta of $p_{e'} = 0.844$ and $p_K = 1.200$ GeV/c were measured by the HES and HKS [24], respectively. The HES and HKS spectrometers have momentum resolutions of $\Delta p/p \simeq 2 \times 10^{-4}$ FWHM allowing us to achieve the best energy resolution in missing mass spectroscopy of hypernuclei [23].

In order to calibrate the absolute energy in the missing mass spectrum, we used the reactions $p(e, e'K^+)\Lambda$ and $p(e, e'K^+)\Sigma^0$ on a polyethylene target (CH$_x$) to produce Λ and Σ^0 hyperons for which we know the masses with uncertainties of only ± 6 and ± 24 keV, respectively [25]. The calibration used the same spectrometer settings as those for hypernuclear production thanks to the large momentum acceptances of the HES and HKS ($\Delta p_{\mathrm{accept}}/p_{\mathrm{central}} = \pm 17.5\%$ and $\pm 12.5\%$, respectively), minimizing the systematic error on the binding energy measurement. The systematic error was evaluated by a GEANT4 Monte Carlo (MC) simulation [26,27] in which precise geometry, materials, and magnetic fields were modeled. The calibration analysis that was used for the real data was applied to several sets of dummy data from the MC simulation to estimate the systematic error on the binding energy. As a result, the systematic errors originating from the energy calibration for the Λ-binding energy and the excitation energy were evaluated to be $\Delta B_{\Lambda}^{\mathrm{sys.}} = 0.11$ and $\Delta E_{\Lambda}^{\mathrm{sys.}} = 0.05$ MeV, respectively. Refer to Refs. [20,23] for details about the calibration method.

In the hadron arm of the HKS spectrometer, backgrounds of π^+'s and protons were rejected to identify K^+'s both on-line (data taking trigger) and off-line (data analysis). To reduce the trigger rate to less than 2 kHz, allowing a data-acquisition live time of over 90%, we incorporated two types of Cherenkov detectors (AC and WC; radiation media of a hydrophobic aerogel and a deionized water with refractive indices of $n = 1.05$ and 1.33, respectively) in the trigger. Off-line, the K^+ identification (KID) was performed by the following three criteria: (KID-1) coincidence time analysis, (KID-2) light yield analysis in AC and WC, (KID-3) analysis of particle-squared mass. The coincidence time is defined as $t_{\mathrm{coin}} = t_{e'} - t_K$ where $t_{e',K}$ are the times at target. The $t_{e',K} = t^{\mathrm{TOF}} - (\frac{l}{v_{e',K}})$ were calculated event by event by using the velocity $v_{e',K}$, the time at the time-of-flight (TOF) detector t^{TOF}, and the path-length (l) from the target to the TOF detector for each particle. The velocity $v_{e',K}$ was obtained from the particle momentum which was calculated by the backward transfer matrix with assumptions of the masses of e' and K^+ for particles in HES and HKS, respectively. A coincidence event of (e' - K^+) could be identified with a resolution of 0.64-ns (FWHM) in the coincidence time. Peaks of other coincidence reactions, such as (e' - π^+) and (e' - p) are located at different times with respect to the (e' - K^+) one because of the wrong assumptions of particle masses for π^+'s and protons. The other coincidence events and most of the accidental coincidence events could be removed by a coincidence time selection with a time gate of ± 1-ns width for the real (e' - K^+) coincidence peak [20]. Only 0.047% and 0.019% of the π^+'s and protons, respectively, survived when KID-2 and 3 were used, whereas $> 80\%$ of the K^+'s remained after these cuts [28].

Figure 1 shows the differential cross section as a function of $-B_{\Lambda}$ for the reaction of ^{9}Be$(e, e'K^+){}^{9}_{\Lambda}$Li. The abscissa is $-B_{\Lambda} = -[M({}^{8}\mathrm{Li}) + M_{\Lambda} - M_{\mathrm{HYP}}]$ where $M({}^{8}\mathrm{Li})$ and M_{Λ} are the masses of the ^{8}Li core nucleus and the Λ which are 7471.36 [29] and 1115.68 MeV/c^2 [25], respectively. The mass of $M({}^{9}\mathrm{Be}) = 8392.75$ MeV/c^2 [29] was used for the target nucleus ^{9}Be to calculate M_{HYP}. The ordinate is the differential cross section in the laboratory frame for the (γ^*, K^+) reaction $(\frac{d\sigma}{d\Omega_K})|_{\mathrm{HKS}}$ that is described in Refs. [21,22]. It must be noted that Q^2 ($= -q^2$ where q is the four-momentum transfer to a virtual photon) was small [$Q^2 = 0.01$ (GeV/c)^2] in our experimental setup, and, thus, the virtual photon may be treated as almost a real photon. The K^+-scattering angle with respect to the virtual photon was $\theta_{\gamma K}^{\mathrm{laboratory}} \simeq 7^\circ$. As the electron spectrometer was tilted out of the horizontal plane [20], the angle between the electron-scattering plane and the reaction plane ϕ_K was approximately 90°. The distribution of accidental coincidence events shown in Fig. 1 was

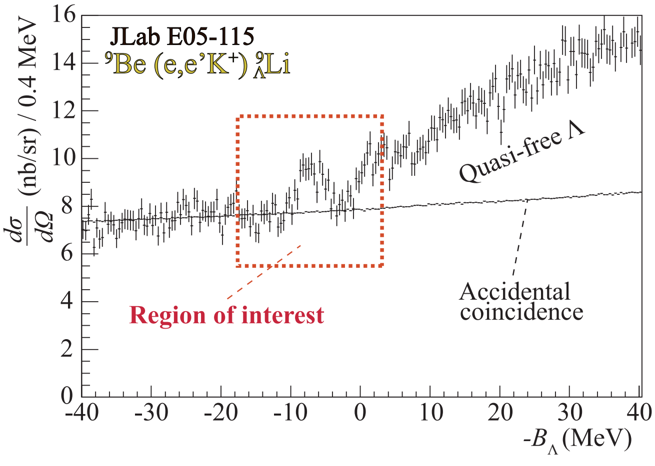

FIG. 1. Differential cross section of the ^{9}Be$(e, e'K^+)^9_\Lambda$Li reaction as a function of $-B_\Lambda$. Events exceeding over the accidental coincidence background in the bound region ($-B_\Lambda < 0$) were analyzed in the present Letter.

obtained by the mixed event analysis in which the missing mass was reconstructed with random combinations of e' and K^+ from different events [30]. The accidental background distribution was subtracted as shown in Fig. 2, and residual events in a region of $-B_\Lambda < 0$ were analyzed as bound states of $^9_\Lambda$Li. Three doublet states for which a Λ residing in the s orbit couples with the 2^+ (ground state), 1^+, and 3^+ states of the core nucleus ^{8}Li are expected to be largely populated in the $^9_\Lambda$Li spectrum [31,32]. In addition, the energy spacings between the states in each spin doublet are theoretically expected to be at most about 0.6 MeV making them difficult to separate given the expected experimental resolution. Therefore, we used three Voigt functions with the same width for fitting the cross-section spectrum. The fitting result with χ^2/n.d.f. = 22.24/22 is summarized in Table I. The full width at half maximum of the Voigt function for each peak was found to be 1.1 ± 0.4 MeV which is consistent

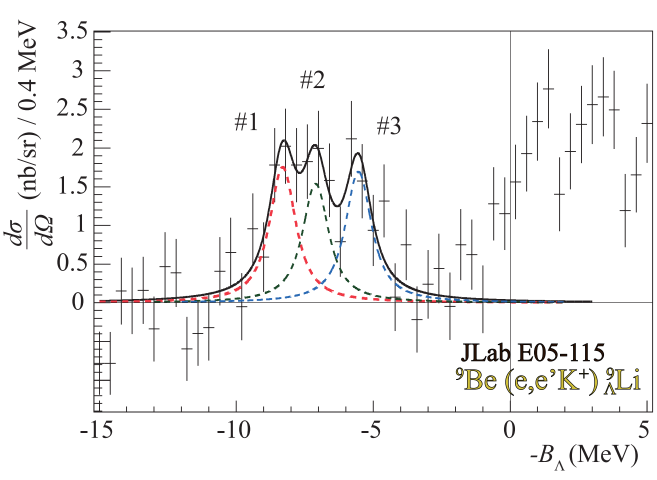

FIG. 2. Fit of the ^{9}Be$(e, e'K^+)^9_\Lambda$Li spectrum by three Voigt functions after the accidental coincidence events obtained by the mixed event analysis (Fig. 1) was subtracted.

with that expected in the MC simulation. The cross-section ratios of peaks no. 2 and no. 3 to that of peak no. 1 are 0.88 ± 0.13 and 0.96 ± 0.15, respectively, whereas the ratios of the corresponding spectroscopic factors C^2S are 0.60 and 0.65, respectively, as measured in the ^{9}Be$(t, \alpha)^8$Li reaction [33]. Peak no. 1 is considered to be the first doublet state, ^{8}Li$(2^+; \text{g.s.}) \otimes s_\Lambda = 3/2^+_1, 5/2^+_1$. It is predicted that the production cross section of the $5/2^+_1$ state is larger than that of the ground-state $3/2^+_1$ by a factor of 5–7, and the doublet separation is 0.5–0.7 MeV [9,31,34]. Assuming this cross-section ratio and doublet separation, the ground-state binding energy is evaluated to be greater than the mean value of peak no. 1 by 0.53 ± 0.10 MeV [$= \Delta B_\Lambda$(g.s.-no. 1)] by a simple simulation leading to the ground-state energy $B^{\text{Hall-C}}_\Lambda(^9_\Lambda\text{Li}; \text{g.s.}) = 8.84 \pm 0.17^{\text{stat.}} \pm 0.15^{\text{sys.}}$ MeV. The obtained B_Λ agrees with $B^{\text{emul.}}_\Lambda(^9_\Lambda\text{Li}; \text{g.s.}) = 8.50 \pm 0.12$ MeV [35], the mean binding energy of 13 emulsion events, and $B^{\text{Hall-A}}_\Lambda(^9_\Lambda\text{Li}; \text{g.s.}) = 8.36 \pm 0.08^{\text{stat.}} \pm 0.08^{\text{sys.}}$ MeV [36,37] within $\pm 2\sigma$ of the uncertainty. The weighted average of the above three measurements including our result is found to be $B^{\text{mean}}_\Lambda(^9_\Lambda\text{Li}; \text{g.s.}) = 8.47 \pm 0.08^{\text{total}}$ MeV.

The excitation energies (E_Λ) for peaks no. 2 and no. 3 were calculated based on the obtained ground-state energy $B^{\text{Hall-C}}_\Lambda(^9_\Lambda\text{Li}; \text{g.s.})$ and are shown in Table I. Figure 3 shows a comparison of the obtained E_Λ with those of shell-model predictions [9,34,38] and the experimental data from JLab Hall A [36,37]. Experimental energy levels of the core nucleus ^{8}Li taken from Ref. [39] are shown as well. The excitation energy of $E_\Lambda(\text{no. 2}) = 1.74 \pm 0.27^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV is consistent with those of the theoretical predictions of $3/2^+_2$ and $1/2^+$ and the experimental result of JLab Hall A. For the third doublet which is considered to correspond to peak no. 3, the cross section of the $7/2^+$ is predicted to be larger than that of $5/2^+_2$ by a factor of 2 or 3 [31,34], and, thus, peak no. 3 is expected to be dominated by the $7/2^+$ state. The energy of peak no. 3 was found to be $E_\Lambda(\text{no. 3}) = 3.30 \pm 0.24^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV. It is found that E_Λ(no. 3) is larger than the predicted energy of $7/2^+$ by a few hundred keV. E_Λ could be larger if the core nucleus is deformed due to a development of clusters because a spatial overlap between the core nucleus and the Λ gets smaller [40]. A cluster model calculation suggests that a He$^5 + t$ structure is more developed for the 3^+ state than for the 2^+ and 1^+ states in ^{8}Li [41]. The larger energy compared to the shell-model predictions for peak no. 3 may indicate the development of clusters for the 3^+ state of the core nucleus ^{8}Li.

The highest excitation energy peak observed by the experiment at JLab Hall A was at 2.27 ± 0.09 MeV [36,37] that differs from E_Λ(no. 3) by about 1 MeV. If we assume 0.23 MeV of the energy separation between the first doublet states instead of the assumption of 0.5–0.7-MeV separation, the central value of the ground-state energy becomes consistent with that of the emulsion experiment ($B^{\text{emul.}}_\Lambda$). Accordingly, the excitation energies are reduced by 0.34 MeV [$=0.53 - (8.50 - 8.31)$ MeV] from those shown in Table I and Fig. 3, and E_Λ(nos. 2 and 3) become more consistent with the theoretical predictions. However, E_Λ(no. 3) obtained with this different assumption is still far from the energy of the most excited state observed at JLab Hall A. Peaks that

TABLE I. Fitting result of the ^{9}Be$(e, e'K^{+})^{9}_{\Lambda}$Li spectrum in JLab E05-115. Three Voigt functions were used for the fitting. The Λ-binding energy of the ground-state $B_{\Lambda}^{\mathrm{g.s.}}$ and the excitation energy E_{Λ} were evaluated with the assumption that the cross-section ratio of the first excited-state $5/2_1^+$ to that of the ground-state $3/2_1^+$ is 5–7 and the doublet separation is 0.5–0.7 MeV [9,31,34].

Peak ID	Possible states	B_{Λ} (MeV)	E_{Λ} (MeV)	$(\frac{d\sigma}{d\Omega_K})\vert_{\mathrm{HKS}}$ (nb/sr)
No. 1	^{8}Li$(2^+)\otimes s_{\Lambda}$ $= 3/2_1^+, 5/2_1^+$	$8.31 \pm 0.17 \pm 0.11^{\mathrm{sys.}}$ $(B_{\Lambda}^{\mathrm{g.s.}} = 8.84 \pm 0.17^{\mathrm{stat.}} \pm 0.15^{\mathrm{sys.}})$	$[\Delta B_{\Lambda}(\mathrm{g.s.\text{-}no.1}) = 0.53 \pm 0.10^{\mathrm{sys.}}]$	$7.6 \pm 0.8^{\mathrm{stat.}} \pm 0.8^{\mathrm{sys.}}$
No. 2	^{8}Li$(1^+)\otimes s_{\Lambda}$ $= 3/2_2^+, 1/2^+$	$7.10 \pm 0.21 \pm 0.11^{\mathrm{sys.}}$	$1.74 \pm 0.27^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$	$6.7 \pm 0.7^{\mathrm{stat.}} \pm 0.7^{\mathrm{sys.}}$
No. 2	^{8}Li$(3^+)\otimes s_{\Lambda}$ $= 5/2_2^+, 7/2^+$	$5.54 \pm 0.17 \pm 0.11^{\mathrm{sys.}}$	$3.30 \pm 0.24^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$	$7.3 \pm 0.8^{\mathrm{stat.}} \pm 0.7^{\mathrm{sys.}}$

originate from different states might be observed due to a difference in kinematics, such as Q^2 and the K^+-scattering angle with respect to the virtual photon. However, the relative strength of the cross section for each state in the present experiment is predicted not to differ so much from that of JLab Hall A in DWIA calculations [42] in which elementary amplitudes of the Saclay-Lyon and BS3 models [43] are used. Further studies are necessary to consistently understand these experimental spectra.

Three events of $^{9}_{\Lambda}$B were identified in the emulsion experiment, and the mean value was reported to be $B_{\Lambda}(^{9}_{\Lambda}\mathrm{B}; \mathrm{g.s.}) = 8.29 \pm 0.18$ MeV [35]. The difference of Λ-binding energies between the $A = 9$ isotriplet hypernuclei was found to be $B_{\Lambda}(^{9}_{\Lambda}\mathrm{B}; \mathrm{g.s.}) - B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li}; \mathrm{g.s.}) = -0.55 \pm 0.29$ MeV to be compared with the prediction of -0.054 MeV [18]. There might be an unexpectedly large CSB effect in the $A = 9$ isotriplet hypernuclei. However, the current experimental precision is not sufficient for $^{9}_{\Lambda}$Li as well as $^{9}_{\Lambda}$B to discuss the ΛN CSB in the system. In order to precisely determine the ground-state energy by an experiment with the $(e, e'K^+)$ reaction, the first doublet states would need to be resolved. The doublet separation of $^{9}_{\Lambda}$Li (between $3/2^+$ and $5/2^+$ states) is predicted

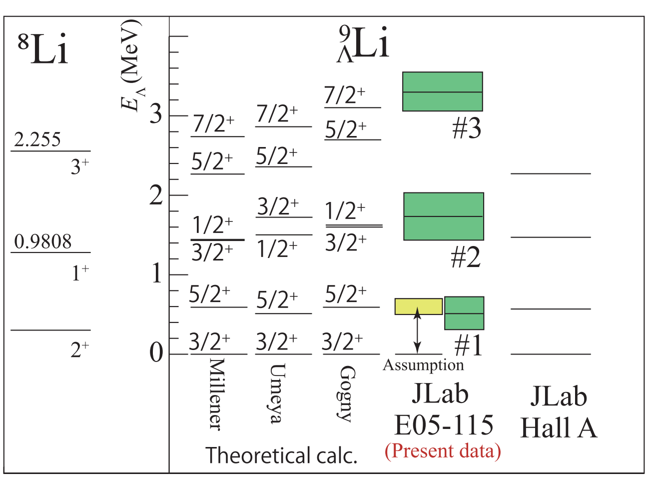

FIG. 3. Comparison of the obtained excitation energy E_{Λ} of $^{9}_{\Lambda}$Li with theoretical calculations [9,34,38] and experimental data taken at JLab Hall A [36,37]. E_{Λ} was obtained with the assumption that the cross-section ratio of the $5/2^+$ state to that of the ground state $3/2^+$ is 5–7 and the doublet separation is 0.5–0.7 MeV [9,31,34].

to be 0.5–0.7 MeV which is much larger than for other p-shell hypernuclei (e.g., the separation between 1^- (g.s.) and 2^- states of $^{12}_{\Lambda}$C was measured to be 0.1615 ± 0.0003 MeV [44]). This is partially due to a large contribution of the ΛN-ΣN coupling [9]. Therefore, an $(e, e'K^+)$ experiment with an energy resolution of 0.5-MeV (FWHM) or better would be a promising way to precisely determine the ground-state energy of $^{9}_{\Lambda}$Li.

To summarize, we measured $^{9}_{\Lambda}$Li by missing mass spectroscopy with the $(e, e'K^+)$ reaction at JLab Hall C. We observed three peaks (nos. 1–3) that are considered to be s_{Λ} states coupling with a ^{8}Li nucleus in the 2^+, 1^+, and 3^+ states. Peak no. 1 that is expected to be the spin doublet state of $[^{8}\mathrm{Li}(2^+)\otimes s_{\Lambda}(= 3/2_1^+, 5/2_1^+)]$ was analyzed to obtain the ground-state energy. The ground-state energy was determined to be $B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li}; \mathrm{g.s.}) = 8.84 \pm 0.17^{\mathrm{stat.}} \pm 0.15^{\mathrm{sys.}}$ MeV using the assumptions that the cross-section ratio of the first excited state $(5/2_1^+)$ to that of the ground-state $(3/2_1^+)$ is 5–7 and that the doublet energy separation is 0.5–0.7 MeV [9,31,34]. Peaks no. 2 and no. 3 are considered to be $[^{8}\mathrm{Li}(1^+)\otimes s_{\Lambda}(= 3/2_2^+, 1/2^+)]$ and $[^{8}\mathrm{Li}(3^+)\otimes s_{\Lambda}(= 5/2_2^+, 7/2^+)]$ states, respectively. We obtained excitation energies to be $E_{\Lambda}(\mathrm{no.}\ 2) = 1.74 \pm 0.27^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$ MeV and $E_{\Lambda}(\mathrm{no.}\ 3) = 3.30 \pm 0.24^{\mathrm{stat.}} \pm 0.11^{\mathrm{sys.}}$ MeV by using the $B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li}; \mathrm{g.s.})$. $E_{\Lambda}(\mathrm{no.}\ 3)$ is larger than predicted by shell-model calculations for which different NN and ΛN interactions are used whereas $E_{\Lambda}(\mathrm{no.}\ 2)$ agrees with the theoretical predictions. The difference of about a few hundred keV supports the idea a ^{5}He + t structure is more developed for the 3^+ state than for the 2^+ and 1^+ states of the ^{8}Li nucleus as a cluster model calculation suggests [41].

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