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

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Missing mass spectroscopy with the $(e, e'K^+)$ reaction was performed at JLab Hall C for the neutron rich Λ hypernucleus ${}^{9}_{\Lambda}$Li. The ground state energy was obtained to be $B_\Lambda^{\text{g.s.}} = 8.84 \pm 0.17^{\text{stat.}} \pm 0.15^{\text{sys.}}$ 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 $[{}^8\text{Li}(3^+) \otimes s_\Lambda = 3/2^+_2, 1/2^+]$ and $[{}^8\text{Li}(1^+) \otimes s_\Lambda = 5/2^+_2, 7/2^+]$ were observed at $E_\Lambda(\#2) = 1.74 \pm 0.27^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV and $E_\Lambda(\#3) = 3.30 \pm 0.24^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV, respectively. The $E_\Lambda(\#3)$ is larger than shell model predictions by a few hundred keV, and the difference would indicate that a ${}^5\text{He} + t$ structure is more developed for the 3^+ state than those for the 2^+ and 1^+ states in a core nucleus ^{8}Li as a cluster model calculation suggests.

The nucleon-nucleon interaction (NN) is informed by a rich data set of scattering and nuclear spectroscopy experiments. On the other hand, the 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 short lifetimes of hyperons. Data from hyperon scattering 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 a key to solving the ΛN CSB issue [6–8]. A neutron rich system is a good environment 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 [9] compared to so called normal Λ hypernuclei. However, there are few data on neutron rich Λ hypernuclei. For example, superheavy hyperhydrogen ${}^{6}_{\Lambda}$H and a superheavy hyperlithium ${}^{10}_{\Lambda}$Li were investigated via double charge exchange reactions using hadron beams. 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 article, 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 Lab'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 the s-shell hypernuclei [5, 14–16], and an interest is extended to CSB in p-shell hypernuclear systems [17–19]. We present new binding energy data of ${}^{9}_{\Lambda}$Li which is 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 at JLab Hall C (Experiment JLab E05-115) [20], and results for ${}^{7}_{\Lambda}$He [21], ${}^{10}_{\Lambda}$Be [22] and ${}^{12}_{\Lambda}$B [23] were published. We acquired data with a ^{9}Be target to produce ${}^{9}_{\Lambda}$Li in the same experimental period. A continuous $E_e = 2.344$ GeV electron beam was incident on a 188-mg/cm^2 ^{9}Be target. The beam had an average on target intensity 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 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 keV and ± 24 keV, respectively [25]. The calibration used the same spectrometer setting as that for hypernuclear production thanks to large momentum bites of 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 [27, 28] 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 in the MC simulation to estimate the systematic error on binding energy. As a result, the systematic errors 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 HKS spectrometer, there were backgrounds of π^+s and protons which were rejected to identify K^+s both on-line (data taking trigger) and off-line (data analysis) stages. To reduce the trigger rate to less than 2 kHz, allowing a data acquisition live time 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 done by the following three analyses: (KID-1) coincidence time analysis, (KID-2) light yield analysis in AC and WC, (KID-3) analysis of particle mass squared. The coincidence time is defined as $t_{\mathrm{coin}} = t_{e'} - t_K$ where $t_{e',K}$ is the time at target. The $t_{e',K} = t^{\mathrm{TOF}} - \left(\frac{l}{v_{e',K}}\right)$ was calculated event by event by using the velocity $v_{e',K}$, the time at a 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 a 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 positions from that of the (e',K^+) peak because of the wrong assumptions of particle masses for π^+s and protons. The other coincidence events and most of 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]. With KID-2 and 3, survival ratios for π^+ and proton were suppressed down to 0.047% and 0.019%, respectively with maintaining $> 80\%$ of K^+ survival ratio [29].

Figure 1 shows the missing mass spectrum for the reaction of ${}^{9}\mathrm{Be}(e, e'K^+){}^{9}_{\Lambda}\mathrm{Li}$. The abscissa is $-B_\Lambda = -[M({}^{8}\mathrm{Li}) + M_\Lambda - M_{\mathrm{HYP}}]$ where $M({}^{8}\mathrm{Li})$ and M_Λ are masses of a core nucleus ^{8}Li and a Λ which are 7471.366 MeV/c^2 [30] and 1115.682 MeV/c^2 [25], respectively. The mass of $M({}^{9}\mathrm{Be}) = 8392.750$ MeV/c^2 [30] was used for a target nucleus ^{9}Be to calculate M_{HYP}. The ordinate is the differential cross section in the laboratory frame for the (γ^*, K^+) reaction $\left(\frac{d\sigma}{d\Omega_K}\right)\Big|_{\mathrm{HKS}}$ that is described in Refs. [21, 22]. It is noted that Q^2 ($= -q^2$ where q is the four momentum transfer to a virtual photon) is small [$Q^2 = 0.01$ (GeV/c)^2] with our experimental setup, and thus, the virtual photon may be treated as almost a real photon. A distribution of accidental coincidence events shown in Fig. 1 was obtained by the mixed event analysis in which the missing mass was reconstructed with random combinations of e' and K^+

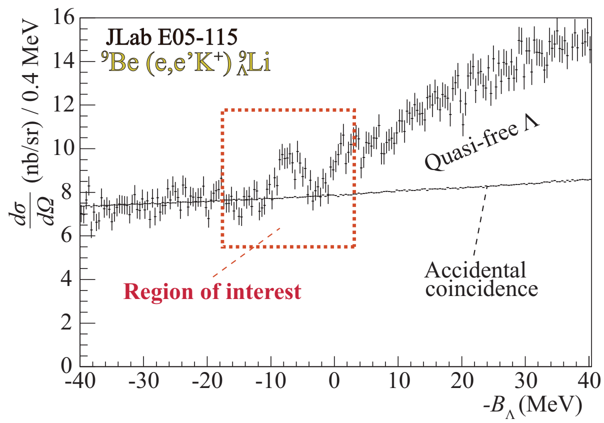

FIG. 1. An obtained spectrum for the ^{9}Be$(e,e'K^+)^9_\Lambda$Li reaction with an abscissa of $-B_\Lambda$. Events that exceeded over the accidental coincidence background in the bound region ($-B_\Lambda < 0$) were analyzed in the present work.

in the analysis [26]. 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 re-

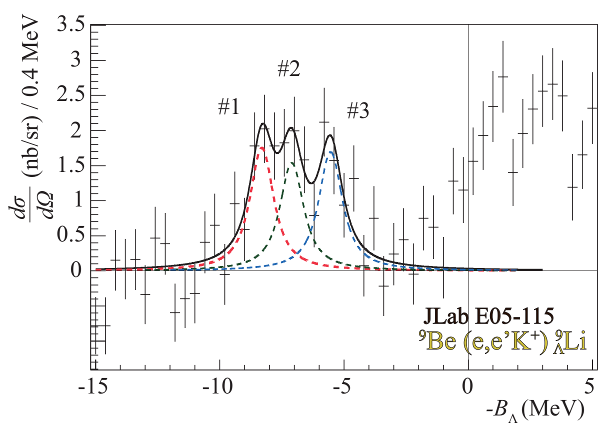

FIG. 2. A fitting result on the ^{9}Be$(e,e'K^+)^9_\Lambda$Li spectrum by three Voigt functions. A distribution of the accidental coincidence events that was obtained by the mixed event analysis (Fig. 1) was subtracted from the original spectrum.

siding 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 each spin doublet states are theoretically expected to be about 0.6 MeV at most making them difficult to separate given the expected experimental resolution. Therefore, we used three Voigt functions with the same width for fitting to the 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 with that expected in the MC simulation. The cross section ratios of peaks #2 and #3 to that of peak #1 are 0.88 ± 0.13 and 0.96 ± 0.15, respectively while ratios of the corresponding spectroscopic factors C^2S are respectively 0.60 and 0.65 that were measured in the ^{9}Be$(t,\alpha)^8$Li reaction [33]. Peak #1 is considered to be the first doublet states, ^{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 the above cross section ratio and the doublet separation, the ground state binding energy is evaluated to be greater than that of the mean value of peak #1 by 0.53 ± 0.10 MeV [$= \Delta B_\Lambda(\text{g.s.}-\#1)$] by a simple simulation leading to the ground state energy $B_\Lambda^{\text{Hall-C}}(^9_\Lambda\text{Li};\text{g.s.}) = 8.84 \pm 0.17^{\text{stat.}} \pm 0.15^{\text{sys.}}$ MeV. The obtained B_Λ agrees with $B_\Lambda^{\text{emul.}}(^9_\Lambda\text{Li};\text{g.s.}) = 8.50 \pm 0.12$ MeV [35], the mean binding energy of 13 emulsion events, and $B_\Lambda^{\text{Hall-A}}(^9_\Lambda\text{Li};\text{g.s.}) = 8.36 \pm 0.08^{\text{stat.}} \pm 0.08^{\text{sys.}}$ MeV from the measurement in JLab Hall A [36, 37] within $\pm 2\sigma$ of the uncertainty. The weighted average of the above three measurements including our result is found to be $B_\Lambda^{\text{mean}}(^9_\Lambda\text{Li};\text{g.s.}) = 8.47 \pm 0.08$ MeV.

The excitation energies (E_Λ) for peaks #2 and #3 were calculated based on the obtained ground state energy $B_\Lambda^{\text{Hall-C}}(^9_\Lambda\text{Li};\text{g.s.})$, 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 $E_\Lambda(\#2) = 1.74 \pm 0.27^{\text{stat.}} \pm 0.11^{\text{sys.}}$ 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 #3, the cross section of the $7/2^+$ is predicted to be larger than that of $5/2^+_2$ by a factor of 2–3 [31, 34], and thus peak #3 is expected to be dominated by the $7/2^+$ state. The energy of peak #3 was found to be $E_\Lambda(\#3) = 3.30 \pm 0.24^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV. It is found that $E_\Lambda(\#3)$ is larger than the predicted energies of $7/2^+$ by a few hundred keV. An E_Λ could be larger if a core nucleus is deformed due to a development of clusters because a spatial overlap between the core nucleus and a 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 #3 may indicate the development of clusters for the 3^+ state of the core nucleus ^{8}Li as suggested.

A peak in the highest excitation observed in the experiment at JLab Hall A was at 2.27 ± 0.09 MeV [36, 37] that differs from $E_\Lambda(\#3)$ 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

TABLE I. Fitting result of the $^{9}\mathrm{Be}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Li}$ 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 an 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)	$\left(\frac{d\sigma}{d\Omega_K}\right)\Big\|_{\mathrm{HKS}}$ (nb/sr)
#1	$^{8}\mathrm{Li}(2^{+})\otimes s_{\Lambda}$ $=3/2_{1}^{+},5/2_{1}^{+}$	$8.31\pm0.17\pm0.11^{\mathrm{sys.}}$ $(B_{\Lambda}^{\mathrm{g.s.}}=8.84\pm0.17^{\mathrm{stat.}}\pm0.15^{\mathrm{sys.}})$	$[\Delta B_{\Lambda}(\mathrm{g.s.}-\#1)=0.53\pm0.10^{\mathrm{sys.}}]$	$7.6\pm0.8^{\mathrm{stat.}}\pm0.8^{\mathrm{sys.}}$
#2	$^{8}\mathrm{Li}(1^{+})\otimes s_{\Lambda}$ $=3/2_{2}^{+},1/2^{+}$	$7.10\pm0.21\pm0.11^{\mathrm{sys.}}$	$1.74\pm0.27^{\mathrm{stat.}}\pm0.11^{\mathrm{sys.}}$	$6.7\pm0.7^{\mathrm{stat.}}\pm0.7^{\mathrm{sys.}}$
#3	$^{8}\mathrm{Li}(3^{+})\otimes s_{\Lambda}$ $=5/2_{2}^{+},7/2^{+}$	$5.54\pm0.17\pm0.11^{\mathrm{sys.}}$	$3.30\pm0.24^{\mathrm{stat.}}\pm0.11^{\mathrm{sys.}}$	$7.3\pm0.8^{\mathrm{stat.}}\pm0.7^{\mathrm{sys.}}$

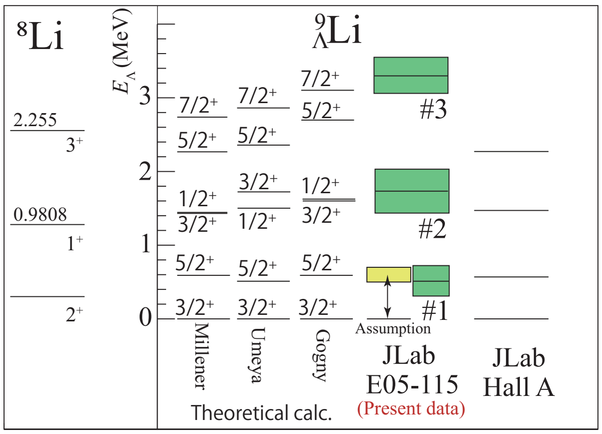

FIG. 3. A comparison of the obtained excitation energy E_{Λ} of $^{9}_{\Lambda}\mathrm{Li}$ with those of theoretical calculations [9, 34, 38] and an experimental data taken at JLab Hall A [36, 37]. E_{Λ} was obtained with the assumption that the cross section ratio of the $5/2^{+}$ state to that of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

($B_{\Lambda}^{\mathrm{emul.}}$). 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 $E_{\Lambda}(\#2,3)$ become more consistent with the theoretical predictions. However, $E_{\Lambda}(\#3)$ obtained with this different assumption is still far from the energy of the most excited state observed at JLab Hall A. Peaks that 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 $^{9}_{\Lambda}\mathrm{B}$ were identified in the emulsion experiment, and the mean value was reported to be $B_{\Lambda}(^{9}_{\Lambda}\mathrm{B};\mathrm{g.s.})=8.29\pm0.18$ MeV [35]. The difference of Λ binding energies between the $A=9$ isotriplet hypernuclei was found to be $B_{\Lambda}(^{9}_{\Lambda}\mathrm{B};\mathrm{g.s.})-B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li};\mathrm{g.s.})=-0.55\pm0.29$ MeV while a prediction is -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 $^{9}_{\Lambda}\mathrm{Li}$ as well as $^{9}_{\Lambda}\mathrm{B}$ 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 $^{9}_{\Lambda}\mathrm{Li}$ (between $3/2^{+}$ and $5/2^{+}$ states) is predicted 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 $^{12}_{\Lambda}\mathrm{C}$ 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 $^{9}_{\Lambda}\mathrm{Li}$.

To summarize, we measured $^{9}_{\Lambda}\mathrm{Li}$ by missing mass spectroscopy with the $(e,e'K^{+})$ reaction at JLab Hall C. We observed three peaks (#1–3) that are considered to be s_{Λ} states coupling with a $^{8}\mathrm{Li}$ nucleus in the 2^{+}, 1^{+} and 3^{+} states. Peak #1 that is expected to be spin doublet states 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 $B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li};\mathrm{g.s.})=8.84\pm0.17^{\mathrm{stat.}}\pm0.15^{\mathrm{sys.}}$ MeV with assumptions that the cross section ratio of the fist excited state ($5/2_{1}^{+}$) to that of the ground state ($3/2_{1}^{+}$) is 5–7 and the doublet energy separation is 0.5–0.7 MeV [9, 31, 34]. Peaks #2 and #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 $E_{\Lambda}(\#2)=1.74\pm0.27^{\mathrm{stat.}}\pm0.11^{\mathrm{sys.}}$ MeV and $E_{\Lambda}(\#3)=3.30\pm0.24^{\mathrm{stat.}}\pm0.11^{\mathrm{sys.}}$ MeV by using the obtained $B_{\Lambda}^{\mathrm{Hall\text{-}C}}(^{9}_{\Lambda}\mathrm{Li};\mathrm{g.s.})$. $E_{\Lambda}(\#3)$ is larger than predicted by shell model calculations for which different NN and ΛN interactions are used while $E_{\Lambda}(\#2)$ agrees with the theoretical predictions. The difference of about a few hundred keV supports the idea a $^{5}\mathrm{He}+t$ structure is more developed for the 3^{+} state than for the 2^{+} and 1^{+} states of the $^{8}\mathrm{Li}$ nucleus, as a cluster model calculation suggests [41].

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[1] G. Alexander et al., Phys. Rev. 173, 5 (1968).
[2] K. Miwa et al., Proposal to J-PARC, E40 Experiment (2011).
[3] A. Esser et al. (A1 Collaboration), Phys. Rev. Lett. 114, 232501 (2015).
[4] F. Schulz et al. (A1 Collaboration), Nucl. Phys. A 954, 149 (2016).
[5] T.O. Yamamoto et al. (J-PARC E13 Collaboration), Phys. Rev. Lett. 115, 222501 (2015).
[6] B.F. Gibson et al., Phys. Rev. C 6, 3 (1972).
[7] Y. Akaishi et al., Phys. Rev. Lett. 84, 16 (2000).
[8] A. Nogga et al., Phys. Rev. Lett. 88, 17 (2002).
[9] A. Umeya and T. Harada, Phys. Rev. C 83, 034310 (2011).
[10] M. Agnello et al. (FINUDA Collaboration), Phys. Rev. Lett. 108, 042501 (2012).
[11] H. Sugimura et al. (J-PARC E10 Collaboration), Phys. Lett. B 729, 39–44 (2014).
[12] R. Honda et al. (J-PARC E10 Collaboration), Phys. Rev. C 96, 014005 (2017).
[13] P.K. Saha et al., Phys. Rev. Lett. 94, 052502 (2005).
[14] R.H. Dalitz and F. Von Hippel, Phys. Lett. 10, 1 (1964).
[15] A.R. Bodmer and Q.N. Usmani, Phys. Rev. C 31, 4 (1985).
[16] D. Gazda and A. Gal, Phys. Rev. Lett. 116, 122501 (2016).
[17] E. Hiyama, Few-Body Syst. 53:189–236 (2012).
[18] A. Gal, Phys. Lett. B 744, 352–357 (2015).
[19] E. Botta et al., Nucl. Phys. A 960, 165–179 (2017).
[20] T. Gogami et al., Nucl. Instrum. Methods Phys. Res. A 900, 69–83 (2018).
[21] T. Gogami et al. (HKS (JLab E05-115) Collaboration), Phys. Rev. C 94, 021302(R) (2016).
[22] T. Gogami et al. (HKS (JLab E05-115) Collaboration), Phys. Rev. C 93, 034314 (2016).
[23] L. Tang et al. (HKS (JLab E05-115 and E01-011) Collaborations), Phys. Rev. C 90, 034320 (2014).
[24] Y. Fujii et al., Nucl. Instrum. Methods Phys. Res. A 795, 351–363 (2015).
[25] P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).
[26] S.N. Nakamura et al. (HKS (JLab E01-011) Collaboration), Phys. Rev. Lett. 110, 012502 (2013).
[27] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res. A 506, 3, 250–303 (2003).
[28] J. Allison et al., Nucl. Instrum. Methods Phys. Res. A 835, 186–225 (2016).
[29] T. Gogami et al., Nucl. Instrum. Methods Phys. Res. A 729, 816–824 (2013).
[30] G. Audi et al., Nucl. Phys. A 729, 1, 337–676 (2003).
[31] M. Sotona and S. Frullani, Prog. Theor. Phys. Suppl. 117, 151 (1994).
[32] T. Motoba et al., Prog. Theor. Phys. Suppl. 185, 224 (2010).
[33] G.-B. Liu and H.T. Fortune, Phys. Rev. C 38, 5 (1988).
[34] D.J. Millener, Nucl. Phys. A 881, 298–309 (2012).
[35] J. Pniewski et al., Nucl. Phys. A 443, 685–690 (1985).
[36] G.M. Urciuoli et al (Jefferson Lab Hall A Collaboration), Phys. Rev. C 91, 034308 (2015).
[37] F. Garibaldi et al. (Jefferson Lab Hall A Collaboration), Phys. Rev. C 99, 054309 (2019).
[38] X.Y. Chen et al., J. Phys. G: Nucl. Part. Phys. 46, 125106 (2019).
[39] D.R. Tilley et al., Nucl. Phys. A 745, 155–362 (2004).
[40] M. Isaka, Y. Yamamoto, and T. Motoba, Phys. Rev. C 101, 024301 (2020).
[41] H. Stöwe and W. Zahn, Nucl. Phys. A 289, 317–328 (1977).
[42] P. Bydžovský, Private Communication (2020).
[43] D. Skoupil and P. Bydžovský, Phys. Rev. C 97, 025202 (2018).
[44] K. Hosomi et al., Prog. Theor. Exp. Phys., 081D01 (2015).