PROPOSAL TO JLAB PAC48

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High accuracy measurement of nuclear masses of Λ hyperhydrogens

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The Λ binding energies of few-body systems are basic information for constructing ΛN interaction models. Recent experimental new findings about light hypernuclei deepened our understanding of the baryonic interaction and at the same time raised new puzzles. In order to settle the confusions, we are proposing high precision measurements on binding energies of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H using the HKS-HRS spectrometer system at Hall A. The expected results provides new constraints to discussions of (1) a conflict between short lifetime and small binding energy of hypertriton, and (2) the ΛN charge symmetry breaking. Basic understanding of simple three or four body systems is essential to understand heavier and more dense nuclear objects such as neutron stars. An additional beamtime of thirteen days with a 50 μA beam (20 μA for calibration data) impinged on cryogenic targets in Hall A to the approved experiment E12-15-008 will enable us to measure ${}^{3}_{\Lambda}$H ($1/2^{+}$ or $3/2^{+}$) and ${}^{4}_{\Lambda}$H (1^{+}) with an accuracy of $|\Delta B_{\Lambda}^{\mathrm{total}}| < 100$ keV.

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I. WHY IS THE STUDY OF SIMPLEST HYPERNUCLEI NECESSARY, NOW?

The precise spectroscopy of Λ hypernuclei, which was established at JLab after a long effort which started in 2000 [1], is now attempting to solve the puzzle of heavy neutron stars (NS). NS can be considered as a single nucleus with a radius of about 10 km and are the most dense object in the Universe. It has special features: 1) isospin asymmetry is almost 1 (number of neutrons $\gg$ number of protons) and its mass number is enormously large. So far, theoretical calculations with the established baryonic force potential models set an upper limit of NS mass as $\sim$1.6 solar mass and thus recent observation of two solar mass NSs triggered hot discussion (hyperon puzzle). Recent observation of gravitational waves from NS merger (GW170817) set a new limit for the maximum mass of NS [2]. Detailed information about baryonic force under high-density and neutron rich environment becomes now more important than before.

It is common understanding that an additional repulsive force other than the established baryonic force is necessary to make the too soft Equation of State hard enough to support two solar mass NSs. The inclusion of a three-body repulsive force with hyperons is the most promising way to explain it. The isospin dependence of light hypernuclei has been studied by detecting the charge symmetry breaking (CSB) effect of light Λ hypernuclei. Originally CSB of the ΛN interaction was discussed in the 1960s with emulsion and NaI γ-ray measurements but the limited precision of data prevented further research on it. Recent precise spectroscopy of $^{7}_{\Lambda}$He at JLab [3, 4] reignited the CSB study with state-of-the-art experimental techniques in the 21st century. The mass number 4 hypernuclear system, the ground state of $^{4}_{\Lambda}$H [5, 6] and the excitation energy of $^{4}_{\Lambda}$He [7] were recently measured very precisely. Though new experimental measurements of excitation energy of $^{4}_{\Lambda}$H and ground state energy of $^{4}_{\Lambda}$He have not yet been measured, it is recognized that systematic study of CSB or the isospin dependence of not only s-shell hypernuclei but also p-shell and heavier hypernuclei is important [8]. There has been no experimental study of isospin dependence for heavier hypernuclei though such information is essential to understand the structure of neutron rich, high density objects like NS. The first attempt to measure binding energies of $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K hypernuclei to study isospin dependence of the ΛNN force (E12-15-008) was already approved by JLab PAC44. Systematic spectroscopy of medium to heavy Λ hypernuclei is also important to extend our knowledge at normal nuclear density (ρ_0) to density of NS core, $3 - 5\rho_0$. Such study with various targets were now planned with high-intensity, high-resolution π beam at J-PARC [9]. In addition, a new proposal of the $(e, e'K^+)$ spectroscopy with a ^{208}Pb target is planned to be submitted to JLab.

Such study will reveal the existence of the ΛNN repulsive force and, its isospin and mass dependencies to solve the hyperon puzzle. In order to investigate the ΛNN force from hypernuclear energies, ΛN interaction needs to be precisely known because information on multi-body effects such as the ΛNN interaction could be extracted from residuals after the two body forces (the NN and ΛN interactions) are taken into account. The simplest bound hypernucleus with a Λ hyperon is hypertriton ${}^{3}_{\Lambda}$H, and thus the Λ binding energy of ${}^{3}_{\Lambda}$H plays an important role to constrain the ΛN interaction. We believed that light hypernuclear systems were reasonably understood based on emulsion data taken in 1960s and various spectroscopic results of hypernuclei. However, the Λ binding energy and lifetimes that were recently reported by heavy-ion beam experiments of the simple hypernucleus ${}^{3}_{\Lambda}$H contradict each other, suggesting we have been missing some important issues. Another mystery on the $A = 3$ hypernuclear system is the possibility of atomic number zero hypernucleus, ${}^{3}_{\Lambda}$n. Events that can be interpreted as a bound $nn\Lambda$ state (${}^{3}_{\Lambda}$n) was reported by HypHI Collaboration at GSI, Germany [10]. However, the existence of ${}^{3}_{\Lambda}$n cannot be explained with any available baryonic potential models [11, 12]. In order to investigate the existence of the bound $nn\Lambda$ three-body system, we planned an experiment with the ${}^{3}\text{H}(e, e'K^{+})nn\Lambda$ reaction at JLab Hall A using two HRSs (E12-17-003) [13]. The data taking of E12-17-003 with a gaseous tritium target [14] was successfully completed in Oct–Nov 2018, and data are being analyzed.

As we described above, new generation experiments on heavier hypernuclear systems as well as light hypernuclei are on-going or proposed at JLab. Academic base is now ready to connect discussion on hypernuclei and NS systematically, and precise determination of the ΛN interaction is important for discussion of heavier hypernuclear systems. Here, we request thirteen days of beamtime sharing a spectrometer configuration of HRS-HKS that will be used for an approved experiment E12-15-008 (${}^{40,48}_{\Lambda}$K spectroscopy). It will enable us to perform the precise measurement of the hyperhydrogen nuclei ${}^{3,4}_{\Lambda}$H that are keys for investigations of (A) the contradiction between the short lifetime and small binding energy of ${}^{3}_{\Lambda}$H, (B) the puzzle of existence of bound $nn\Lambda$ state, and (C) the CSB in the ΛN interaction.

A. A contradiction between the short lifetime and small Λ binding energy of ${}^{3}_{\Lambda}$H

The Λ binding energy of hypertriton ${}^{3}_{\Lambda}$H was measured to be $B_{\Lambda} = 130 \pm 50$ keV in the emulsion experiment [15]. The Λ hypertriton is considered to be a loosely bound system of a Λ and a deuteron, and the spatial extent can be simply estimated by the root mean square radius of a two body system as follows:

$$\sqrt{< r^2 >} \simeq \frac{\hbar}{\sqrt{4\mu B_\Lambda}} \tag{1}$$

where, μ is the reduced mass $\mu = m_\Lambda m_d/(m_\Lambda + m_d)$ which is about 76% of the nucleon mass. The root mean square radius $\sqrt{< r^2 >}$ of hypertriton is then evaluated to be about 10 fm which is about five times larger than that of deuteron. Figure 1 shows a calculated density distribution of Λ hypertriton for which only s-waves are included [16]. In such a Λ-halo hypernuclear system, a wave

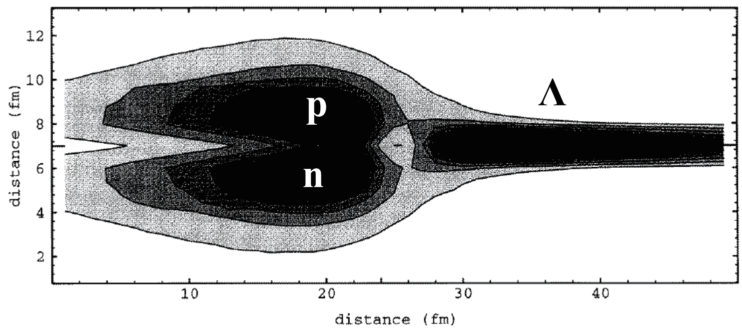

FIG. 1. A theoretical calculated probability distribution of a proton, a neutron and a Λ in Λ hypertriton [16]. Center of mass is fixed at the center of the figure and only s-waves are included for the calculation. The distance between dense parts of nucleons and Λ is apart by more than 10 fm, and Λ and nucleons have little overlap.

function overlap between the core nucleus and Λ is small, and the Λ is almost free from interactions due to the core nucleus. Therefore, the hypertriton lifetime is naively expected to be similar to that of a free Λ hyperon. A theoretical calculation by a three-body Faddeev equations with realistic NN and YN interactions predicts that the lifetime of the hypertriton nearly unchanged from that of a Λ hyperon (shorter by only 3%) [18].

However, recent heavy-ion beam experiments at GSI, LHC and RHIC consistently showed much shorter lifetime of hypertriton than a free Λ by 10–50% that is apart from theoretical predictions. Rappold *et al.* applied statistical analysis for old data including heavy-ion data at GSI, and the hypertriton lifetime was deduced to be 216^{+19}_{-16} ps which is about 18% shorter than that of Λ [19]. Figure 2 shows experimental data and theoretical calculations of Λ hypertriton lifetime [20]. An average of recent five data that were obtained in heavy ion experiments shows the Λ hypertriton lifetime is shorter by $30 \pm 8\%$. Gal and Garcilazo recently took into account the pion final state interaction in a calculation of the hypertriton decay process [20]. It was found that the pion FSI could enhance the decay rate and the about 20% shortage of hypertriton lifetime from a free Λ

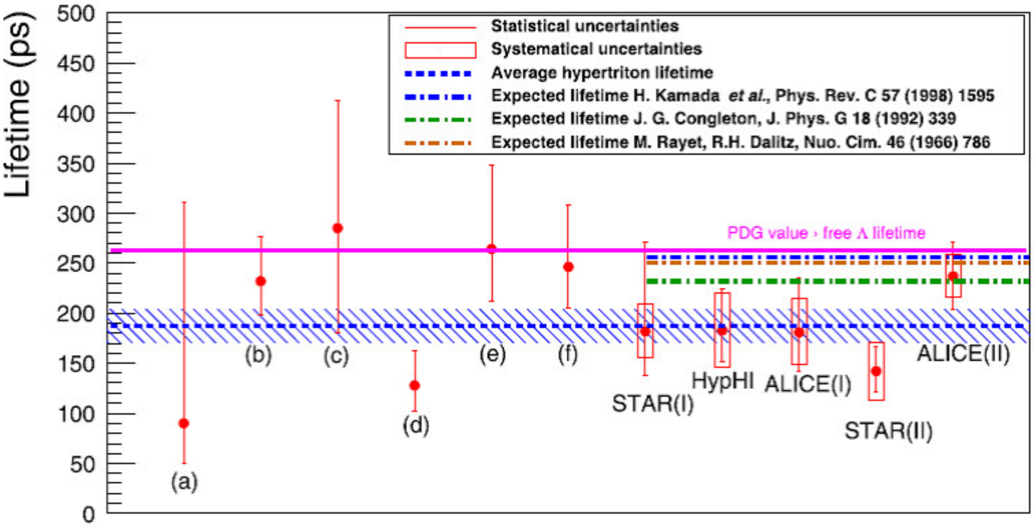

FIG. 2. Lifetime of Λ hypertriton summarized in Ref. [20]. Experimental data labeled as (a)–(f) were obtained in bubble chamber and emulsion experiments.

is conceivable. The theoretical calculation with the pion FSI is consistent with the most recent measurement of hypertriton lifetime by ALICE Collaboration [21] who used a Pb-Pb collision at $\sqrt{S_{NN}} = 5.02$ TeV. In order to experimentally confirm the hypertriton lifetime, new experiments are now being prepared. At FAIR using a heavy-ion beam, the lifetime of ${}^{3}_{\Lambda}$H will be measured with higher statistics by more than a factor of ten [22] than that obtained in GSI. While the new heavy ion-beam experiment at FAIR would show high accuracy in the hypertriton-lifetime measurement, it is important to measure the lifetime with various reactions or methods from a point of minimizing systematic error which might be appeared depending on experimental techniques. Now, new experiments are planned to directly measure the hypertriton lifetime by the (γ, K^+) reaction at ELPH [23], and (π^-, K^0) [24, 25] and (K^-, π^0) [26] reactions and J-PARC.

The fact of small binding energy of ${}^{3}_{\Lambda}$H contradict the short lifetime in a framework of the ΛN and ΛNN interactions that were constructed mainly by Λ hypernuclear energies measured in the old experiments. It is of great significance to determine $B_\Lambda({}^{3}_{\Lambda}\mathrm{H})$ which is the most basic quantity for the ΛN interaction study by using modern experimental techniques in which the systematic uncertainty is well controlled and understood. We are proposing an accurate measurement of the Λ binding energy of ${}^{3}_{\Lambda}$H with the $(e, e'K^+)$ missing-mass spectroscopy established at JLab [27].

B. The connection of ${}^3_\Lambda$H to the existence of the $nn\Lambda$ state

The Λ hypertriton is considered to be the lightest bound hypernucleus which is an iso-singlet state $I = 0$ in the $A = 3$ system. Iso-triplet states in the $A = 3$ system ($pp\Lambda$, ${}^3_\Lambda\mathrm{H}^{I=1}$, $nn\Lambda$) are predicted to be unbound. In an invariant mass spectroscopy at GSI, events that can be interpreted to be the three body system of two neutrons and a Λ, which is so called ${}^3_\Lambda$n ($I = 1$), were found [10]. The observation of the pionic weak decay process indicated the existence of bound $nn\Lambda$ state (${}^3_\Lambda$n), while the experimental accuracy for the Λ binding energy did not allow for confirming the bound state at the threshold region in the invariant mass spectrum. However, the bound $nn\Lambda$ state cannot be explained maintaining reasonable reproduction of other light hypernuclear binding energies with the various interaction models. On the other hand, a resonant state of $nn\Lambda$ is predicted to exist [28, 29]. In order to experimentally investigate the $nn\Lambda$ state, we carried out the E12-17-003 experiment at Hall A in Oct–Nov 2018. A gaseous tritium target was used to produce the $nn\Lambda$ state, and the $nn\Lambda$ energy was measured with the missing mass spectroscopy which is sensitive to a resonant state as well as a bound state. Analyses particularly for a careful energy calibration are in progress. The energy level of the iso-triplet state of ${}^3_\Lambda$H should be similar to that of the $nn\Lambda$ state because these are iso-triplet partners in the $A = 3$ hypernuclear system. Figure 3 shows expected energy levels of ${}^3_\Lambda$H with an ordinate axis of $-B_\Lambda[= M_{\mathrm{HYP}} - (M_d + M_\Lambda)]$. The first excited state ($3/2^+$) with $I = 0$ and the $I = 1$ state are shown as boxes since energies for these states have not been measured.

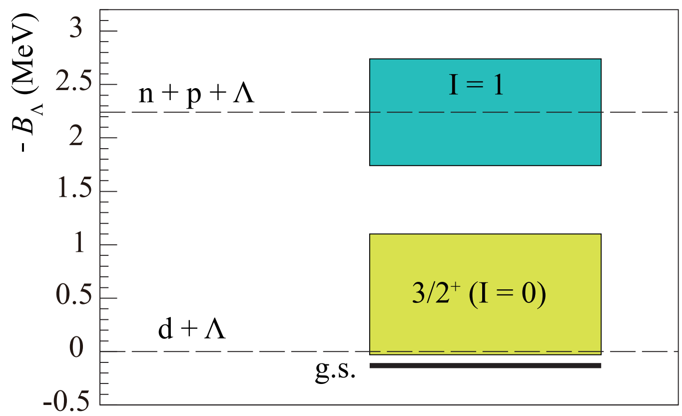

FIG. 3. Expected energy levels for the first excited state ($3/2^+$) with $I = 0$ and the $I = 1$ state in the Λ hypertriton. The energy for the $I = 0$ state energy should be similar to that of $nn\Lambda$ because these are iso-triplet partners in the $A = 3$ hypernuclear system. The measurement of ${}^3_\Lambda$H ($I = 1$) would pin down the existence of the bound $nn\Lambda$ state.

The proposed experiment in which precise spectroscopy of the $^3\text{He}(e, e'K^+)^3_\Lambda\text{H}$ is possible would determine the energy level of $^3_\Lambda\text{H}$ $(I = 1)$ if the production cross section for the iso-triplet state is reasonably large (e.g. more than the order of 0.1 nb/sr). The $^3_\Lambda\text{H}$ $(I = 1)$ measurement will give us a strong constraint to the existence of the bound $nn\Lambda$ state. If the energy measurements of both $^3_\Lambda\text{H}$ $(I = 1)$ and $nn\Lambda$ states are realized by respectively this proposed experiment and E12-17-003 (or others), the ΛN CSB could be investigated in the $A = 3$ hypernuclear system for the first time.

C. Charge symmetry breaking effect in the $A = 4$ hypernuclei

It is known that the strong interactions between baryons that consist of u and d quarks, i.e. nucleons, are (almost) flavor blind and have charge symmetry. However, it was found that the charge symmetry is considerably broken (CSB) between a nucleon and a Λ which includes a s quark. The CSB was experimentally observed in the $A = 4$ iso-doublet Λ hypernuclear system ($^4_\Lambda\text{He}$ and $^4_\Lambda\text{H}$). Figure 4 shows the Λ binding energies of the 0^+ and 1^+ states in $^4_\Lambda\text{He}$ and $^4_\Lambda\text{H}$. There

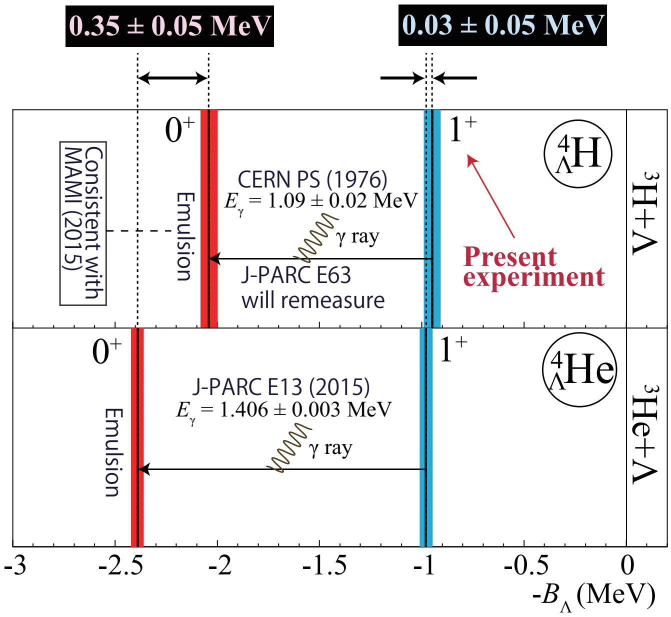

FIG. 4. The Λ binding energies of $A = 4$ iso-doublet Λ hypernuclei.The present experiment aims to measure the absolute value of B_Λ ($^4_\Lambda\text{H}$; 1^+) using the electron beam missing-mass spectroscopy established at JLab [1].

is a large binding energy difference for the ground state being $\Delta B_\Lambda(^4_\Lambda\text{He} - ^4_\Lambda\text{H};\ 0^+) = 350 \pm 50$ keV which was obtained from old emulsion experiments. After the Coulomb correction, the energy of about 400 keV is attributed to an effect of the strong interaction [30–32]. This difference is larger than that for the case of ordinal nuclear system (^3H and ^3He) by a factor of about five, and thus the charge symmetry looks to be broken in the ΛN interaction. Recently, MAMI successfully measured $B_\Lambda({}^4_\Lambda\mathrm{H};\ 0^+)$ by the decay pion spectroscopy which measured monochromatic pions emitted from two body decays of hypernuclei at rest [5, 6]. The result was consistent with the emulsion experiment, and clarified the existence of the ΛN CSB for the ground state of $A = 4$ hypernuclear iso-doublet.

The energy spacings between 0^+ and 1^+ were measured by Λ hypernuclear γ-ray spectroscopy. The Λ binding energies for the 1^+ state were derived by using the 0^+ energies and the energy spacings measured in respectively the nuclear emulsion experiment and γ-ray spectroscopy. It was believed that the energy difference for the 1^+ state is $\Delta B_\Lambda({}^4_\Lambda\mathrm{He} -{}^4_\Lambda\mathrm{H};\ 1^+) = 290 \pm 60$ keV according to the old γ-ray measurements using a NaI detector. It showed there are the large CSB for both the 0^+ and 1^+ states. However, J-PARC E13 experiment re-measured ${}^4_\Lambda\mathrm{He}(1^+)$ by using germanium detector array which had better precision [7], and the data was updated to be $\Delta B_\Lambda({}^4_\Lambda\mathrm{He} -{}^4_\Lambda\mathrm{H};\ 1^+) = 30 \pm 50$ keV that means there is little binding energy difference for 1^+. Surprisingly, it turned out the ΛN CSB is spin dependent.

The ΛN-ΣN coupling is considered to be a key issue of the ΛN CSB. However, it is difficult to understand the $A = 4$ iso-doublet hypernuclear system maintaining consistency with low lying energies of other light-Λ hypernuclei even when the ΛN-ΣN coupling is taken into account [33, 34]. There might be further important factors to be considered in the theoretical models. On the other hand, it is necessary to confirm B_Λ for not only $A = 4$ Λ hypernuclei but also particularly light hypernuclei with new experimental techniques as the cases for ${}^4_\Lambda\mathrm{He}$ (1^+) and ${}^4_\Lambda\mathrm{H}$ (0^+).

For the $A = 4$ iso-doublet hypernuclei, ${}^4_\Lambda\mathrm{H}$ (1^+) and ${}^4_\Lambda\mathrm{He}$ (0^+) remain depending old experimental data taken in 1960s and should be re-measured with modern experimental techniques. However, the ground state of ${}^4_\Lambda\mathrm{He}$ measured by the emulsion experiment, can be considered more reliable compared to that of ${}^4_\Lambda\mathrm{H}$ because binding energies obtained from two body decay and three body decay processes are consistent. Therefore, a re-measurement on $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$ is being waited by priority. There is a plan to measure M1 transition γ-rays $(1^+ \to 0^+)$ of ${}^4_\Lambda\mathrm{H}$ at J-PARC (J-PARC E63) [35], that needs the ground state energy to deduce the excited state energy. Figure. 5 shows the ground state energy obtained by a recent result by A1 Collaboration at MAMI and other old measurements [5]. The γ ray spectroscopy can determine the energy with a precision of a few keV. However, the energy of the excited state (g.s. + γ-ray energy) will have an uncertainty of about 100 keV due to the error on the ground state energy if the result by the A1 Collaboration at MAMI is used. The J-PARC E63 experiment has been approved to be performed at the J-PARC K1.1 beam line that will be newly constructed. However, the construction of the K1.1 beam line is not

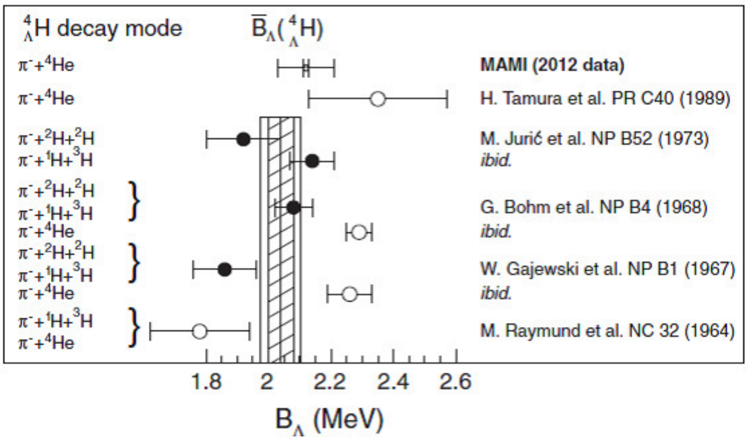

FIG. 5. The ground state Λ binding energy of $^4_\Lambda$H (0^+) measured in the past experiments [5]. The γ ray spectroscopy (J-PARC E63) that aims to measure $B_\Lambda(^4_\Lambda\text{H}; 1^+)$ needs the ground state energy measured in the other experiments.

specifically on a few years time-line yet. Here, we propose to perform the first direct measurement of the absolute Λ binding energy of $^4_\Lambda$H (1^+) by the $(e, e'K^+)$ reaction at JLab.

II. PREVIOUS MEASUREMENT

Previously, nuclei of Λ hyperhydrogens were investigated with the $^{3,4}\text{He}(e, e'K^+)^{3,4}_{\Lambda}\text{H}$ reaction at JLab Hall C [36, 37]. In the experiment, HMS and SOS spectrometers were used for detection of a scattered electron and a K^+, respectively. While Λ binding energies were not obtained due to a limited missing mass resolution, differential cross sections at the several K^+ scattering angles with respect to a virtual photon direction $\theta_{\gamma^* K}$ were measured [37]. The invariant mass of a virtual photon and the total energy were $Q^2 = 0.35$ (GeV/c)^2 and $W = 1.91$ GeV, and they are close to those of the proposed experiment. At the forward scattering angle at which we are proposing the new experiment in Hall A, the production cross sections were obtained to be 5 and 20 nb/sr for $^3_\Lambda$H and $^4_\Lambda$H, respectively. The previous experiment tells us that the differential cross sections for the electroproduction of the Λ hyperhydrogens $^{3,4}_{\Lambda}$H are large enough at the small $\theta_{\gamma^* K}$ where we aim to measure in the proposed experiment.

III. PROPOSED EXPERIMENT

We present the goal of the experiment and the requested beamtime and conditions in Sections III A and III B. Then, the experimental setup and expected results are shown in Sections III C

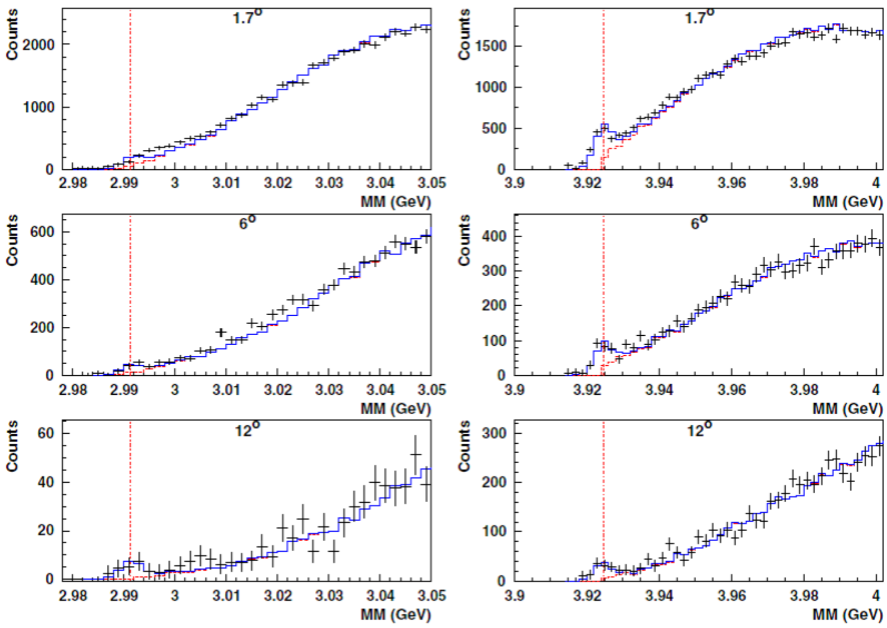

FIG. 6. Missing mass spectra for ${}^{3}_{\Lambda}$H (left) and ${}^{4}_{\Lambda}$H (right) obtained at JLab Hall C [37].

and III D, respectively.

A. The goal of the proposed experiment

1. ^{3}He$(e, e'K^{+})^{3}_{\Lambda}$H

The ground state binding energy of ${}^{3}_{\Lambda}$H was reported from the emulsion experiments as shown in Table I. Juric *et al.* complied and reanalyzed these data, and deduced the Λ binding energy being $B_{\Lambda}({}^{3}_{\Lambda}\text{H}) = 130 \pm 50$ keV [15]. However, it was obtained as the average of results of two-body and three-body decay channels with scattered values. Table I shows $B_{\Lambda}({}^{3}_{\Lambda}\text{H})$ for various decay channels and different experiments. While the statistical error of each data set is about 100 keV, there are apparently large systematic errors which were not taken into account for averaging of them, depending on decay modes as seen also in the cases of ${}^{4}_{\Lambda}$H, ${}^{5}_{\Lambda}$He, ${}^{9}_{\Lambda}$Be and so on (refer to Tables 1 and 3 in [15]). Recently, the masses of hypertriton and anti-hypertriton were reported from the STAR Collaboration who used the heavy ion collision at RHIC [38]. The hyperon binding energy was obtained by averaging the hypertriton and anti-hypertriton energies being $B_{\Lambda}({}^{3}_{\Lambda}\text{H}) = 410 \pm 120^{\text{stat.}} \pm 110^{\text{sys.}}$ keV. This is the first high precision measurement on B_{Λ} $({}^{3}_{\Lambda}\text{H})$ by a counter experiment. However, the hypertriton binding energies obtained from two and three body processes seem to differ with each other by more than two sigmas of the error ($\sim$400 keV) [39] which evoke a similar issue with the emulsion experiments. There may be an additional systematic error to be considered. An accurate measurement of $B_\Lambda({}^{3}_{\Lambda}\mathrm{H})$ which is the most fundamental ingredients for the study of ΛN interaction are being awaited.

It is worth noting that the HKS (JLab E05-115) Collaboration measured ${}^{10}_{\Lambda}\mathrm{Be}$ [40], and the ground-state Λ binding energy was obtained to be $B_\Lambda = 8.60 \pm 0.07^{\mathrm{stat.}} \pm 0.16^{\mathrm{sys.}}$ MeV that differs from the result of old emulsion experiment ($B_\Lambda = 9.11 \pm 0.22$ MeV [41]) by about 0.5 MeV. In addition, we suggested that Λ binding energy of ${}^{12}_{\Lambda}\mathrm{C}$ measured in the emulsion experiment has a shift of about a half MeV by a careful comparison between the (π^+, K^+) and emulsion data [40]. The shift of about a half MeV for the ${}^{12}_{\Lambda}\mathrm{C}$ binding energy is also addressed by the FINUDA Collaboration [42]. The need of the half MeV correction on $B_\Lambda({}^{12}_{\Lambda}\mathrm{C})$ has a large impact because Λ binding energies for many of hypernuclei were measured by the (π^+, K^+) experiments in which $B_\Lambda({}^{12}_{\Lambda}\mathrm{C})$ was used for their energy calibration. Now, the correction for the hypernuclear energies is widely used for construction and tests of the ΛN interaction models [43, 44]. These updates and series of measurement on B_Λ for p-shell hypernuclei by the $(e, e'K^+)$ experiments at JLab provided new insights into the ΛN interaction research; e.g. resulted in solving a puzzle of the large CSB in p-shell hypernuclear systems [4, 40].

TABLE I. The obtained Λ binding energy of ${}^{3}_{\Lambda}\mathrm{H}$ by the emulsion experiments.

Emulsion data	$\pi^- + {}^3\mathrm{He}$	$\pi^- + {}^1\mathrm{H} + {}^2\mathrm{H}$
	Λ binding energy (keV)	
M. Juric (1973) [15]	$+60 \pm 110$ (23 events)	$+230 \pm 110$ (58 events)
G. Bohm (1968) [17]	$+50 \pm 80$ (86 events)	-110 ± 130 (16 events)

Figure 7 shows the Λ-d rms radius versus the Λ binding energy obtained by using various NN and ΛN interactions [16]. There is a general correlation between Λ-d rms radius and the Λ binding energy. Choice of the interaction model gives a small effect on it. The Λ-d rms radius directly affects the hypertriton lifetime since it corresponds to the wave function overlap between a deuteron and a Λ. If $B_\Lambda = +230+110 = 340$ keV which is the deepest bound case in Table I is taken, the Λ-d rms radius becomes about 7 fm. This rms radius is much shorter than the case of $B_\Lambda = 130$ keV by more than 30%. There is an idea that such a deep binding energy could explain the short lifetime of the hypertriton [45]. The Λ binding energy is crucial for solving the hypertriton-lifetime puzzle, and needs to be determined with a less uncertainty.

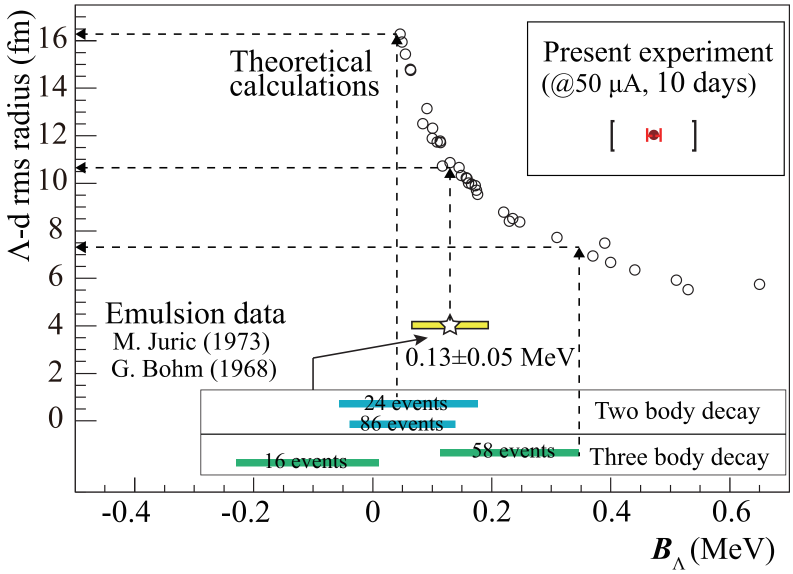

FIG. 7. The Λ-d rms radius versus the Λ binding energy [16]. Experimental data of the emulsion experiments were taken from Refs. [15, 17].

The spin-parity J^π of the ground state of ${}^3_\Lambda$H was deduced to be $J^\pi = 1/2^+$ by a branching ratio of the two body π^- decay mode to the all of decay modes with a π^- [46, 47]. Therefore, the ground state binding energy of ${}^3_\Lambda$H is dominated by the spin-singlet S-wave $p\Lambda$ interaction. For the analysis of $N\Lambda$ scattering data [48], the $B_\Lambda({}^3_\Lambda\mathrm{H}; \mathrm{g.s.})$ was used as a constraint of a relative strength of the spin-singlet to the spin-triplet [49, 50]. The spin-singlet scattering length was obtained to be $a_s = -1.8^{+2.3}_{-4.2}$ fm [48]. Figure 8 shows correlation between the scattering length a_s and $B_\Lambda({}^3_\Lambda\mathrm{H}; \mathrm{g.s.})$ by various theoretical predictions, and all of these predictions of the scattering length are within the error of scattering experiment. The result from the emulsion experiment (130 ± 50 keV) supports interactions of the chiral Effective Field Theory (NLO13 and NLO19 with a cut off parameter of $\Lambda = 500$ MeV) [49] and Nijmegen Soft-Core models (NSC89 and NSC97f) [50]. On the other hand, the recent result of the ALICE Collaboration which is larger binding energy ($410 \pm 120 \pm 110$ keV) is more preferable for the interactions of the SU(6) quark model (fss2) [51] and the chiral EFT for which the scattering length is adjusted (NLO19-A,B,C) [49]. The proposed experiment aims to determine the $B_\Lambda({}^3_\Lambda\mathrm{H}; \mathrm{g.s.})$ with an accuracy of $|\Delta B_\Lambda^{\mathrm{total}}| < 100$ keV, and to pin down the validation of the interaction models as shown in Fig. 8. In addition, our measurement would be a constraint of the spin-singlet $p\Lambda$ scattering length with a precision of about ± 1.5 fm.

There is a possibility that we can measure the first excited state ($I = 0$, $J^\pi = 3/2^+$) which has not been observed yet. A theory predicts that the first excited state is produced more than

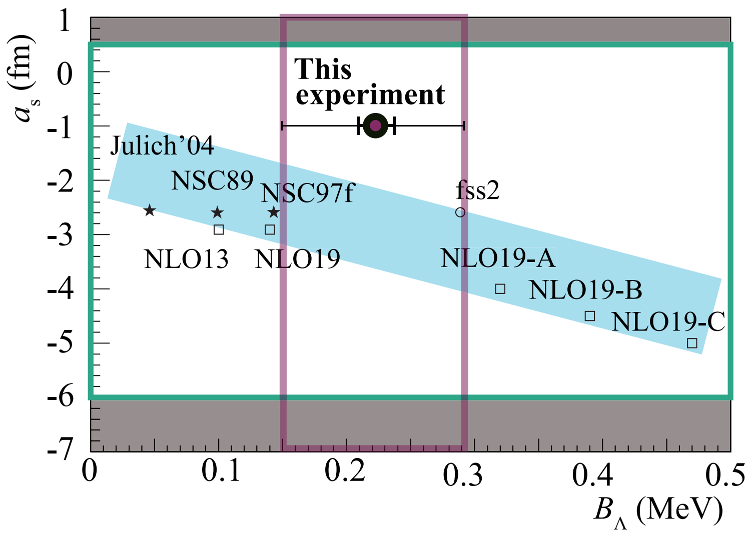

FIG. 8. The spin-singlet Λp scattering length a_s as a function of $B_\Lambda({}^3_\Lambda\mathrm{H};\mathrm{g.s.})$ for various interaction models [49–51]. The accuracy aimed in this proposed experiment is represented as error bars ($|\Delta B_\Lambda^{\mathrm{stat.}}| <$ 20 keV, $|\Delta B_\Lambda^{\mathrm{sys.}}| = 70$ keV).

the ground state in the case of the $(e, e'K^+)$ reaction by a factor of about eight [52] if the $3/2^+$ state does exist. If this is the case, we will be able to determine the Λ binding energy of the $3/2^+$ state instead of the ground state ($J^\pi = 1/2^+$). The $B_\Lambda({}^3_\Lambda\mathrm{H}; 3/2^+)$ will be a strong constraint for the spin-triplet Λp interaction because the $3/2^+$ state is dominated by the S-wave spin-triplet partial wave. Furthermore, the iso-triplet state ($I = 1$, $J^\pi = 1/2^+$) may be observed. An expected accuracy for the ${}^3_\Lambda\mathrm{H}^{I=1}$ state is $|\Delta B_\Lambda^{\mathrm{stat.}}| \simeq 50$ keV assuming the (γ^*, K^+) cross section is 0.5 nb/sr that corresponds to a smaller cross section than that for the ground state by an order of magnitude. The precise measurement of ${}^3_\Lambda\mathrm{H}^{I=1}$ will be fateful about the existence of bound $I = 1$ three-body nuclei with a Λ hyperon such as the $nn\Lambda$ state.

We aim to measure the Λ binding energy of ${}^3_\Lambda\mathrm{H}$ with an accuracy of $|\Delta B_\Lambda^{\mathrm{stat.}}| < 20$ keV that can be achieved in ten days beamtime with a 50-μA beam impinged on a 168-mg/cm^2 gaseous-^{3}He target. A precise measurement on the Λ binding energy of the Λ hypertriton that can be realized by the experiment proposed here will be an important key to examine the hypertriton lifetime puzzle. Low energy properties of the ΛN interaction are hard to be precisely investigated by a scattering experiment due to experimental difficulties originating from short lifetimes of hyperons. We know that two body systems with a Λ are not bound. Therefore, the Λ binding energy of the Λ hypertriton which is the lightest bound system with a Λ is significant to constrain the ΛN interaction model. The accurate binding energy measurement on the Λ hypertriton should be done with an experiment in which a systematic error is well controlled, and we propose here the best measurement for the purpose. Furthermore, we have a chance to observe excited states (the iso-singlet $J^{\pi} = 3/2^{+}$ and iso-triplet $J^{\pi} = 1/2^{+}$ states). The precise measurements of the excited states of the Λ hypertriton is able to be done only at JLab at present. Experiments, such as an emulsion experiment and a heavy ion experiment, in which particles from weak decay processes are detected have little sensitivity to the excited state. The proposed experiment is very unique to provide one of fundamental quantities for studies of the baryon interaction and the strangeness nuclear physics.

2. $^{4}\mathrm{He}(e, e'K^{+})^{4}_{\Lambda}\mathrm{H}$

As discussed in Section I C, the high precision measurement of $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H};\ 1^{+})$ with a modern experimental techniques is awaited by priority to ensure the discussion about $A = 4$ ΛN CSB. The missing-mass spectroscopy with the $(e, e'K^{+})$ reaction was established at JLab, and has a unique capability to directly determine the absolute energy of $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H};\ 1^{+})$. The high precision measurement of $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H};\ 1^{+})$ is possible thanks to (i) the high quality electron beam at JLab, (ii) the high resolution spectrometer system HRS + HKS, and (iii) a large amplitude of spin flip probability due to the (virtual) photon reaction. The excited state (1^{+}) which we aim to measure and the ground state (0^{+}) could not be resolved by an expected missing mass resolution in the proposed experiment. However, a strong selectivity of the 1^{+} state production is expected by the $(e, e'K^{+})$ reaction due to the fact of (iii), and the production cross section of the 1^{+} state is predicted to be larger than that of the 0^{+} state by more than two orders of magnitude at the forward K^{+} scattering angle where we will cover. The absolute energy of $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H};\ 1^{+})$ measured by the proposed experiment will be complementary with a combined information $[\Delta E(1^{+} - 0^{+}) + B_{\Lambda}(0^{+})]$ of the γ-ray spectroscopy $[\Delta E(1^{+} - 0^{+})]$ and the decay pion spectroscopy or emulsion experiment $[B_{\Lambda}(0^{+})]$.

We aim to measure $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H};\ 1^{+})$ with a total error of $|\Delta B_{\Lambda}^{\mathrm{total}}| < 100$ keV ($|\Delta B_{\Lambda}^{\mathrm{stat.}}| \simeq 20$ keV, $|\Delta B_{\Lambda}^{\mathrm{sys.}}| = 70$ keV) in one day beamtime by using a 50-μA beam impinged on a 312-mg/cm^{2} gaseous-^{4}He target.

B. Requesting conditions and beamtime

1. Beam

We request a 50-μA beam at $E_e = 4.5$ GeV (two passes) with a bunch frequency of 500 MHz (250 MHz repetition rate will result in worse accidental background rate though it is still acceptable). In order to achieve a sufficient precision in a resulting missing-mass spectrum, the beam energy spread and energy centroid are required to be $\Delta p/p \leq 1 \times 10^{-4}$ (FWHM). A beam raster with an area of about 2×2 mm^2 may need to be applied to avoid a damage on a target cell due to an overheat.

2. Target

Standard cryogenic systems of gaseous helium-3,4 and LH$_2$ in Hall A are required for the present experiment. We need a more compact target system than existing ones because of a limitation of space around the target. Therefore, we will design a new target cell as shown in Fig. 11, and install four identical target cells in a vacuum chamber in which the cells will be attached on the same ladder system as the one used for the solid targets of E12-15-008. Three of the target cells will be filled with ^{3}He gas, ^{4}He gas, and liquid hydrogen (LH$_2$). One cell will be used for an empty run that will help an off-line analysis to subtract background events from the target cell material.

The missing mass would be shifted depending on a position of hypernuclear production point. In order to correct the shift, the position information of production point is necessary event by event. A displacement from the beam center in the x and y directions (vertical to the beam axis) can be derived from applied currents on dipole magnets used for the beam raster. On the other hand, a production position in the z direction (parallel to the beam axis) needs to be reconstructed from a magnetic optics analysis. For a calibration of reconstructed z, we will use a multi-foil carbon target which is an absolute position reference in z direction. The multi-foil target will have three carbon foils with a thickness of 100 mg/cm^2 being aligned 2.5 cm apart from each other.

3. Magnetic spectrometer

We request to use the exactly same spectrometer setup as the E12-15-008 experiment in which the isospin dependence of the $\Lambda N/\Lambda NN$ interactions will be investigated through the ^{40,48}Ca$(e, e'K^+)^{40,48}_{\Lambda}$K reaction [53]. Existing spectrometers, (L)HRS and HKS, combined with a new pair of charge separation dipole magnets (PCS) will be used for e' and K^+ detection. Construction and an excitation test of PCS have been completed in a Japanese company TOKIN in March 2020. PCS will be ready for transport to JLab soon. Central momenta of HRS and HKS are set to be respectively 3.0 and 1.2 GeV/c, and the system covers a kinematical region of the $^{3,4}\mathrm{He}(e,e'K^+)^{3,4}_{\Lambda}\mathrm{H}$ reaction as shown in Fig. 9. Not only Λ but also Σ^0, which will be used for an

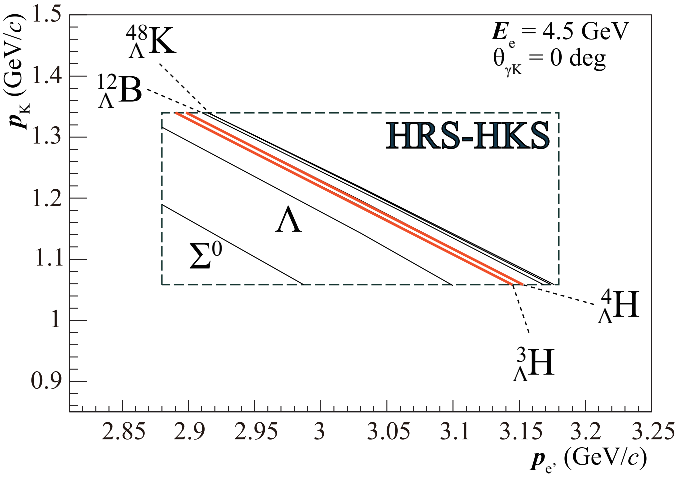

FIG. 9. Momentum acceptance of the HRS-HKS spectrometer system at $E_e = 4.5$ GeV, $\theta_{\gamma K} = 0$ degree.

absolute energy calibration, will be measured with the same spectrometer setting for physics run thanks to the large momentum coverage of HKS ($\Delta p/p_{\mathrm{central}} > \pm 10\%$). Measuring both Λ and Σ^0 masses without a change of spectrometer setting minimizes a systematic error on B_Λ. Another important feature of HKS is a short path length. The path length of PCS + HKS is about 12 m, and thus 26% of K^+s survive at 1.2 GeV/c. This gains a yield of Λ hypernuclei by a factor of more than three compared to HRS in which K^+s travel more than 23.4 m to be detected.

4. Beamtime

Table II shows requested beamtime for the present experiment. We request eleven days for $^3_\Lambda$H and $^4_\Lambda$H production, and two day for calibration data. In total, we request 13 days of beamtime.

C. Experimental setup

The experiment is planned to be performed with spectrometers HRS [54] and HKS [55] for respectively e' and K^+ detection as shown in Fig. 10. This experimental setup and kinematics are the same as those in the approved experiment E12-15-008. Electron beams at $E_e = 4.5$ GeV

TABLE II. Requested beamtime.

Mode	Hypernucleus	Target (mg/cm^2)	Beam current (μA)	Beamtime (day)	Yield
Physics	${}^{3}_{\Lambda}$H	^{3}He (168)	50	10	1050 (1/2$^+$, 3/2$^+$)
	${}^{4}_{\Lambda}$H	^{4}He (312)	50	1	587 (1$^+$)
	Subtotal			**11**	-
Calibration	Λ	LH$_2$ (174)	20	0.5	3900
	Σ^0				1300
	${}^{12}_{\Lambda}$B$^{\mathrm{g.s.}}$	Multi foil (100 × 3)	50	1	300 × 3
	-	Multi foil + Sieve slit	20	0.2	-
	-	Empty cell	20	0.1	-
	-	Empty cell + Sieve slit	20	0.2	-
	Subtotal			**2**	-
Total				**13**	-

are impinged on a helium target to produce ${}^{3,4}_{\Lambda}$H, and scattered electrons and K^+s with central momenta of 3.0 and 1.2 GeV/c are measured by HRS and HKS, respectively. One of important features of the HRS and HKS spectrometers is a good momentum resolution which would lead to a missing mass resolution of 1 MeV FWHM.

What we need to prepare in addition to the experimental setup of E12-15-008 is a cryogenic target system for ^{3}He, ^{4}He, LH$_2$, and a multi-foil carbon target. The LH$_2$ and multi-foil target will be used for calibrations of an energy scale and a z reconstruction analysis. A thick target deteriorate the missing-mass resolution due to momentum straggling and multiple scattering. In order to keep the effects of the momentum straggling and multiple scattering on the missing-mass resolution to be small enough compared to those of the momentum and angular resolutions of the spectrometer system, the target thickness is designed to be less than a few hundred mg/cm^2 including cell material for the present experiment. Figure 11 shows the schematic of a target cell of ^{3,4}He. A diameter of the target cell which defines a target length in z is set to be 50 mm so that background events from the cell wall can be separated clearly in off-line analysis by using information of a reconstructed reaction position in z ($\Delta z_{\mathrm{react}} \simeq$ 15-mm FWHM at 16 degrees [54]). Using events in $|z_{\mathrm{react}}| \leq 12$ mm for analyses, about 2σ events that come from the target cell are rejected. For ^{3}He, ^{4}He and LH$_2$, the 24-mm length in z direction corresponds to 174, 312 and 168 mg/cm^2 assuming the densities are 72, 130 and 70 mg/cm^3, respectively [54].

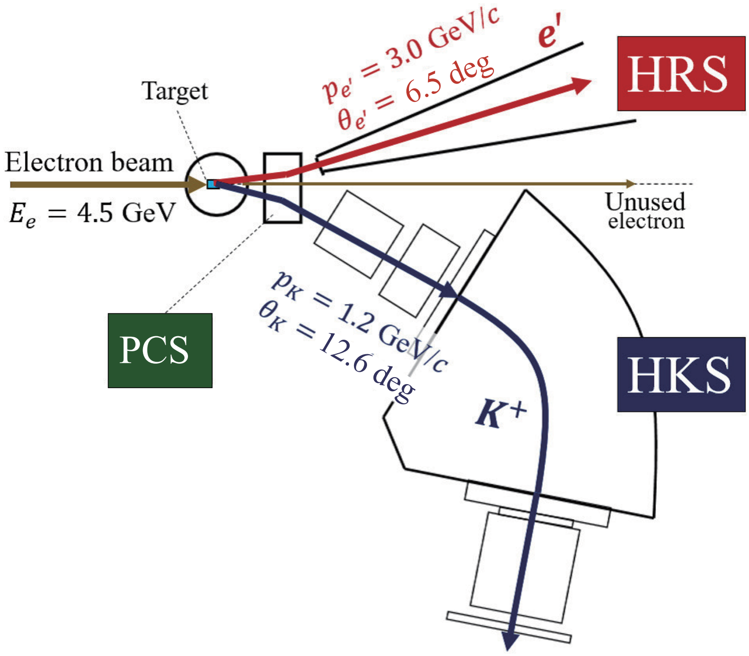

FIG. 10. A schematic of the experimental setup. Electron beams at $E_e = 4.5$ GeV impinged on the helium target which is enclosed in a vacuum chamber located in front of the pair of charge separation magnets (PCS). The scattered electrons and K^+ with central momenta of 3.0 and 1.2 GeV/c are momentum-analyzed by HRS and HKS, respectively.

TABLE III. Basic parameters of the present experiment.

Beam	$\Delta p/p$	$< 1 \times 10^{-4}$ FWHM
	E_e	4.5 GeV
PCS + HRS (e')	D(PCS) + QQDQ	
	$\Delta p/p$	2.6×10^{-4} FWHM
	$p_{e'}$	3.0 GeV/$c \pm 4.5\%$
	$\theta_{ee'}$	6.5 ± 1.5 deg
	Solid angle $\Omega_{e'}$	2.4 msr
PCS + HKS (K^+)	D(PCS) + QQD	
	$\Delta p/p$	4.2×10^{-4} FWHM
	p_K	1.2 GeV/$c \pm 10\%$
	θ_{eK}	12.6 ± 4.5 deg
	Solid angle Ω_K	7 msr
	Optical length	12 m
	K^+ survival ratio	26%

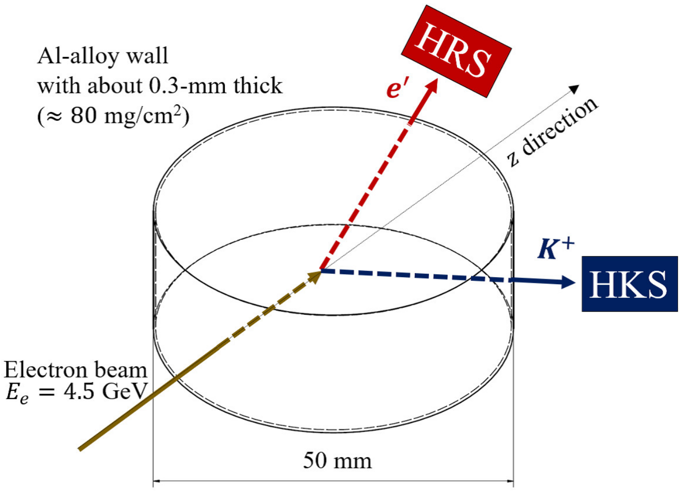

FIG. 11. A schematic of a target cell for a gaseous helium (^{3,4}He) and a liquid hydrogen (LH$_2$). A diameter of the target cell which defines the target length in the beam direction (z-direction) is 50 mm. If events in $|z_{\mathrm{react}}| \leq 12$ mm are used for analyses, about 2σ events ($\Delta z_{\mathrm{react}} \simeq$ 15-mm FWHM [54]) coming from the target cell are rejected. For ^{3}He, ^{4}He and LH$_2$, the 24-mm length in z corresponds to 174, 312 and 168 mg/cm^2 assuming the densities are 72, 130 and 70 mg/cm^3, respectively [54].

We are planning to use a cell of tuna-can type in the proposed exepriment so that the path length of scattered particles in the cell can be minimized. In the case of a cell of ciger type which was used for the $nn\Lambda$ prouction with a tritium gas, the path length is much longer in the target cell because we used a spectrometer setting with a samll scattering angle at $\theta_{\mathrm{HRS}} = 13.2$ degrees. The areal density in the cell was about $[0.04\ (\mathrm{cm}) \times 2.8\ (\mathrm{g/cm^3}) \times \frac{1}{\sin\theta_{\mathrm{HRS}}} \simeq]$ 500 mg/cm^2 which is equivalent to about 2000 mg/cm^2 of helium in the radiation length. The large amount of materials in the radiation length caused deterioration particularly for the angular resolution due to the multiple scattering. The angular resolution is more sensitive to a missing mass resolution for a light hypernuclear system than that for a heavier system, and thus it is important to minimize the multiple scattering effect for precise spectroscopy of the proposed experiment. The path length in the radiation length in target cell is designed to be redued by more than 80% in the proposed experiment compared to that in the tritium experiment with the small scattering angle.

D. Expected results

1. *Missing-mass resolution and yield*

The missing mass resolution was estimated by a Monte Carlo (MC) simulation in which magnetic field maps generated by the finite element calculation software, Opera3D (TOSCA), were used [56]. It is noted that our Geant4 simulation for the E12-17-003 ($nn\Lambda$ experiment which used two HRSs at Hall A) could reproduce missing mass resolutions of data for Λ and Σ^0 production which is about 3.5 MeV (FWHM) [57]. The same framework of the Geant4 simulation for the $nn\Lambda$ experiment was applied to a simulation for the proposed experiment. Momentum vectors of scattered electrons and K^+s at a production point which varied randomly in the target (along z axis) were calculated event by event with the kinematics of the ${}^{3,4}\mathrm{He}(e, e'K^+)^{3,4}_{\Lambda}\mathrm{H}$ reaction. The scattered electrons and K^+s were generated in the MC simulators, PCS + HRS and PCS + HKS, according to the above kinematics calculation. The scattered electrons and K^+s were measured at focal planes of the spectrometers taking into account realistic position and angular resolutions of the particle detectors. Then, the information of particle positions and angles at the focal planes were converted into momentum vectors at the production point by using backward transfer matrices to reconstruct a missing mass. For reconstruction of the momentum vectors at the production point, information of production vertex z was used. Particularly, HKS needs the z information in addition to the focal plane information because HKS is a horizontal bending spectrometer and the z position (which corresponds to x at target) strongly couples with momentum as well as angle at target. The production vertex z was reconstructed by a backward transfer matrix in HRS. A resolution of the reconstructed z was about 1.5 cm (FWHM). While the momentum resolution of HKS was estimated to be $\Delta p/p = 1.2\times10^{-3}$ FWHM when the the z information was not used, the momentum resolution of HKS was recovered to be $\Delta p/p = 4.2 \times 10^{-4}$ FWHM by using the reconstructed production z position. The resolution of $\Delta p/p = 4.2 \times 10^{-4}$ FWHM is still worse than the original design of HKS by a factor of about two. However, the deterioration of the resolution in HKS has no big effect on the the missing mass resolution because a contribution from HRS is much larger in our kinematics. Expected momentum and angular resolutions for the PCS + HRS and PCS + HKS are summarized in Table IV. In addition, effects of the energy straggling and multiple scattering due to the target cell filled with helium gas were also simulated. It was found that the target materials deteriorate the momentum and angle resolutions by 10% and 40%, respectively. As a result, the missing mass resolution was estimated to be 1 MeV FWHM.

TABLE IV. Resolutions of momenta and angles which were reconstructed by backward transfer matrices taking into account particle detector resolutions in the Monte Carlo simulations.

Spectrometer system	$\Delta p/p$ (FWHM)	$\Delta\theta$ (mrad)
PCS + HRS	2.6×10^{-4}	0.6
PCS + HKS	4.2×10^{-4}	1.5

The yield of hypernuclei (N_{HYP}) was estimated as follows:

$$N_{\mathrm{HYP}} = \Gamma^{\mathrm{int}} \times N_{\mathrm{beam}} \times N_{\mathrm{target}} \times \left(\frac{d\sigma}{d\Omega}\right) \times \Omega_K \times \epsilon \tag{2}$$

where N_{beam}, N_{target}, $\left(\frac{d\sigma}{d\Omega}\right)$, Ω_K, and ϵ are the number of incident electrons, the number of target nuclei (cm^{-2}), differential cross section of the $(\gamma^{(*)},K^+)$ reaction (cm^2 msr^{-1}), the solid angle of the K^+ spectrometer (msr), and total experimental efficiency (DAQ, detector, analysis, K^+ survival ratio etc.) being 19.5% [$\simeq 0.26$ (K^+ survival ratio) $\times$ 0.75] for the present estimation. The Γ^{int} is the virtual photon flux integrated over the PCS + HRS acceptance (notations can be found in [1]):

$$\Gamma^{\mathrm{int}} = \iint_{\mathrm{HRS}} \frac{\alpha}{2\pi^2 Q^2} \frac{E_\gamma}{1-\epsilon} \frac{E_{e'}}{E_e} dp_{e'} d\theta_{e'} \tag{3}$$

$$= 1.7 \times 10^{-5} \quad (/\mathrm{electron}). \tag{4}$$

The differential cross sections of the $^3\mathrm{He}(\gamma,K^+)^3_\Lambda\mathrm{H}$ and $^4\mathrm{He}(\gamma,K^+)^4_\Lambda\mathrm{H}$ reactions with a similar $\sqrt{s}$ and scattering angle ($\theta \simeq 0$ deg) to those of our experiment were measured in a past experiment at JLab Hall C (E91-016) [36], although the Λ binding energies were not determined in this experiment because the energy resolution was not enough. The differential cross sections were obtained to be about 5 and 20 nb/sr for the $^3_\Lambda\mathrm{H}$ and $^4_\Lambda\mathrm{H}$ production [37]. By the photoproduction, excited states are preferably produced since the spin-flip amplitude is large. Figure 12 shows the differential cross section of $^4\mathrm{He}(e,e'K^+)^4_\Lambda\mathrm{H}$ predicted by DWIA calculation [58]. At the forward K^+ scattering angle with respect to a photon direction, the differential cross section of the first excited state (1^+) is predicted to be larger than that of the ground state (0^+) by two orders of magnitude. In the case of $^3_\Lambda\mathrm{H}$ photoproduction, the $3/2^+$ state is expected to be a larger cross section by a factor of eight [52] if the $3/2^+$ state exists. Expected yield per day with a beam current of 50 μA is summarized in Table V.

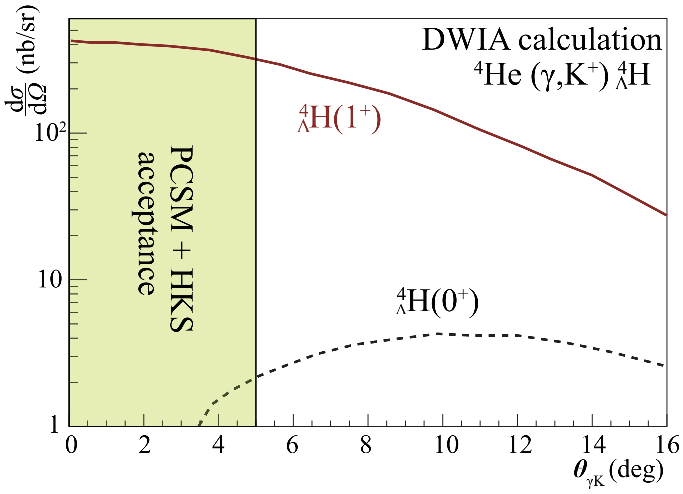

FIG. 12. A theoretical prediction of the differential cross section of ^{4}He$(\gamma, K^+)^4_\Lambda$H by DWIA [58].

TABLE V. Expected yields for $^3_\Lambda$H and $^4_\Lambda$H in the present experiment.

Hypernucleus		Target (mg/cm^2)	Cross section (nb/sr)	Yield per day at 50 μA
$^3_\Lambda$H	$1/2^+$	^{3}He	5	105
	$3/2^+$	(168)		
$^4_\Lambda$H	0^+	^{4}He	-	-
	1^+	(312)	20	587

2. Accidental background

Accidental $e'K^+$-coincidence events would be a background in a resulting missing-mass spectrum. To estimate the accidental background events, real data which were taken in the last hypernuclear experiment at JLab Hall C (E05-115) were used. With a 0.2-g/cm^2 ^{7}Li target at $I_e = 32$ μA in the E05-115 experiment [59], counting rates in the K^+ spectrometer HKS were:

$$K^+ : \pi^+ : p = 300(\equiv R_K^{\mathrm{ref}}) : 25000 : 34000 \quad \mathrm{Hz}. \tag{5}$$

The HKS has Cherenkov counters with radiation media of aerogel ($n = 1.05$) and water ($n = 1.33$) to reject π^+s and protons. The Cherenkov counters reduced the fractions of π^+s and protons down to 0.5% and 10%, respectively, at the trigger level. In off-line analysis, π^+s and protons could be reduced to 4.7×10^{-4} and 1.9×10^{-4} by using information on light yields in the Cherenkov counters and reconstructed particle-mass squared [60]. The most important off-line analysis for K^+ identification (KID) is a time-of-flight (TOF) analysis. The TOF from the target to the timing counter was 10 m in HKS, and the TOF resolution was $\sigma = 0.26$ ns. Thus, a time separation of K^+s from π^+s and protons at 1.2 GeV/c were more than 6σ and 20σ respectively when an event selection was applied to select the $e'K^+$ coincidence with a time gate of ± 1 ns [1]. Therefore, accidental coincidence events in the missing mass spectrum originated mainly from $e'K^+$ coincidence which was made by quasi-free Λ and $\Sigma^{0,-}$ production. The KID performance of HKS in the present experiment without any an additional detector will be the same and enough as we achieved in E05-115 since the central momentum is the same.

The K^+ rate in the present experiment R_K is estimated assuming the production-cross section of quasi-free Λ is proportional to $A^{0.8}$:

$$R_K = R_K^{\rm ref} \times \frac{0.1}{0.2} \times \frac{50}{32} \times \frac{\Gamma^{\rm int}}{\Gamma^{\rm int}_{\rm ref}} \times \frac{A^{0.8}}{7^{0.8}} \times \frac{7}{A} \quad \left[\frac{\rm Hz}{(100\ {\rm mg/cm^2})(50\ \mu{\rm A})}\right] \tag{6}$$

$$= 234 \times \frac{\Gamma^{\rm int}}{\Gamma^{\rm int}_{\rm ref}} \times \left(\frac{7}{A}\right)^{0.2} \quad \left[\frac{\rm Hz}{(100\ {\rm mg/cm^2})(50\ \mu{\rm A})}\right] \tag{7}$$

where the rate is normalized to be per a target-thickness of 100 mg/cm^2 and per a beam current of 50 μA. The $\Gamma^{\rm int}_{\rm ref}(= 5.67 \times 10^{-5})$ is the integrated virtual photon flux in E05-115. Similarly, e' rates in HRS were estimated from that in the E05-115 experiment ($R_{e'}^{\rm ref} = 2.2 \times 10^6$ Hz) assuming a major contribution comes from Bremsstrahlung process [61]. For the estimation, a rate-reduction effect due to the smaller acceptance of HRS compared to that of the e' spectrometer in E05-115 (HES) was also taking into account. The expected singles rates of scattered electrons and K^+s in HRS and HKS are summarized in Table VI. The accidental $e'K^+$-coincidence background observed

TABLE VI. Expected singles rates in HRS (e') and HKS (K^+) at $I_e = 50$ μA. The expected number of events of the accidental $e'K^+$- coincidence background in a resulting missing-mass spectrum is shown in the last column.

Target	Rate		Accidental background
(mg/cm^2)	K^+ (Hz)	e' (Hz)	(/MeV/day)
^{3}He (168)	263	655	1.8
^{4}He (312)	462	1004	6.7

in the missing mass spectrum of ^{7}Li$(e, e'K^+)^7_\Lambda$He in E05-115 was about 6.5 [(nb/sr)/0.375 MeV] ($\equiv h^{\rm acc}_{\rm ref}$) [4]. For the present experiment, the accidental coincidence background is estimated as follows:

$$h^{\rm acc} = h^{\rm acc}_{\rm ref} \times \frac{R_{e'} R_K}{R_{e'}^{\rm ref} R_K^{\rm ref}} \times \left(\frac{I_e}{50} \times \frac{t}{100}\right)^2 \quad \left[\frac{\rm (nb/sr)}{0.375\ {\rm MeV}}\right] \tag{8}$$

where $R_{e'}$ and R_K are singles rates per 50-μA beam current per 100-mg/cm^2 target thick. The I_e and t are the beam current (μA) and areal density of target (mg/cm^2), respectively. The number of events of the accidental $e'K^+$-coincidence which was evaluated by Eq. (8) is shown in the last column of Table VI.

3. Statistical error on B_Λ

Figure 13 shows an expected B_Λ spectrum for ${}^{3}_{\Lambda}$H. The quasi-free Λ distribution was assumed to be a linear distribution for which the energy resolution of 1 MeV FWHM is taken into account as the Gauss distribution. The number of events in the quasi-free Λ relative to that in the bound region is assumed to be the same as reported in the past experiment [36]. The spectrum was fitted by a Gaussian function for the peak, and linear functions for the quasi-free Λ and accidental $e'K^+$ backgrounds. An expected statistical error is $|\Delta B_\Lambda^{\rm stat.}| < 20$ keV. If the first excited state ($3/2^+$)

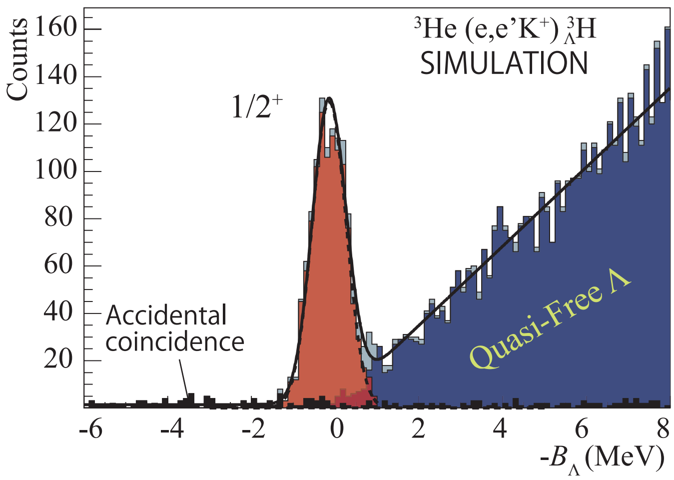

FIG. 13. An expected B_Λ spectrum for the ^{3}He$(e,e'K^+){}^3_\Lambda$H reaction with a 50-μA beam in ten days.

exists, the production cross section with the $(e,e'K^+)$ reaction is larger than that of the ground state by a factor of eight [52]. Figure 14 shows the expected spectrum assuming the existence of the 3/2 state. The Λ binding energy of the $3/2^+$ state may be observed for the first time with a statistical uncertainty of $|\Delta B_\Lambda^{\rm stat.}| < 20$ keV instead of the ground state.

The B_Λ spectrum for the ^{4}He$(e,e'K^+){}^4_\Lambda$H reaction was also estimated (Fig. 15) and $\Delta B_\Lambda^{\rm stat.}$ was evaluated in the same way as simulated for ${}^{3}_{\Lambda}$H. As a result, it was found that $|\Delta B_\Lambda^{\rm stat.}| \simeq 20$ keV for a measurement on the ${}^{4}_{\Lambda}$H(1^+) state in the proposed experiment.

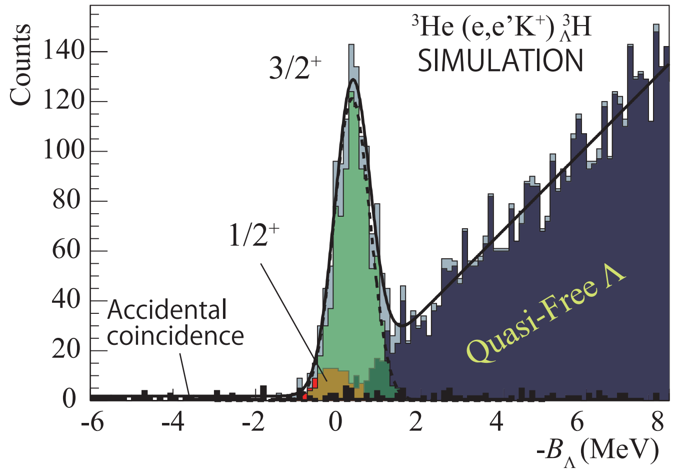

FIG. 14. An expected B_Λ spectrum for the ^{3}He$(e,e'K^+)^3_\Lambda$H reaction with a 50-μA beam in ten days, assuming the $3/2^+$ does exist. A ratio of production cross section of the $3/2^+$ state to that of the ground state was assumed to be eight [52].

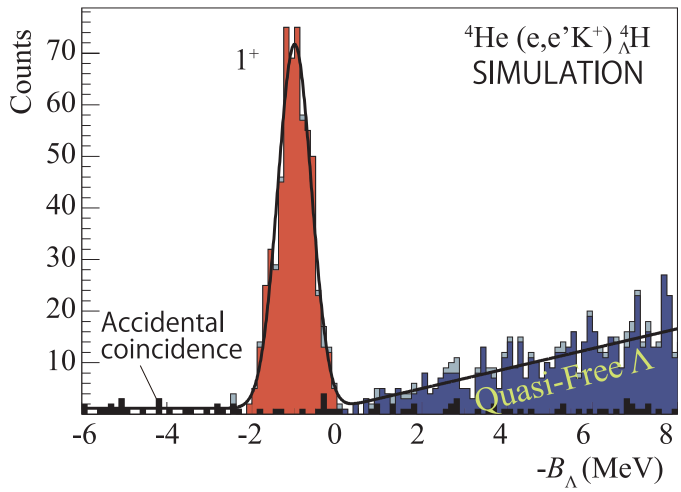

FIG. 15. An expected B_Λ spectrum for the ^{4}He$(e,e'K^+)^4_\Lambda$H reaction with a 50-μA beam in one day.

4. Calibrations and expected B_Λ accuracy

The various calibrations are needed in order to minimize the systematic error on B_Λ. There are five major calibrations and checks to be done as follows:

- **Momentum calibration by using elastic scattering**

  Elastic scattering data for momentum calibration of each spectrometer is planned to be taken in the approved experiment E12-15-008 for $^{40,48}_{\Lambda}$K spectroscopy, and these data can be shared for the present data analysis.

- **Angle calibration by using a sieve slit**

  The sieve slit data is planned to be taken with a solid target in E12-15-008. In addition (or instead), we need sieve slit data with the multi-foil target, and they will be used for calibration for the angle measurement at target which depends on production vertex z.

- **z reconstruction calibration by using the multi-foil target**

  In the present experiment, reconstructed information on the production vertex z will be used for reconstructions of momentum vectors of particles by using backward transfer matrices. In order to calibrate the reconstructed z position, the multi-foil carbon target which is the absolute position reference in z will be used.

- **Absolute energy scale calibration by using events of Λ and Σ^0**

  The absolute energy scale will be calibrated by Λ and Σ^0 masses. A polyethylene target will be used for Λ and Σ^0 production in E12-15-008. As shown in the previous item, we will apply the z correction for the missing mass. In order to confirm that the z correction does not deteriorate the mean value of measured B_Λ, data of Λ and Σ^0 production with the liquid hydrogen target in the target cell which is identical with those for gaseous ^{3,4}He targets need to be taken.

- **Checking the energy scale with different z positions by using $^{12}_{\Lambda}$B**

  The absolute energy scale will be guaranteed by using Λ and Σ^0 production as described above. In order to check the energy scale with a different mass region as well as z positions, we will check the Λ binding energy of $^{12}_{\Lambda}$B hypernuclei produced from different z position of the multi-foil target. This check will be important to minimize the systematic error on final results. The $^{12}_{\Lambda}$B hypernuclear production would also be used for momentum calibration if necessary as was used in the previous hypernuclear experiment at Hall C (E05-115) [1].

There are some factors that could contribute to the systematic error on B_Λ, and principal contributions are from the energy scale calibration and the target materials. The error that comes from statistical uncertainties of Λ and Σ^0 are less than 10 keV. Most of systematic error of the calibration with the hyperons would originate from mass uncertainties of hyperons ($\pm$6 and $\pm$24 keV for Λ and Σ^0) and a differential non-linearity of the energy scale ($\pm$50 keV). In addition, uncertainty of the energy loss correction for the the target material are estimated to be about $\pm$40 keV assuming uncertainty of the gas (liquid) density and a variation of uniformity of target cell thickness are $\pm$2% and $\pm$10%, respectively. In total, the systematic error is expected to be

$|\Delta B_{\Lambda}^{\rm sys.}| = 70$ keV.

IV. SUMMARY

We request thirteen days of beamtime including calibration runs for the accurate spectroscopy of $^{3,4}{\rm He}(e,e'K^+)^{3,4}_{\Lambda}{\rm H}$ by using the same experimental setup of the approved experiment E12-15-008. The present experiment aims to determine Λ binding energies of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H with a statistical uncertainty of about $|\Delta B_{\Lambda}^{\rm stat.}| \leq 20$ keV. A total error would be $|\Delta B_{\Lambda}^{\rm total}| < 100$ keV taking into account an expected systematic error of $|\Delta B_{\Lambda}^{\rm sys.}| = 70$ keV. The proposed experiment in which the energies of light hypernuclei will be determined with the best accuracy among counter experiments would give strong constraint for the study of ΛN interaction. Particularly, these data will be crucial to solve the puzzles of (a) the short-lifetime and small binding energy of Λ hypertriton, and (b) the ΛN CSB.

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