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High accuracy spectroscopy of 3- and 4-body Λ hypernuclei at Jefferson Lab

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Abstract. JLab E12-19-002 Experiment is planned to measure the Λ-binding energies of ${}^{3}_{\Lambda}\mathrm{H}$ [$J^{\pi} = 1/2^{+}$ or $3/2^{+}(T = 0)$] and ${}^{4}_{\Lambda}\mathrm{H}$ (1^{+}) at JLab Hall C. The expected accuracy for the binding-energy measurement is $|\Delta B_{\Lambda}^{\mathrm{total}}| \simeq 70$ keV. The accurate spectroscopy for these light hypernuclei would shed light on the

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puzzle of the small binding energy and short lifetime of ${}^{3}_{\Lambda}$H, and the charge-symmetry breaking in the ΛN interaction. We aim to perform the experiment in 2025.

1 Introduction

Experimental studies for light Λ hypernuclei have been playing an important role to investigate the ΛN interaction. Particularly hypertriton (${}^{3}_{\Lambda}$H) which is the lightest bound system ever confirmed, and the 4-body iso-doublet ($T = 1/2$) hypernuclei (${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He) are of great importance.

The ground-state ($J^{\pi} = 1/2^{+}$) binding energy of ${}^{3}_{\Lambda}$H was found to be $B_{\Lambda} = 0.13 \pm 0.05^{\text{stat.}}$ MeV in an emulsion experiment [1] whereas the STAR collaboration recently reported a larger value $B_{\Lambda} = 0.41 \pm 0.12^{\text{stat.}} \pm 0.11^{\text{sys.}}$ MeV [2]. There is an argument that the small binding energy from the emulsion experiment does not allow for the short lifetime that was reported by recent heavy-ion beam experiments. On the other hand, the binding energy as large as the report by the STAR collaboration may allow the predicted lifetime to be consistent with the measured short lifetime [3]. Here, we should say that the experimental data for both binding energy and lifetime are not determined well enough, and need to confirm them by more accurate experiments. There are many experimental attempts which are on-going or are being prepared to shed light on the puzzle of the hypertriton's binding energy and lifetime at the present day [4–8]. In addition, the first excited state ($3/2^{+}$) of ${}^{3}_{\Lambda}$H has not been observed, and its existence is open question [9–11]. A difference of the ground-state (0^{+}) binding energy between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He is a firm evidence of the charge symmetry breaking (CSB) in the ΛN interaction [12, 13]. The energy levels for the first excited states (1^{+}) of these hypernuclei also give us fundamental information about CSB. A recent γ-ray measurement by Germanium detector at J-PARC updated the energy of ${}^{4}_{\Lambda}$He(1^{+}) [14], and it turned out that the binding energy is consistent with that of existing data for its mirror state ${}^{4}_{\Lambda}$H(1^{+}). Similarly, the data of ${}^{4}_{\Lambda}$H(1^{+}), which is a weighted average of three of γ-ray measurements by NaI counters [15–17], are awaited to be improved and/or confirmed by modern experimental techniques.

The context shown above motivated us to launch an experimental project (JLab E12-19-002 Experiment) in which the Λ-binding energies of ${}^{3}_{\Lambda}$H [$1/2^{+}$ or $3/2^{+}$ ($T = 0$)] and ${}^{4}_{\Lambda}$H (1^{+}) are determined with the accuracy of $|\Delta B_{\Lambda}^{\text{total}}| \simeq 70$ keV by using the $(e, e'K^{+})$ reaction at Jefferson Lab (JLab) [18, 19]. The present experiment and other experimental attempts such as ${}^{3}_{\Lambda}$H ($1/2^{+}$, $T = 0$) measurement by decay-pion spectroscopy at MAMI [20], ${}^{4}_{\Lambda}$H (1^{+}) measurement by γ-ray spectroscopy at the J-PARC K1.1 beam line (J-PARC E63 Experiment) [21] etc. are complementary because they use totally different experimental techniques which may have different origins of systematic errors on results. The experiment E12-19-002 is being prepared aiming to be performed in 2025.

2 What to consider for the experiment

E12-19-002 was originally proposed to be carried out at JLab Hall A [22] to investigate the nuclear masses of hyperhydrogens, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H [18, 19]. However, it turned out the experiment could be performed earlier in Hall C. We considered the experimental feasibility in Hall C in order to seek the earliest occasion of beam time because tackling the physics problems shown above is urgent. However, in the case of Hall C, given a required momentum resolution and acceptance, High resolution Election Spectrometer (HES) [23] of which the maximum central momentum is 0.844 GeV/c is the first option to use for the e' measurement. The limit of the maximum momentum of HES does not allow us to use the beam energy as high as the case of Hall A. The lowered beam energy causes an increase of background electrons from the Bremsstrahlung process occurred in an experimental target, possibly leading to worse S/N. In addition, the background rate due to the Bremsstrahlung process is proportional to about the square of proton number of target material ($Z^2_{\mathrm{targ.}}$) [24]. The effect of the Bremsstrahlung background is not negligible even for our light mass targets, which are ^{3,4}He gases, because the gaseous targets need to be contained by metal cells which have an enough strength against inner pressures. However, there is an important merit in the Hall-C option. The missing-mass resolution gets better due to the lower energies for both the incident and scattered electrons.

We examined the background rate and S/N for considerable experimental conditions, based on particle rates from the previous hypernuclear experiment [25–28]. As a result, it was found that the experiment at Hall C is feasible, although a fine tuning for the experimental design is ongoing to find an optimal condition that maximizes physics output. This article shows the expected result for a certain experimental condition at JLab Hall C.

3 Expected result

3.1 Assumption of the experimental condition

E12-19-002 performs missing-mass spectroscopy with $(e, e'K^+)$ reaction. The scattered electron (e') and K^+ are detected by HES and High resolution Kaon Spectrometer (HKS) [29, 30], respectively. The HES is assumed to be a vertical bending spectrometer whereas the modification plan from the original horizontal bending to the vertical one is now being examined. The introduction of the vertical bending spectrometer is vital for the present experiment because we need a reaction vertex information for an analysis of the gas targets. The spectrometers HES and HKS will be combined with a new Pair of Charge-Separation dipole magnets (PCS) which was already constructed and transferred to JLab from Japan in 2022. The PCS makes the detectable scattering angle more forward to increase the hypernuclear yield. The continuous electron beam at $E_e = 2.24$ GeV with the rastered beam size of 2×2 mm^2 is impinged on the target. The beam current is assumed to be 20 μA. The helium-3,4 gases that have the areal densities of 192 and 262 mg/cm^2, respectively, are contained in cylindrical cells with the diameter of 200 mm. It is noted that the areal density and the cell diameter for a hydrogen gas, which is used for the energy calibration, are 54 mg/cm^2 and 220 mm, respectively. The cell is made of aluminum alloy Al-7075 with the wall thickness of 0.3 mm. The central momenta are set to 0.74 and 1.2 GeV/c and the scattering angles with respect the incident beam are $\theta_{ee'} = 8^\circ$ and $\theta_{eK} = 10.2^\circ$ for HES (e') and HKS (K^+), respectively. These conditions determine the square of four-momentum transfer taken with the negative sign ($Q^2 = -q^2$) and the K^+-scattering angle with respect to the virtual photon in the laboratory frame to be $Q^2 \sim 0.04$ GeV^2 and $\theta_{\gamma^* K} \sim 6^\circ$, respectively. Assumed beam times for the helium-3 and 4 targets are 480 and 96 hours, respectively, which exclude calibration runs.

3.2 Expected spectra for the $^3_\Lambda$H and $^4_\Lambda$H productions

The expected number of events for the $^3_\Lambda$H and $^4_\Lambda$H is about 200 for each. The yield estimation is based on the following assumptions. The differential cross sections, which are 5 and 20 nb/sr for the $^{3,4}\mathrm{He}(\gamma^*, K^+)^{3,4}_\Lambda\mathrm{H}$ reactions, are taken from the previous measurement [31, 32]. The assumed detection efficiency (detector, analysis, data acquisition) and the K^+-survival ratio against its decay are 0.75 and 0.26, respectively. The gas density is expected

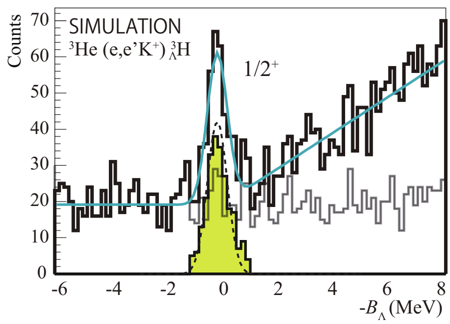

Figure 1. Expected spectrum for the $^{3}_{\Lambda}$H production in JLab E12-19-002.

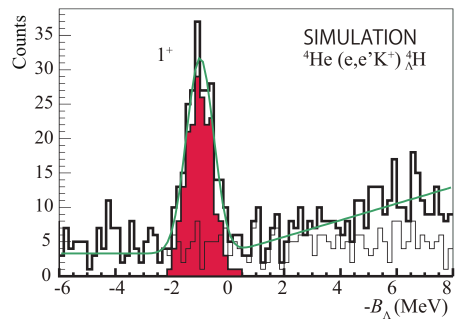

Figure 2. Expected spectrum for the $^{4}_{\Lambda}$H production in JLab E12-19-002.

be reduced due to a local temperature rise by the beam exposure, and the gas-density reduction is conservatively assumed to be 0.5. In the analysis, an event selection by the production vertex along the beam direction (v_z) is applied to eliminate a contamination from the target cell as was done in the previous hypernuclear experiment [33–35] with a gaseous tritium target [36]. The v_z resolution of HES is assumed to be $\Delta v_z = 2$ cm in FWHM. The fraction of remained signals by the v_z cut is assumed to be 0.8 which corresponds to the suppression of the event contamination from the target cell by 98%.

The missing-mass resolution is estimated to be about 1 MeV/c^2 in FWHM considering an effect of the finite volumes of gas targets. It is worth noting that the resolution could get better to about 0.6 MeV/c^2 (FWHM) in the case of solid targets which are much thinner; they are mostly as much as the order of 0.1 mm. Measurements of other hypernuclei, $^{40,48}_{\Lambda}$K [37] and $^{208}_{\Lambda}$Tl [38], which use solid targets with the areal density of about 100 mg/cm^2, are planned to be performed with the same experimental setup as that of the present experiment.

The expected spectrum for the ^{3}He$(e, e'K^+)^3_\Lambda$H is shown in Fig. 1. Only a peak for the ground state $(1/2^+, T = 0)$ is assumed to exist in the simulated $^{3}_{\Lambda}$H spectrum. However, the first excited state $(3/2^+, T = 0)$, which has not been observed, may have a larger cross section than that of the ground state by a factor of eight [39, 40]. Therefore, instead of the ground-state measurement, the binding energy for the $3/2^+$ state may be able to be determined for the first time if the state exists. In addition, the $1/2^+(T = 1)$ state may also be observed at about 2-MeV higher energy from the $1/2^+(T = 0)$ state if its production-cross section is reasonably large and decay width is small enough. Theoretical predictions of the production-cross sections as well as the energy levels are desired. Particularly relative cross-section strengths for the states would help a lot for the spectrum analysis. Figure. 2 shows the expected spectrum for the ^{4}He$(e, e'K^+)^4_\Lambda$H reaction. The cross section for the 1^+ is predicted to be dominant [41], and thus the 1^+ state would be a prominent peak as shown in the figure. The statistical error for the peak fitting is $|\Delta B_\Lambda^{\text{stat.}}| \leq 40$ keV for both $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H measurements. The systematic error on the binding-energy measurement is evaluated to be $|\Delta B_\Lambda^{\text{sys.}}| \simeq 60$ keV [42]. Therefore, the total accuracy that takes into account both statistical and systematic errors is $|\Delta B_\Lambda^{\text{total}}| \simeq 70$ keV when we take a square root of their quadratic sum.

4 Summary

JLab E12-19-002 Experiment measures the Λ-binding energies of $^{3}_{\Lambda}$H $[J^\pi = 1/2^+$ or $3/2^+(T = 0)]$ and $^{4}_{\Lambda}$H (1^+) at JLab Hall C. The total accuracy for the binding energy measurement is expected to reach $|\Delta B_\Lambda^{\text{total}}| \simeq 70$ keV. The accurate spectroscopy for the light hypernuclei would shed light on the puzzle of the binding energy and lifetime of hypertriton, and the ΛN CSB. We have been preparing for the experiment aiming to perform it in 2025.

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