Proposal to Jefferson Lab PAC 48, August 2018

Extension request for E12-17-003: Determining the unknown *Λ-n* interaction by investigating the *Λnn* resonance

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Introduction

The *ΛN* interaction is an essential element in producing a unified baryonic interaction model that describes the strangeness flavor and beyond. However, only limited data exist for *Λp* scattering, while **no** *Λn* scattering data exist at all. For the *NN* interaction studied by the binding energy difference between ^{3}H and ^{3}He, corrected for the Coulomb energy, the Charge-symmetry-breaking (CSB) was found to be negligibly small. Recent high precision experiments on the A = 4 isospin mirror pair ($^{4}{}_{\Lambda}He$ and $^{4}{}_{\Lambda}H$) hypernuclei have proven that the CSB for the *ΛN* interaction is several times larger than that of the *NN* interaction. To understand the origin of the non-negligible CSB in the *ΛN* interaction, obtaining experimental data that can be used to extract the *Λn* interaction becomes critically important.

Since the HypHi experiment at GSI that suggested existence of a bound *Λnn* ($^{3}{}_{\Lambda}n$) hypernuclei, number of subsequent theoretical studies has ruled out such possibility. However, theoretical studies with different approaches suggested that the *Λnn* resonance is likely possible. More importantly, they pointed out that such a *Λnn* resonance with its measured binding (or excitation) energy and natural width can provide experimentally for the first time the crucial information in determining the unknown *Λn* interaction. Obviously, a precision mass spectroscopy using the $^{3}H(e,e'K^{+})(\Lambda nn)$ reaction with the excellent CEBAF beam is unique to perform such measurement.

Taking advantage of an existing Tritium target that would be shared by a group of approved experiments, E12-17-003 was proposed to and approved by PAC45. With only the standard equipment and configuration, the system was obviously not optimized for the $(e,e'K^+)$ experiment with unknown cross section which was expected to be small. However, it was definitely the only chance to search for such a resonance from precision mass spectroscopy. E12-17-003 was approved for 10 days of data collection on the *Λnn* events plus 2 days of calibration with the H target from which the free Λ and Σ^0 were produced.

Detailed physics motivation and experimental discussions for the E12-17-003 experiment, can be found in the previous E12-17-003 proposal that is attached in the **Appendix** in this proposal.

E12-17-003 and its result

The E12-17-003 experiment was carried out successfully in fall of 2018 as the last experiment using the Tritium target in Hall A. The beam energy stability and spread were controlled and monitored to be at a level of $\sigma \approx 6.5\times10^{-5}$ which is excellent for the experiment. A GEANT4 simulation provided the effective energy and momentum straggling corrections and ensured their contributions to the missing mass resolution less than 100 keV. The multi-foil-Carbon target run provided data for excellent z-vertex reconstruction with a resolution of $\sigma \approx 4.5$ mm (see Fig.1). The sieve slit data were used to calibrate the angular matrices and the angular resolution was estimated to be $\sigma_\theta \approx 3.4$ mr. A time resolution of $\sigma_t \approx 370$ ps was achieved for the coincidence time (see Fig.2), sufficient to cleanly separate the real and accidental coincidence events. Since the two available aerogel counters (one with index n = 1.015 and one with n = 1.05) are more than 20 years old, the average number of photoelectrons was very low (~3-4). They did not have sufficient rejection power to the background pions and protons. The accidental coincidences were only from the background pions and protons. In addition, the kaon detection efficiency was below 50% (the most severe loss was from the proton cut).

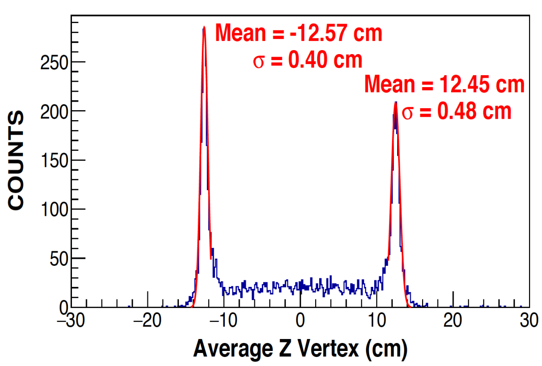

Fig. 1. Z-vertex averaged by the z reconstructions from the LHRS (e') and RHRS (K^+). The resolution is estimated to be $\sigma_z \approx 4.5$ mm.

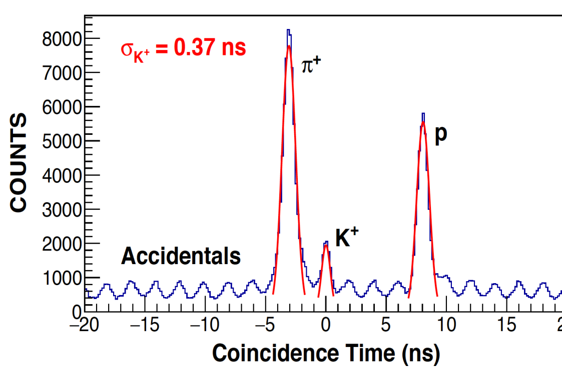

Fig. 2. The coincidence time between e' and K^+. The time resolution is about $\sigma_t \approx 370$ ps, while the CEBAF's beam bunch separation is 2 ns.

The momentum matrices and the absolute kinematics scale were optimized using the data collected from the H target with the Λ and Σ^0 production (see Fig. 3). To disentangle the contributions to the missing mass resolution from the angular and momentum uncertainties, events from the Al end caps were also involved in the momentum matrix optimization so that the missing mass resolution reached the level as predicted by a simulation on the missing mass resolution with the A dependence. Figure 4 shows the Tritium data analyzed using the H kinematics. The visible Λ peak at $B_\Lambda = 0$ MeV has agreement with other Tritium experiments on the ~ 2% H contamination.

Analyzed with the optimized matrices the T data, see Fig. 5, exhibits the mass spectroscopy in terms of the binding energy B_Λ of the Λnn hypernuclei with the threshold mass defined at the rest mass of the Λnn three-body system. The distribution formed by the green crosses shows the accidental background that was obtained by analyzing the events selected from 38 accidental coincidence peaks to minimize the statistical uncertainty, then reduced by a factor of 38. The distribution above the accidental background is dominated by the Λ quasi-free production events. Due to a limited kinematics acceptance, the Σ quasi-free productions were severely cut off (that started about 30 MeV below the $\Sigma^0 nn$ and $\Sigma^- np$ thresholds shown by the two black vertical dash lines). The red solid-line is the quasi-free distribution combining both the Λ and Σ productions simulated using the Atti momentum distribution [1] of a nucleon in three-body baryonic systems. The simulation was done by the early $(e,e'K^+)$ experiment (JLab E91-016) in 1996 in Hall C which studied the $^3_\Lambda$H with almost the identical 4- and 3-momentum transfers to the E12-17-003 experiment, but with a kinematics acceptance covering almost the entire Σ quasi-free production region. The extended red dash-line shows the extended tail of the Λ quasi-free production. On top of it are the combined $\Sigma^0 nn$ and $\Sigma^- pn$ quasi-free production events. The fitted quasi-free distribution was normalized to the height below the ~2% H contamination which produced free Λ with broadening due to the T kinematics.

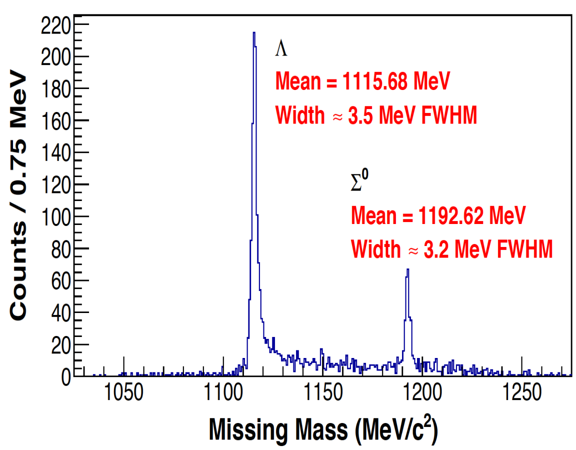

Fig. 3. Λ and Σ^0 production from the H target used for optimizations of kinematics and momentum matrices.

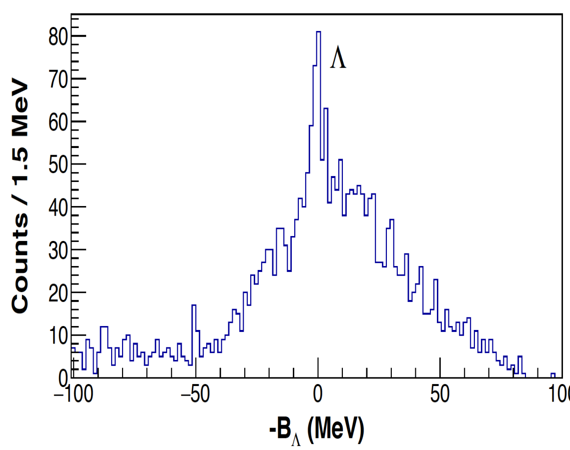

Fig. 4. Free Λ appeared in the Tritium data, agreed with other Tritium experiments that there was a ~ 2% H contamination in the Tritium cell.

There appears to be a small peak at the Λnn threshold, with the binding energy B_Λ found to be around 0.0 ± 0.6 MeV and a width of 0.81 ± 0.5 MeV (σ); it appears to be the (T = 1) Λnn state for which the experiment was searching. Since the statistics is too low, the fitted values had large statistical uncertainty. Excluding the intrinsic resolution (that was predicted to be 0.67 MeV in σ for the A = 3 system), the natural width ($\Gamma/2$) appears to be ~ 0.55 MeV, if it does exist. In addition, there is a second peak at B_Λ = 8.05 ± 0.51 MeV and width of 1.0 ± 0.36 MeV (σ). Although it appears to be an unbound resonance in the continuum, it is not expected. Its nature is, therefore, unclear if it is indeed real. Due to the low statistics and the poor signal to background ratio from this experiment, neither of the two peaks has sufficient significance to permit a definitive identification.

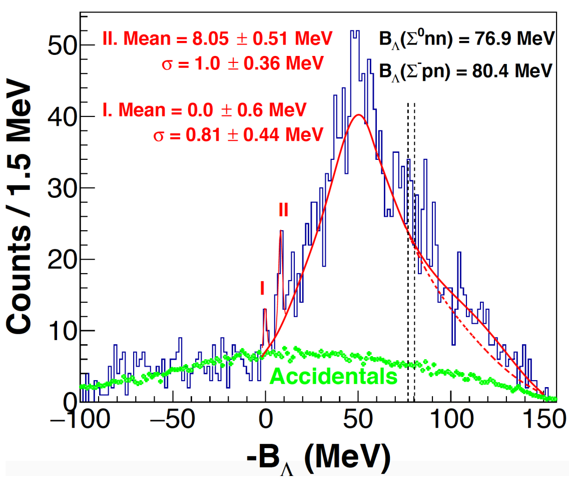

Fig. 5. The mass spectroscopy plotted in terms of the binding energy B_Λ of the Λnn hypernuclei. The accidental background shape is shown by the distribution of the green crosses. The red solid line shows the combination of the simulated Λ and Σ quasi-free distributions, while the continued red dash line is the extended Λ quasi-free production tail. The vertical black dash lines indicate the locations of the $\Sigma^0 nn$ and $\Sigma^- pn$ thresholds.

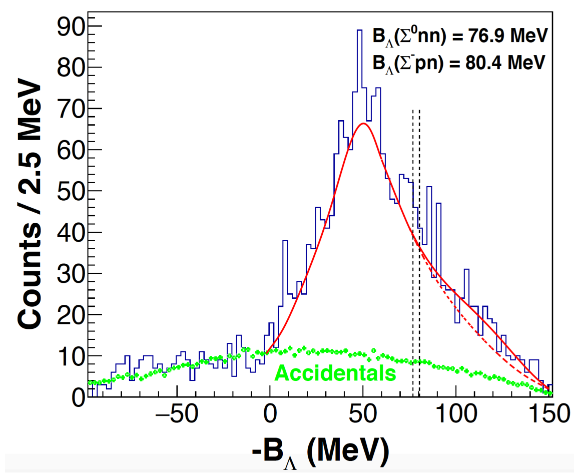

Fig. 6. The same mass spectroscopy plotted in terms of the binding energy B_Λ of the Λnn hypernuclei but with a larger bin size to enhance the view with less statistical fluctuation around the Σ thresholds.

Another interesting observation is the excessive distribution of events above the quasi-free distribution around the Σ thresholds. To make clearer observation in this region by reducing the statistical fluctuation, the spectrum was also plotted with a large bin size (see Fig. 6). There appears to be a broad enhancement, estimated to be at about ~ 1.7 MeV below the $\Sigma^0 nn$ threshold and having a width of about ~ 5 MeV (FWHM), can be observed. Although bound A = 3 and 4 Σ hypernuclei were predicted long ago, only an A = 4 Σ hypernucleus ($^4_\Sigma$He) was experimentally found [2], by means of the (K^-, π^-) reaction on a He target at the BNL-AGS. Because the Σ^+ production threshold is lower than that of the Σ^0 production, it was claimed to be a bound Σ^+ hypernucleus with a binding energy and width of 4.4 MeV and 7 MeV (FWHM), respectively. The A = 3 and

4 Σ hypernuclei were also studied in the early Hall C ($e,e'K^+$) experiment (JLab E91-016) using ^{3}He and ^{4}He targets. In both cases, there was not any visible strength above the quasi-free distribution. Thus, no bound Σ hypernuclei was found in either case. In case of electroproduction, the Σ^0 threshold is lower. Therefore, this observed enhancement might be a bound $\Sigma^0 nn$ hypernucleus, although the statistics are not sufficient to investigate it more precisely.

The result from E12-17-003 has proven the feasibility and the uniqueness of using the ($e,e'K^+$) reaction to search and study the Λnn resonance and bound $\Sigma^0 nn$ state which will provide crucial information on the Λn and Λ-Σ interactions. However, the result does not have the sufficient statistics to make definitive identification on their existences, nor have the measured binding energy and width precise enough to make determinations on these interactions. Therefore, we are proposing to do this experiment again with the optimized HKS-HRS system.

The importance for the extension of E12-17-003

The result from the E12-17-003 experiment exhibited the possible findings of the Λnn resonance and the bound $\Sigma^0 nn$ hypernuclei. If these observations are real, their production yield rates are now well known. With the optimized HKS-HRS system that will be used by the approved E12-15-008 experiment, the extended E12-17-003 can significantly improve the statistics and achieve the original goal of the E12-17-003 experiment.

In case of the Λnn resonance, the improved statistics and S/B ratio (>10) not only can unambiguously determine the existence of such a resonance, but also measure its binding energy and natural width with high precision, < ±50 keV (stat.). The systematic uncertainty is determined by the precision on the Λ and Σ^0 production from the H target, which is also depending on statistics. The goal is to < ±70 keV. This precision is critically needed in determining the unknown Λn interaction.

In case of the bound state of $\Sigma^0 nn$ hypernucleus (if it is proven exist), it will provide for the first time the crucial information in determining the strength of the $\Lambda N - \Sigma N$ interaction which cannot be measured by other means but plays an essential role for a bound A = 3 hypernuclei [3]. This Λ-Σ coupling may have strong isospin dependence that might be the reason that only bound $\Sigma^0 nn$ (A =3) and $\Sigma^+ pnn$ (A = 4) hypernuclei exist. Therefore, solidly confirming it with improved statistics and better measured Σ quasi-free distribution will provide critical and unique information in determining $\Lambda N - \Sigma N$ interaction.

Optimized E12-17-003 experiment

The optimized E12-17-003 experiment proposes to use the same HRS-HKS system that is designed for the E12-15-008 hypernuclear experiment without configuration or equipment change, except targets. The required targets and the safety regulations can be installed and established after completion of E12-15-008.

Figure 7 is a schematic illustration of the HKS-HRS configuration. With the two new septum magnets, the central angle of the scattered electrons is at 6.5° (updated design for the E12-15-008 experiment), significantly reduced from 13.2° that was the minimum angle limited by the equipment in the previous E12-17-003. This angle reduction increases the integrated virtual photon flux by a factor of 7 (taking into account of the ΔE and ΔΩ).

The HKS spectrometer is at the virtual photon momentum direction (i.e. $\theta_{\gamma^*K} = 0°$), the same as the previous E12-17-003 configuration. The much shorter HKS path length (~11 meters) gives a kaon survival rate of ~26%, 2.9 times larger than that of RHRS (~9%) used for kaons in the previous E12-17-003.

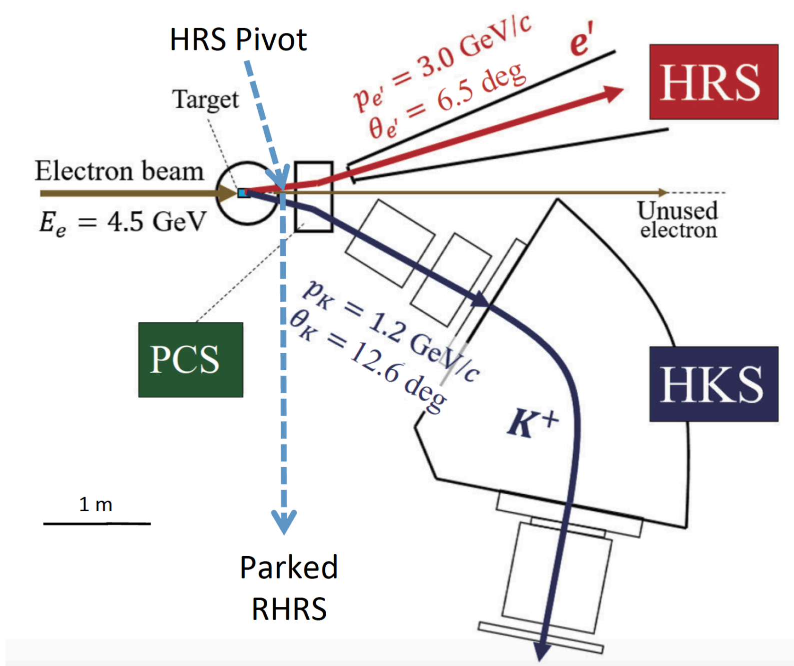

Fig. 7 Schematic illustration of the HKS-HRS configuration to be used for the hypernuclear experiments that are going to share the same or separate target chambers without configuration change.

The HKS has larger momentum acceptance (± 10%) that is better matched to the electron arm (Left HRS). This increases the kinematics acceptance (so is the yield rate) by a factor of 1.4.

The HKS has an excellent KID system, including 3 layers of segmented aerogel Čerenkov counters for pion rejection, 2 layers of segmented water Čerenkov counters for proton rejection and kaon detection, and 3 layers of segmented time-of-flight counters with timing resolution of σ ≈100 ps for β measurement. This combined KID system has proven by the previous HKS experiments in Hall C to have 100% rejection power to the pion and proton background and better than 80% of the overall kaon detection efficiency. This increases the yield rate by a factor of 1.6.

For this proposed extension, a shorter tritium target (16 cm long and 2 cm diameter) is considered due to the space limitation of the new target chamber. Combining with worse Z-vertex reconstruction resolution that needs tighter gate, the effective gas target thickness is reduced by a factor of 2 (or gain factor of 0.5).

The gain factors are listed in Table I. The overall combined gain from the optimized HKS-HRS over the previous HRS-HRS will be 22.7.

Table I. Itemized gain factors from the optimized HKS-HRS over the previous HRS-HRS used by the previous E12-17-003.

Item	**Gain Factor by HKS-HRS / HRS-HRS**
Integrated virtual photon flux ($\int \Gamma \Delta E \Delta \Omega$)	7.0
K^+ survival rate	2.9
Kinematics acceptance	1.4
Improved KID efficiency	1.6
Target length reduction	0.5
Total overall	**22.7**

With 140 hours of requested beam time, the total Λ quasi-free production should yield more 28,000 events (with yield rate of ~200 counts/hours). In addition, due to a much larger HKS momentum acceptance, the Σ quasi-free distribution (containing ~6,000 events) will also be measured more precisely, improving the measurement of the bound ΣNN state.

If the first Λnn peak is real, the previous E12-17-003 obtained only about 12 counts, 10 times smaller than that hoped to be obtained. With the optimized HKS-HRS system and 140 hours of beam, this resonance will have about ~ 270 events. Since the excellent KID in the HKS system is able to remove almost 100% background from pions and protons, the S/B ratio will be > 10 at the Λnn threshold. This statistics and the good S/B ratio are sufficient for high precision determination of its binding energy and natural width, ≤ ±50 keV (stat.) and ≤ ±70 keV (sys), see how it impacts the physics from the E12-017-003 proposal in Appendx. In case of the bound ΣNN state, there will be > 750 events in the peak and the Σ quasi-free distribution will also be clearly measured.

Due to the limited beam time and un-optimized configuration, the previous E12-17-003 was not able to collect the crucially needed data for the momentum calibration that is crucial to the missing mass resolution. Therefore, for the extended E12-17-003, a dedicated beam time for a set of calibration data with sufficient statistics will be needed, including productions of Λ and Σ^0 and the well known ground state of the ${}^{12}_{\Lambda}B$ hypernuclei.

The anticipated missing mass resolution is about 2 MeV FWHM, sufficient for the needed precision on the binding energy and natural width of the *Λnn* resonance. Since the bound *ΣNN* state is naturally broad, so that mainly the statistics and the shaping of the *Λ* and *Σ* quasi-free distributions dominate the precision on its binding energy.

Targets and requested beam time

The proposed extension of E12-17-003 requests the following primary targets.

The proposal experiment requests the same pressurized gas Tritium target but shorter in length, 16 cm long instead of 25 cm that was used in Hall A in 2018. This shortening is due to the limitation of the target chamber size. This target can be installed after completion of all the approved experiments that use the HKS-HRS system.

A multi-foil-C target similar to that used in 2018 run will be used for calibrations on the Z-vertex reconstruction, angular reconstruction, and momentum reconstruction. Since the Z-vertex reconstruction precision will be worse due to smaller electron scattering angle, only 5 foils (0.40 mm thick each) over the 16 cm length with 4 cm separation between the adjacent two foils will be required. This target will be used for three types of runs: (1) single arm trigger with full collimators for the Z-vertex reconstruction; (2) single arm trigger with sieve slit collimators for the angular reconstruction; and (3) coincidence trigger for the momentum reconstruction using the known ground state of $^{12}{}_{\Lambda}$B hypernuclei. The total thickness of the 5 C foils is 453 mg/cm^2. With a 22 μA beam, the yield rate of the ground state of $^{12}{}_{\Lambda}$B hypernuclei is more than 54 counts per hour. With 48 hours of beam, there should be about 2600 counts in total from this well-known state. This data with good statistics is needed to ensure optimization of the momentum matrices and uniformity in the kinematics space. The goal of the missing mass resolution for the A = 3 system is ≤ 2.0 MeV FWHM, same as the previous E12-17-003.

An empty cell target is required to estimate the background from the events produced from the Al end caps but leaked through the Z-vertex gate.

A pressurized H_2 gas target with the same cell design will be required for production of free *Λ* and Σ^0 for calibration of the absolute missing mass scale. With 8 hours of beam time and 22 μA beam current, there will be more than 4,500 free *Λ* and 1,100 Σ^0 produced, ensuring small statistical uncertainty which is crucial to the systematic error for the measurement of the A = 3 systems.

The total required beam time is 204 hours (8.5 days), which includes 140 hours of production data collection and 64 hours to collect various essentially needed calibration data. Table II shows the detailed breakdown of the required beam time.

Summary

Although the previously completed E12-17-003 experiment showed possible findings that are highly interesting and demonstrated the uniqueness of the electroproduction, the poor statistics did not allow a solid identification nor provided sufficiently precise measurements that are needed to determine the *Λn* and $\Lambda - \Sigma$ interactions. Therefore, this experiment needs to be repeated with an optimized system so that both the statistical and systematic uncertainties can be smaller than 20 keV. We are here proposing to run it again along with the E12-15-008 experiment using the HKS-HRS system.

Table II. Required beam time for the high precision measurement

Target	Run Description	Beam Time (hours)
Tritium (T_2)	Production run for the Λnn resonance and bound $\Sigma^0 nn$ state (Coincidence trigger)	140
Hydrogen (H_2)	Calibration run for precise kinematics scale Using the known masses of Λ and Σ^0 (Coincidence trigger)	8
Empty cell	Al background calibration (HRS single arm trigger)	2
Multi-foil-C	(1) Z-vertex calibration with open collimator (HRS single arm trigger)	2
	(2) Angle calibration with sieve slits (Single arm triggers)	4
	(3) Calibration data from the ${}^{12}_{\Lambda}B$ g.s. (Coincidence trigger)	48
C-hole	Beam location verification (safety)	-
Total required beam time		**204 (8.5 days)**

Reference

1. C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53**, (1996)1689-1710.
2. T. Nagae *et al*., Phys. Rev. Lett. Vol. **80** No. **8**, (1998)1605-1609.
3. I.R. Afnan and B.F. Gibson, Phys. Rev. C **47**, (1993)1000.

APPENDIX

Proposal to Jefferson Lab PAC 45, July 2017
Determining the Unknown *Λ-n* Interaction by Investigating the *Λnn* Resonance

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Abstract

The ΛN interaction is an essential element in producing a unified baryonic interaction model that describes the strangeness flavor and beyond. However, only limited data exist for Λp scattering, and **no** Λn scattering data exist at all. In contrast to the normal nuclear situation (in which the binding energy difference between ^3H and ^3He, corrected for the Coulomb energy, is relatively small and charge symmetry is a good approximation for the NN interaction), recent precision experimental results on the mass of the $^4{}_\Lambda H$ ground state and the γ transition between the first excited state and the ground state of $^4{}_\Lambda He$ show that charge symmetry breaking (CSB) in the ΛN interaction is apparently much more significant. Thus, determining the unknown Λn interaction is critically important to understanding CSB in the strangeness nuclear physics sector.

While a bound 3-body Λnn system is ruled out so far by published theoretical analyses, an actual physical resonance in such a 3-body system has been shown likely to exist with as little as only an ~5% increase in the strength of the Λn interaction over that of the Λp interaction. Even a strong sub-threshold resonance would be evident. By investigating the Λnn resonance, knowledge of the nn interaction would allow one to provide a significant constraint on the low-energy properties of the Λn system; that is, investigation of the 3-body Λnn resonance provides a unique opportunity to determine the unmeasured Λn interaction. Such a Λn interaction determination would quantify the important CSB difference relative to the measured Λp interaction, would provide a

realistic interaction basis for understanding the long existing Λ-hypernuclei data, and would constrain the modeling of neutron stars.

The only way to investigate the Λnn resonance with sufficient precision is to use electroproduction of K^+ from a ^{3}H target, *i.e.* the $^3H(e,e'K^+)(\Lambda nn)$ reaction with a high precision beam at JLab. Currently, there are four approved experiments in Hall A using a common ^3H target that will exist until the end of August in 2018. The last one to be executed in this run group is a coincidence experiment (E12-14-011) with the $(e,e'p)$ reaction using a 4.4 GeV beam (we assume 4.524 GeV if the injector energy is included). It is found that with only a kinematic change in momentum and angle of the two HRS spectrometers, a $^3H(e,e'K^+)(\Lambda nn)$ reaction experiment can be carried out with an energy resolution of ~2MeV FWHM and an absolute missing mass precision of ~ ±0.20 MeV. With a similar kinematic condition as in E91-016 (Hall C kaon production from H, D, ^3He, and ^4He targets) but keeping $\theta_{\gamma K} = 0°$ (maximizing the Λ photoproduction cross section), a beam time of 5 PAC days would be required to obtain a missing mass spectroscopy with the minimally required statistics in order to meaningfully investigate the Λnn resonance.

This short experiment can generate, for the first time (and possibly for the last time if not forever), Λnn resonance data with high precision that can be used to determine the Λn interaction. This can only be done at JLab.

I. Introduction and Physics Motivation

A. Background on the ΛN interaction and Λ-hypernuclei

A primary goal of nuclear physics is to investigate and understand the behavior of many-body systems bound by the strong interaction as well as the mechanisms that build all forms of nuclear matter observed in the universe today, from few-body nuclei to nuclear matter in the astronomical scale such as neutron stars. Although fundamental particles at the level of mesons and baryons and the level of quarks and gluons are relatively well understood, the actual interaction that gives rise to different properties and formation of matter still remains largely undetermined. Understanding the baryonic interaction that builds the variety of baryonic many-body systems is one of the essential tasks in the overall mission of nuclear physics.

The most current and broadly applied baryonic interaction models (Nijmegen [1–4] or Jülich [5, 6]) are based on the existence of an extensive amount of *NN* scattering data but extremely limited or non-existent data beyond *NN* scattering. For example, in the case of the ΛN interaction, data exist only for Λp scattering (obtained more than 50 years ago, where statistics are poor with only several hundred events in total and insufficient to provide stringent limits to models). Λn scattering data do not exist at all and are impossible to obtain directly. Thus, the two interactions are basically treated as identical in the models. Exploring the formation and properties of Λ-hypernuclei, which have one of the nucleons in an ordinary nucleus replaced by a Λ, becomes the only practical mean to extend the investigation of the baryonic interaction to flavors beyond the nucleons. Although the ΛN interaction described by current models appears to be reasonably well understood when experimental and theoretical structure studies of Λ-hypernuclei are examined and compared, some obvious puzzles remain, such as the charge symmetry breaking (CSB) in the ΛN interaction.

New high precision mass spectroscopy on the binding energy of the 0^+ ground state of ${}^4_\Lambda H$ [7] and the energy of the γ transition between the 1^+ first excited state and 0^+ ground state of ${}^4_\Lambda He$ [8] now determine a Λ separation energy difference between the ground states of ${}^4_\Lambda H$ and ${}^4_\Lambda He$ to be 0.27 ± 0.06 MeV. With the Coulomb effect expected to be at level of ~0.05 MeV, CSB in ΛN interaction suggested by the pair of A = 4 hypernuclei is surprisingly several times that of the smaller CSB in the ${}^3H$ and ${}^3He$ pair due to the NN interaction. Its origin is unknown. Obviously, any opportunity for an experimental determination of the low-energy properties of ΛN interaction will be extremely valuable, especially in the case of the unmeasured Λn interaction.

B. A neutral three-body Λnn system - ${}^3_\Lambda n$

A recent experiment (HypHI at GSI) studied the data collected from the reaction of ${}^6Li$ projectiles at 2A GeV on a fixed graphite (${}^{12}C$) target for the invariant mass distributions of $d + \pi^-$ and $t + \pi^-$ [9], considered to be from weak decays of few-body (A = 2 and 3) hypernuclei produced by heavy ion collisions. The estimated mean values of the invariant mass of $d + \pi^-$ and $t + \pi^-$ systems were reported to be 2059.3 ± 1.3 ± 1.7 MeV/c^2 and 2993.7 ± 1.3 ± 0.6 MeV/c^2, respectively. Their lifetimes were estimated to be $181\,{}^{+30}_{-24} \pm 25$ ps and $190\,{}^{+47}_{-35} \pm 36$ ps, respectively, significantly shorter than the lifetime of a free Λ (~260 ps). These final states were interpreted as the two-body and three-body decay modes of a bound 3-body hypernucleus, thus suggesting a possible observation of a bound neutral ${}^3_\Lambda n$ system. Note that the identical method of analysis was successfully applied in the case of the Λ, ${}^3_\Lambda H$, and ${}^4_\Lambda H$ [10].

Subsequently, several theoretical analyses concluded that such a bound state cannot exist [11-13] based upon our current understanding of the ΛN interaction. This is because of the fact that the hypertriton (${}^3_\Lambda H$) is a barely bound $T = 0$ state [$B_\Lambda({}^3_\Lambda H) = 0.13 \pm 0.05$ MeV], while a Λnn state should be a $T = 1$ system. Changing from the $T = 0$ state to the $T = 1$ state, the (${}^3S_1 - {}^3D_1$) np interaction, that supports a bound deuteron state, would be replaced by the ${}^1S_0$ nn interaction that yields an unbound *di-neutron* state.

The contradiction between the experimental suggestion and the theoretical analyses raises the question of to what extent do we understand the ΛN interaction. Although current theoretical models can reasonably well interpret the basic nature of the so far experimentally observed spectroscopy of Λ hypernuclei (except this ${}^3_\Lambda n$ system), the properties of the Λp interaction rely on very sparse Λp scattering data from early bubble chamber experiments with no Λn scattering data existing at all. The Λn interaction is assumed to be identical to the Λp interaction with no CSB as concluded from the NN interaction (*i.e.*, the nucleon separation energy between the ${}^3H$ and ${}^3He$ systems with Coulomb correction). However, new high precision data on ${}^4_\Lambda H$ and ${}^4_\Lambda He$ [7, 8] have established that CSB in the case of the ΛN interaction is indeed quite significant, at a level of ~270 keV. Although CSB within the A = 4 system was recently revisited in a calculation including Λ-Σ coupling [14] that claims good agreement with the experimental results, the contradiction with regard to a bound ${}^3_\Lambda n$ system remains, *i.e.* no theory supports a bound ${}^3_\Lambda n$.

C. The *Λnn* resonance and the *Λn* interaction

The questions are then "can a physical resonance exist" and "can such a *Λnn* resonance provide clear clues about the *Λn* interaction" for which we do have no experimental data? Recently, a theoretical investigation took an alternative approach, aiming to answer these questions. It looked into the possibility of the existence of a *Λnn* three-body resonance and how it relates specifically to the *Λn* interaction [15]. The conclusion is that an experimental observation of this resonance with good precision can provide a valuable resource to determine properties of the *Λn* interaction with rigorous constraints.

In this theoretical investigation, the authors used pairwise interactions of rank one, separable form that fit effective range parameters of the *nn* system (for which experimental data exist) and those predicted for the yet-to-be-observed *Λn* system by two different Nijmegen one-boson exchange potentials [16, 17], the Jülich one-boson exchange potential [18], and a chiral *ΛN* potential [19] based upon the currently existing *Λp* scattering data. The use of rank-one separable potentials allowed the authors to analytically continue the *Λnn* Faddeev equations into the second complex energy (*E*) plane in search of resonance poles, by examining the eigenvalue spectrum of the kernel of the Faddeev equations (see detailed discussion on the rank one *S*-wave separable potentials in Ref. 15). Consistency was checked by comparing the result of the code with those of the authors' previous investigation of the hypertriton ($^3_\Lambda H$) binding energy. In both cases, no *Λ-Σ* coupling and *ΛNN* three-body interactions were included.

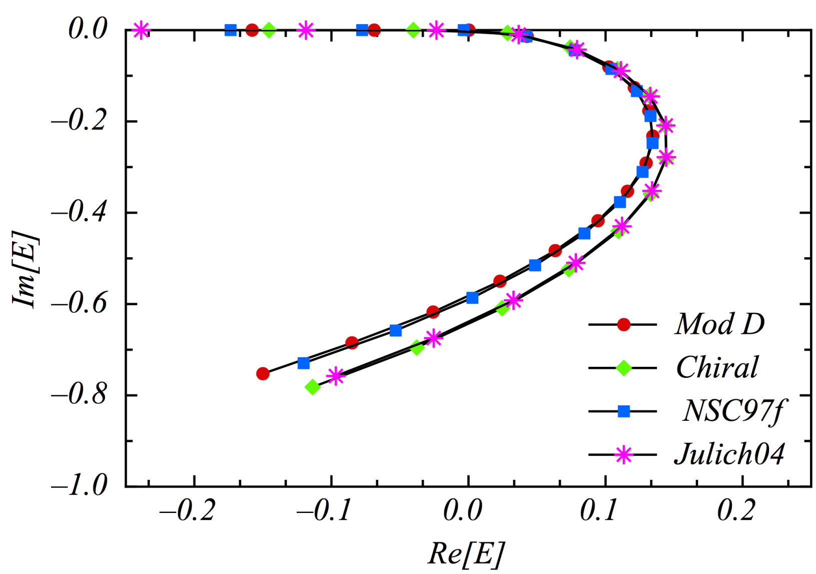

Figure 1. Trajectory of the resonance pole as one varies only the strength of the *Λn* interaction by a scaling factor "*s*" with a *Δs* = 0.025 (2.5%) increment for the four different *ΛN* potentials which fit the *Λp* scattering data and with the same fitted *nn* potential [Fig. 2 in Ref. 15]. The energy scale is in MeV.

With the above four *ΛN* potentials that assumed *Λn* = *Λp*, the results showed consistently no physical resonance; instead each produced a sub-threshold resonance with

$R(E) < 0$, which lies just below the Λnn breakup threshold. Since this sub-threshold resonance appears so close to the threshold, the interesting question became how easy would it be to convert this pole into a physical resonance. To explore this question a scaling factor "s" ($s = 1.0 + \Delta s$) was applied to the strength of the Λn potential in both the $^1S_0$ and $^3S_1$ Λn channels with the increment Δs starting from 0 and increasing in steps of 0.025 (2.5%). The continuous incrementing of the scaling factor forms trajectories of resonance pole in the complex energy E plane using the four different ΛN potentials (with the Λp and nn potentials remaining fixed as they were fitted to the scattering data), as shown in Fig. 1 (from Fig.2 in Ref 15).

The path of these trajectories start from the lower left with $\Delta s = 0.0$. All four current ΛN potentials indicate a sub-threshold resonance with $R(E) < 0$ and no bound state with $Im(E) < 0$ for the Λnn system. Following the path, however, it was found that the sub-threshold pole turns first into a real physical unbound Λnn resonance with as little as a 5% increase in the Λn potential for all four models, and then into a bound state that requires a change of at least 25%.

This means that a resonance possibility for the Λnn system certainly lies well within the uncertainties of the observed Λp scattering data. In contrast the existence of a bound state would seem to be ruled out by Λp scattering data unless there exists a sizable charge symmetry breaking well beyond the uncertainties in the Λp scattering length and effective range. On the other hand, this resonance pole investigation suggests that one may use the Λnn system as a tool to examine the strength of the Λn interaction while constraining the Λp interaction within the uncertainties of the Λp scattering data.

D. Uniqueness for a JLab experiment in determining the Λn interaction

The low energy properties of the Λn interaction cannot be determined without Λn scattering data or experimental data that can at least provide a rigorous constraint on its properties. This unfortunate situation will last forever without a Λ beam and a pure neutron target.

There exist some other possible experiments but each has its difficulty. One example is the consideration of producing a Λn system from a D target using either (K^-, π^0), ($e,e'K^+$), or (γ,K^+) reactions. A Λn system is clearly unbound and the hope would be to model the final-state interaction (*FSI*) to extract the properties of the Λn interaction. Actually, in this type of analysis it is very difficult to obtain unambiguous results because of the strong model dependence due to there being three strongly interacting particles in the final state. Another suggestion is an experiment using the (K^-_{stop}, γ) reaction to obtain a *FSI* for only the Λn system. Model dependence will be much less severe. However, the difficulty lies in detecting a γ with energy of ~300 MeV and needing a resolution of better than 1%. Such a detector system requires funds in the millions of dollars. It appears unrealistic.

Because the HypHI experiment suggested a state of the Λnn system was observed, regardless of whether it is a bound state or an unbound resonance state, its binding energy should likely be within ~ ±1 MeV around the three-body threshold. The above-presented theoretical study shows that it is highly likely to be an unbound resonance. It can be easily produced by the ($e,e'K^+$) reaction with a tritium (^3H) target and with good precision utilizing the JLab beam and experimental conditions. It has clear and clean advantages over the other possibilities to obtain the *Λn* interaction.

For a resonance, the *Λnn* system is a pure $T = 1$ three-body system which is dominated by the *Λn* and *nn* interactions, while the *nn* interaction can be modeled in terms of existing experimental data. The influence from the *FSI* involving the K^+ will be rather minor but calculable even though some level of model dependence exists. Therefore, with this data available, investigating the *Λnn* final state (resonance or sub-threshold resonance) is feasible; modeling the position and shape of the spectrum, taking into account the possible CSB in the *ΛN* interaction, would provide significant constraints on the scattering length and effective range of the heretofore un-measured *Λn* interaction.

The opportunity is thus so unique, only for an experiment at JLab, because of the achievable energy resolution (a few MeV FWHM) and precision (~ ±100-200keV) in determination of the binding energy. There already exist four approved Hall A experiments (E12-10-103, E12-11-112, E12-14-109, and E12-14-011) which will share a common tritium target, as well as other gas targets such as H_2, D_2, and ^3He for different physics. The tritium target will be available just at the beginning of the first tritium target experiment then remain in the target chamber until completion of all four experiments within a one-year limit. The four experiments will all use the same Hall A HRS spectrometers but with different kinematic configurations and beam energy. Under the current scheduling consideration, the three single arm experiments will run in the beginning of the schedule, while the (*e,e'p*) coincidence experiment will run last.

By carefully examining the running conditions of this (*e,e'p*) coincidence experiment, we have found that using the same beam energy as this last experiment, simply reconfiguring the kinematics by setting the two HRS spectrometers at different angles and momenta, we can reconfigure this experiment into a ($e,e'K^+$) experiment without any additional investment. The switch can be done within a few hours. Although using HRS as a K^+ spectrometer is not ideal, because of the small kaon survival rate that limits the production yield, but with the exceptionally precise characteristics of the entire system as well as the level of cleanliness of the resonance relative to the quasi-free distribution, even a limited number of events obtained in the resonance region can offer a very productive outcome and certainly will be the only experimental data for determination of the *Λn* interaction for decades to come.

II. Experiment and Measurement

E. Experimental configuration

The basic concepts in designing this experiment are (1) utilizing the existing tritium target as well as the other targets for calibration of K^+ production (such as the LH_2 target) and (2) using only the standard Hall A equipment (the HRS system). Only kinematic change is needed and most of the operational and calibration studies should already exist and be helpful through the front running experiments, especially the coincidence experiment E12-14-011. An additional short run on K^+ production with the LH_2 target is to establish K^+ particle identification, calibrate the absolute missing mass, and to obtain the energy resolution (and peak shaping).

The experiment will use the same beam energy, 4.4 GeV (4.524 GeV assumed to include the injector energy), as that used by E12-14-011. Thus, no beam energy change is needed. The HRS(left) used for scattered electrons (*e'*) will be relocated at 12.5° (assumed minimum angle of the spectrometer) and its central momentum will be set for 2.725 GeV/c. This is to maximize the virtual photon flux with the electron arm set at the smallest angle ($|Q^2|$ minimized to ~0.58 GeV^2). The virtual photons ($W = E - E'$ = 1.8 GeV) will be emitted to the right at a central angle of 17.5° with respect to the beam axis. The kinematics (experimental configuration) is summarized in Table 1.

Table 1. Kinematic configuration of the proposed experiment

Electron beam energy (2-passes, 2.2 GeV per pass)	4.524 GeV
e' HRS central momentum (acceptance)	2.725 GeV/c (±4.5%)
e' HRS central angle (acceptance)	12.5° (6 msr)
K^+ HRS central momentum (acceptance)	1.5 GeV/c (±4.5%)
K^+ HRS central angle (acceptance)	17.5° (6 msr)

The HRS(right) used for reaction kaons (K^+) will be set at the virtual photon emission angle, 17.5°, so that $\theta_{\gamma K} = 0°$. At this angle, the momentum transfer to the Λ is minimized (~450 MeV/c) to maximize the Λ "sticking" probability to the nn system, *i.e.* maximizing the production cross section (or yield) of the Λnn system.

This experimental configuration is the same as that of the previously completed Hall C experiment E91-016, when the K^+ production from a ^3He target was measured at $\theta_{\gamma K} =$ 0°, except a 3.245 GeV beam was used by E91-016 with HMS for *e'* at 15° and SOS for K^+ at 13.33°. The physics outcome will be different. What E91-016 produced in the Λ production region at this kinematics point was a mixture of $T = 0$ Λd two-body plus Λpn three-body and $T = 1$ Λpn three-body systems. The measured production was mainly the quasi-free production, since the bound $^3_\Lambda H$ state is too close to the Λ break-up threshold (B_Λ was measured to be only *~0.13 MeV*); thus, its cross section is too small (due to large momentum transfer to Λ) for E91-016 to see. Furthermore, without a real resonance, the overall strength of the FSI for the $T = 0$ Λd two-body plus Λpn three-body and $T = 1$ Λpn three-body systems is weak (the thresholds are slightly different for the two-body and three-body systems). In addition, the energy resolution was only of the order of ~4-5 MeV; thus, the limited number of events showing FSI effects were simply smeared near and above the threshold region.

The quasi-free $T = 1$ Λnn three-body system produced by the $^3H(e,e'K^+)$ reaction from the proposed experiment is basically the same as the $T = 1$ Λpn three-body system by the $^3He(e,e'K^+)$ reaction from E91-016. However, a Λnn system is pure and has no mixing of the $T = 0$ channels, so that calculation of the FSI is significantly easier. On the other hand, for a real resonance close to the threshold, its strength will be significantly stronger than that of final states without a resonance. It will be much easier to observe a peak-like structure within the ~ ±2.0 MeV region around the three-body break-up threshold. The resonance will be dominated by *Λn and nn* interactions while the FSI involving K^+ will not have as strong an influence as in the non-resonance cases. Overall, the spectroscopy of Λnn around a narrow threshold region should be much cleaner and simpler.

The only extra equipment requirement for this experiment is installation of the existing aerogel Čerenkov detector into the HRS spectrometer that will be used for hadrons at least before the (*e, e'p*) tritium experiment. This is to add π^+ online rejection capability. In offline analyses, K^+ is relatively easy to be separated from π^+ and p using our standard technique (combining TOF, coincidence time, Čerenkov and *dE/dx*).

F. Yield estimation

F.1 Quasi-free Λ production from E91-016 with $^3He(e,e'K^+)$ reaction

Figure 2 shows the measured missing mass spectrum obtained by E91-016 at the kinematic point with $\theta_{\gamma K} = 0°$ [20]. With the measured quantities and known parameters from E91-016, the yield-estimate using Λ photoproduction cross section can be verified for consistency. Details are presented in the next sub-section.

The yield of quasi-free Λ is estimated to be 0.7 counts/sec or 2.5×10^3 /hour. The total number of quasi-free Λ was extracted to be ~86,000 in the spectrum after excluding Σ^0 and Σ^-, as well as the accidental background [20]. It means this spectrum was obtained in ~34 hours of running time with average beam current of 25 μA. The yield rate estimate made by using the Λ photoproduction cross section is only slightly under estimated (<10%). It is sufficient for the purpose of this proposal.

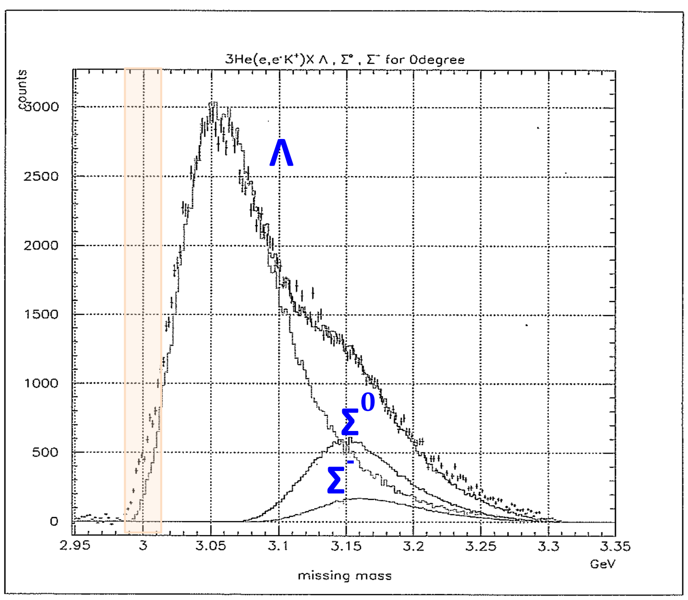

Figure 2. Missing mass spectrum obtained by E91-016 from the ^{3}He target at the kinematic point with $\theta_{\gamma K} = 0°$. The Λ, Σ^0, and Σ^- quasi-free distributions were simulated by SIMC using an Atti spectral function. The solid lines are scaled simulation and sum [20].

In addition, the number of events that contain the enhancement over the quasi-free distribution at the threshold region due to the FSI can also be estimated from this measured spectrum. In case of the ^3He target, there are two Λ thresholds, at 2.9913 GeV for the Λd two-body system and 2.9935 GeV for the Λpn three-body system and their average is at 2.9925 GeV. The energy resolution for E91-016 is ~5 MeV FWHM. Therefore, the FSI enhancement can be smeared to about 30 MeV wide around the averaged threshold. The cross section of $^3_\Lambda H$ ground state is very small and locates almost right at the threshold. A ~30 MeV shaded area in Fig. 2 illustrates the considered region for FSI enhancement plus small contribution of $^3_\Lambda H$ ground state. The SIMC simulation made by using an Atti spectral function estimates the missing mass distribution of the Λ quasi-free. The extra events distributed above this quasi-free distribution were considered to be from FSI enhancement. Counting only within the shaded region, the number of events is ~2600, which is ~3.0% of the overall Λ production. In case of the ^3H target, both FSI and Λ quasi-free contain only T = 1 channel so that the ratio (3%) remains the same.

F.2 Quasi-free Λ production estimation with $^3H(e,e'K^+)$ reaction for the proposed experiment

The following shows the yield estimation using the same method and the known Λ photoproduction cross section.

Beam energy (E): 4.5238 GeV;
Scattered e' (E'): 2.725 GeV (±4.5% with HRS)
Scattering angle ($\theta_{e'}$): 12.5° (acceptance: $\Delta\Omega_{e'}$ = 6 msr with HRS)
Beam current: 20 μA (i.e. $20 \times 6.24 \times 10^{12} = 1.25 \times 10^{14}$ e/s)
Integrated virtual photon flux: $N\gamma = 9.47 \times 10^{-6}$ γ/e × 1.25×10^{14} e/s = 1.18×10^{9} γ/s
Target: ^3H (T_2 gas) (A = 6 and N_p = 2 per molecule); Target length (d): 25 cm
Target density (ρ): 0.0033 g/cm^3; Mass thickness (t): 0.083 g/cm^2

Number of scattering centers (protons) per cm^2:

$$N_{target} = \frac{t}{A} N_A \bullet N_p = \frac{0.083\ [g/cm^2]}{6.0\ [g/mol]} \times 6.022 \times 10^{23}\ [/mol] \times 2 = 1.67 \times 10^{22}\ [/\mathrm{cm}^2]$$

Assumed photoproduction cross section: $\dfrac{d\sigma_\gamma}{d\Omega_k} \approx 0.390$ [μb/sr] = 3.9×10^{-31} cm^2/sr

K^+ momentum (P_K): 1.50 GeV/c (±4.5% with HRS)
K^+ angle ($\theta_{\gamma K} = 0°$): 17.5° (acceptance: $\Delta\Omega_K$ = 6 msr with HRS)
K^+ survival rate (path length of 24 m): ~12%
K^+ detection efficiency: ~80%
K^+ combined efficiency ε_k: ~0.10 (10%)

Thus, the Λ production rate is:

$$N_\Lambda = N\gamma \times N_{target} \times \frac{d\sigma_\gamma}{d\Omega_k} \times \Delta\Omega_K \times \varepsilon_k$$
$$= 1.18 \times 10^{9}\ [\gamma/s] \times 1.67 \times 10^{22}\ [/\mathrm{cm}^2] \times 3.9 \times 10^{-31}\ [\mathrm{cm}^2] \times 0.006\ [\mathrm{Sr}] \times 0.10$$
$$\approx \mathbf{0.00461\ /sec} \text{ or } \approx \mathbf{16.6\ /hour}$$

Under the assumption of a minimum data collection time of 5 PAC days, the total number of Λ in the quasi-free production will be ~2000 counts. The shape of the Λ part (as well as the Σ^0 part) of quasi-free distribution will be similar to that shown in Fig. 2, except the Σ^- quasi-free production from neutrons is expected to be enhanced by a factor of 2 relatively. Statistically, it is like the vertical scale of the distribution in Fig. 2 being reduced by a factor of ~44, while the Σ^- quasi-free is twice higher.

F.3 <u>Yield of the Λnn resonance</u>

Since *Λnn* system is a pure $T = 1$ three-body system without additional structures, significant strength should be pulled into this single resonance from the entire effective region for FSI. It is thus expected that the number of events in the resonance should be ~3% (or more) of the quasi-free Λ production estimated previously in section ***F.1***. If one assumes 3% to be the minimum, the minimum number of events in the resonance will be ~**60** counts for the data collection time of 5 PAC days. This minimum is certainly a small number. However, energy resolution, peak location in the spectrum, and the accidental background will play key roles in extracting important information from analysis of this resonance when the obtained statistics is limited.

III. Expected Result, Uncertainties, and Beam Time Request

G. Simulation for expected result

Since the missing mass distribution of quasi-free Λ production is basically known and the resonance is expected to locate very close to the Λ separation threshold, the expected result can be simulated to study the significance, uncertainty, and thus the needed beam time.

The simulation assumed: (1) an energy resolution of 2.0 MeV (FWHM) and (2) resonance is simplified with a Gaussian distribution and locates at $B_\Lambda = 0.5$ MeV with a natural width of 0.5 MeV (FWHM). SIMC with the Atti spectrual function was used to generate the *Λnn three-body* quasi-free distribution with desired statistics. Since Σ production ($B_\Lambda > 76$ MeV) has no influence to the resonance peak but only the K^+ singles rate, it was ignored in the simulation. Using the E91-016 accidental rate, taking into account the new 4ns beam pulse separation and singles rate reduction due to smaller acceptance of the HRS spectrometers and lower K^+ survival rate, the maximum accidental background rate was entered in the simulation. Due to much thinner target thickness, the real accidental rate should be actually lower than that was assumed.

Figure 3 shows the expected spectroscopy for two difference statistics: (a) running time of 5-PAC days as previously discussed, i.e. 2000 events for the Λ quasi-free and 60 events (3%) for the resonance; and (b) running time of 10-PAC days with 4000 events for the Λ quasi-free and 120 events for the resonance. The peak significance for 5-PAC days is ~6σ while for 10-PAC days it is > 8σ. A data collection with 5-PAC days appears to be sufficient to at least identify the resonance clearly.

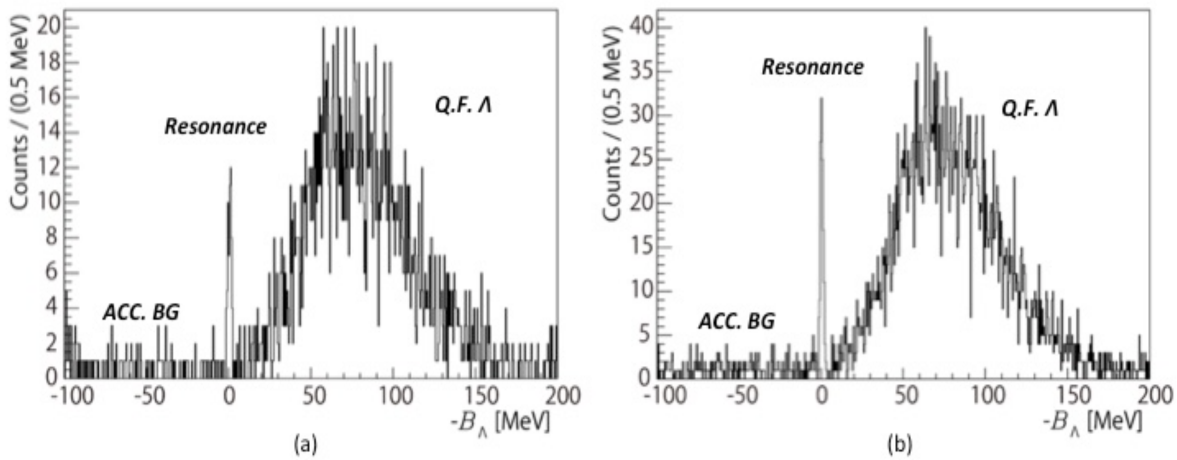

Figure 3. Simulated spectroscopy that contains the *Λnn* resonance and the *Λ* quasi-free production only with two different statistics: (a) 2000 events for the *Λ* quasi-free and 60 for the resonance and (b) 4000 events for the *Λ* quasi-free and 120 for the resonance. The resonance is assumed to locate at $B_\Lambda = 0.5$ MeV with a natural width of 0.5 MeV (FWHM) and experimental resolution of 2 MeV (FWHM).

H. Uncertainties

However, the statistical uncertainty for determination of the binding energy (or excitation energy) of the *Λnn* resonance (B_Λ) and its natural width should be the main concern. Thus, a few sets of independent dummy data were generated and were fitted with a Gaussian function for the resonance peak, simply with a polynomial function for the *Λ* quasi-free, and the known accidental background function (which can be typically obtained precisely with high statistics using mixing-events analysis technique). The uncertainty was then examinated by comparison bewteen the fitted and given values.

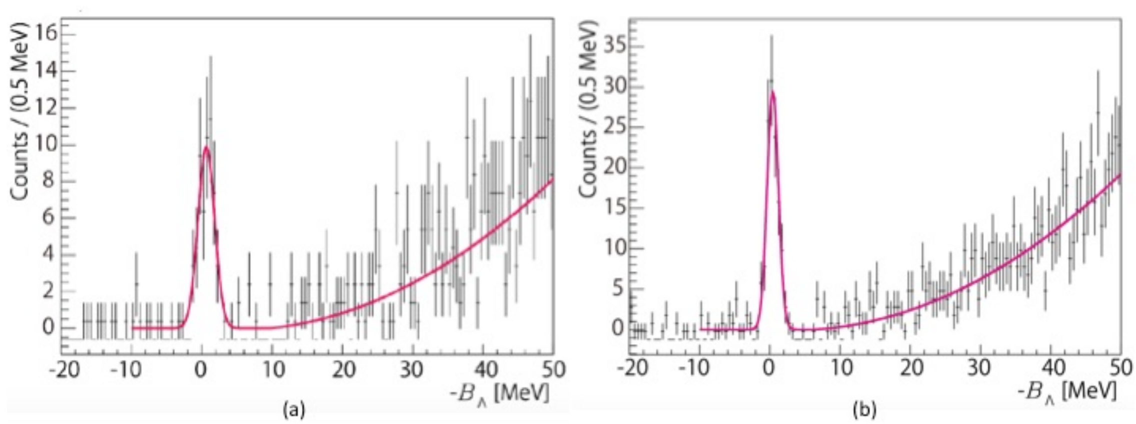

Figure 4. Example of fitting the dummy data with two different statistics: (a) 2000 events for the *Λ* quasi-free and 60 for the resonance and (b) 4000 events for the *Λ* quasi-free and 120 for the resonance. The resonance is assumed to locate at $B_\Lambda = 0.5$ MeV with a natural width of 0.5 MeV (FWHM) and experimental resolution of 2 MeV (FWHM).

Figure 4 shows examples of the spectroscopy fitting with simplified functions and two different statistics (5-PAC days and 10-PAC days). Result of these two fitting studies is shown in Table 2 for comparison. Uncertainties are improved significantly for number of events in the resonance increased from 60 to 120.

Table 2. Statistical uncertainties for the fitted parameters, binding energy B_Λ, peak width σ, and number of events N, in the resonance with two different statistics.

Statistics vs parameters	$-B_\Lambda$ (MeV)	Width σ (MeV)	Number of events
5-PAC days (Given value)	0.71 ± 0.18 (0.5)	0.95 ± 0.20 (0.875)	53 ± 16 (56)
10-PAC days (Given value)	0.43 ± 0.09 (0.5)	0.81 ± 0.07 (0.875)	118 ± 18 (120)

Studies were also done for further increased beam time, up to 16-PAC days. It showed that further improvement of the uncertainty for the fitted binding energy B_Λ and width becomes small (δB_Λ from ±0.090 MeV to ±0.073 MeV and $\delta\sigma$ from ±0.07 MeV to ±0.06 MeV for beam time from 10-PAC days to 16-PAC days). The turning point for the significance of uncertainty improvement appears around 10-PAC days.

The systematic uncertainty for binding energy B_Λ and width of resonance depends on the calibration using H_2 target and production *of* Λ and Σ^0 whose masses are known. This calibration is critical and is the same technique used by the HKS experiment to obtain ≤ ±0.07 MeV systematic uncertainty for binding energy B_Λ [21]. The peak shape and width of Λ and Σ^0 will be used to obtain the energy resolution and radiative tail effect to the Gaussian shape in order to extract the natural width of the resonance with a systematic uncertainty ≤ ±0.06 MeV. This systematic uncertainty depends on the statistics of Λ and Σ^0.

The H_2 gas target (with identical cell geometry) to be used by the approved tritium experiments has a density of 2.75 μg/cm^3 and 68.8 mg/cm^2 thickness. Assuming the same beam current (20 μA), the same calculation as in previous section ***F.2*** (with A = 2 and N_p = 2 per molecule) results **42**/hour yield rate for Λ. 2000 events of Λ can be obtained in 2-PAC days while there will be ~300-400 events for Σ^0. This is the needed statistics to ensure the above systematic uncertainties for the binding energy and width of the Λnn resonance.

J. Beam time request

The required beam time impacts the unertainty of the scaling factor "Δs" for the Λn interaction in the resonance pole search from the uncertainty of B_Λ (*Re[E]*) and width (*Im[E]*) of the resonance measurement. To illustrate this, uncertainty boxes are drawn onto the resonance pole trajectory figure at arbitrary points with two different statistics assumptions, as shown in Fig. 5.

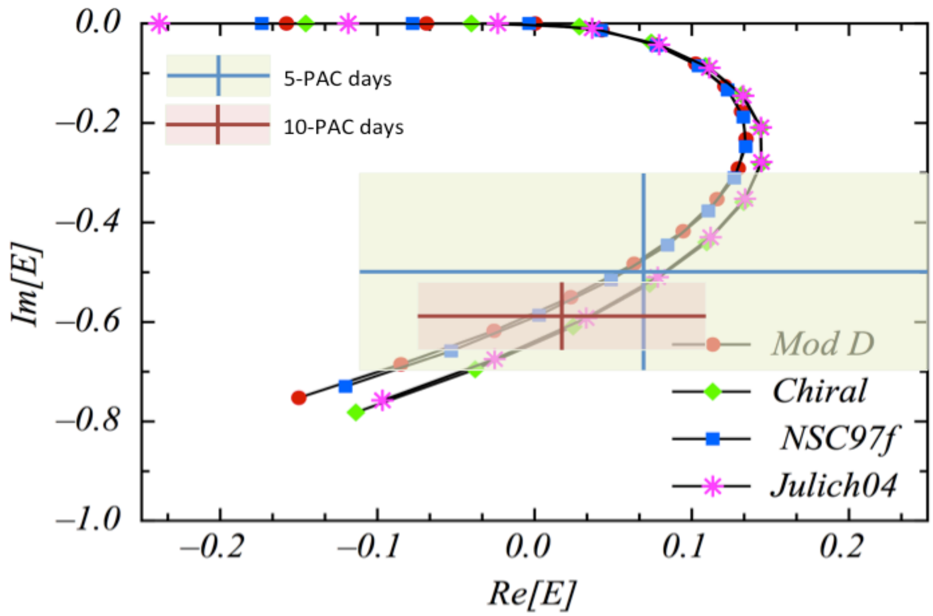

Figure 5. Illustration of the impact to the pole search scaling factor "Δs" by the uncertainty size with the two different statistics assumptions.

It should be emphasized that control of the uncertainty size is not primarily aiming to distinguish which of the baryonic interaction models (of the four used in this study) is more correct. It actually impacts the scaling factor "Δs" that is the percentage increase of the Λn interaction strength over the Λp interaction. Under the current assumption of Λp equal to Λn (without CSB), all four models consistently predict that no physical resonance or bound state of Λnn system exists (the lower left four points in Fig. 1 and 5). Depending on the point location measured by the proposed experiment, the uncertainty in "Δs" given by the statistics from 5-PAC days is ~6-8% (better controlled by the width *Im[E]*), while that given by the statistics from 10-PAC days is ~3-4%.

Given that the Λn interaction will be determined by this resonance measurement together with the Λp interaction fitted to the currently existing Λp scattering data and the more precisely and most recently measured CSB (0.27 ± 0.06 MeV), the uncertainty in "Δs" from the statistics of 5-PAC days is just barely compatible to the other two known pieces of information. On the other hand, the statistics of 10-PAC days will give the uncertainty in "Δs" better than the other two, especially the Λp interaction. Since there are efforts to obtain further improved Λp scattering data, a better "Δs" uncertainty would certainly have more of a key impact on the ΛN inetraction, especially when there is no other possibility to obtain actual Λn scattering data at all. Therefore, we make a beam time request based on the minimum and maximum impacts in the determination of the ΛN inetraction, as listed in Table 3. We should point out here that the minimum impact does not mean nothing is determined. The proposed experiment will, for the first time and probably the last time, provide precision experimental data that can be used to determine the Λn interaction. The maximum option is to be preferred in order to minimize the "Δs" uncertainty to almost the lowest level possible from such type of a resonance spectroscopy experiment.

Table 3. Beam time request based on the level of impact on physics

Minimum impact	T_2 run (*Λnn* spectroscopy) H_2 run (Calibration with Λ and Σ^0	5 PAC days 2 PAC days
Maximum impact	T_2 run (*Λnn* spectroscopy) H_2 run (Calibration with Λ and Σ^0	10 PAC days 2 PAC days

IV. Summary

The availability of a T_2 gas target for the four currently approved Hall A experiments provides a unique and the only opportunity for an experiment to measure the *Λnn* three-body resonance. Only at JLab with the $(e,e'K^+)$ reaction, its binding (or excitation) energy and width can be measured with the minimally required precision. With this data, a theoretical resonance pole search technique can be used to determine experimentally for the first time the *Λn* interaction together with the *Λp* scattering and CSB data. Different baryonic models can then be used in calculations of hypernuclear spectroscopy (from few-body to heavy nuclei) and further investigation of the isospin dependence, *ΛNN* three-body force, and the EoS for neutron stars.

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