K.N. Suzuki, T. Gogami et al., Prog. Theor. Exp. Phys. 2022, 013D01 (2022)
DOI: 10.1093/ptep/ptab15

京都大学 KYOTO UNIVERSITY

HYP 2022 PRAGUE

HYP 2022, Czech Republic (2022)
http://rafael.ujf.cas.cz/hyp2022/

Cross-section measurement of virtual photoproduction of iso-triplet three-body hypernucleus, Λnn

T. Gogami [1], K. N. Suzuki [1], B. Pandey [3], K. Itabashi [2], S. Nagao[2], K. Okuyama[2], S. N. Nakamura [2], L. Tang[3,4], D. Abrams[5], T. Akiyama [2], D. Androic [6], K. Aniol [7], C. Ayerbe Gayoso[8], J. Bane [9], S. Barcus[8], J. Barrow [9], V. Bellini [10], H. Bhatt[11], D. Bhetuwal [11], D. Biswas[3], A. Camsonne [4], J. Castellanos[12], J-P. Chen [4], J. Chen[8], S. Covrig[4], D. Chrisman [13,14], R. Cruz-Torres[15], R. Das[16], E. Fuchey [17], K. Gnanvo[5], F. Garibaldi[10,18], T. Gautam[3], J. Gomez [4], P. Gueye [3,13,14], T. J. Hague [19], O. Hansen[4], W. Henry [4], F. Hauenstein [20], D. W. Higinbotham[4], C. E. Hyde [20], M. Kaneta [2], C. Keppel [4], T. Kutz [16], N. Lashley-Colthirst [3], S. Li [21,22], H. Liu[23], J. Mammei [24], P. Markowitz [12], R. E. McClellan [4], F. Meddi [10,25], D. Meekins[4], R. Michaels[4], M. Mihovilovic [26,27,28], A. Moyer[29], D. Nguyen[15,30], M. Nycz [19], V. Owen[8], C. Palatchi [5], S. Park[16], T. Petkovic [6], S. Premathilake [5], P. E. Reimer[31], J. Reinhold [12], S. Riordan[31], V. Rodriguez[32], C. Samanta [33], S. N. Santiesteban [21], B. Sawatzky [4], S. Širca [26,27], K. Slifer[21], T. Su[19], Y. Tian[34], Y. Toyama [2], K. Uehara [2], G. M. Urciuoli [10], D. Votaw [13,14], J. Williamson[35], B. Wojtsekhowski [4], S. A. Wood [4], B. Yale [21], Z. Ye [31], J. Zhang[5], and X. Zheng [5]

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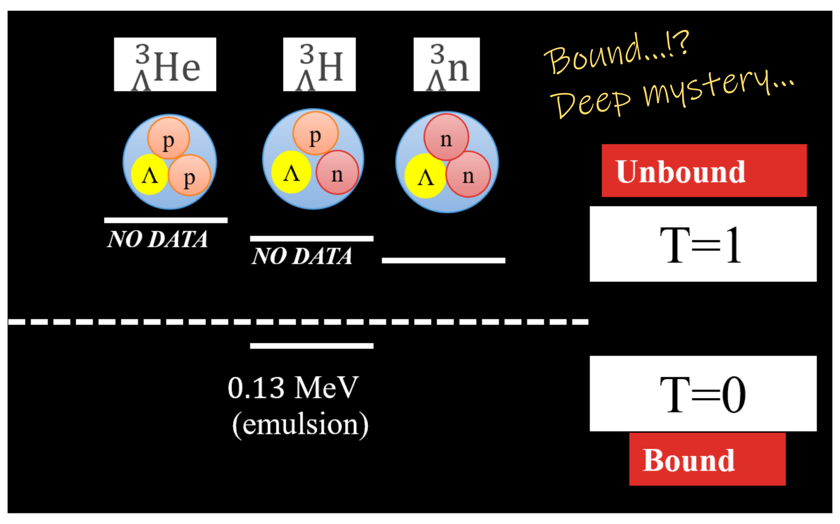
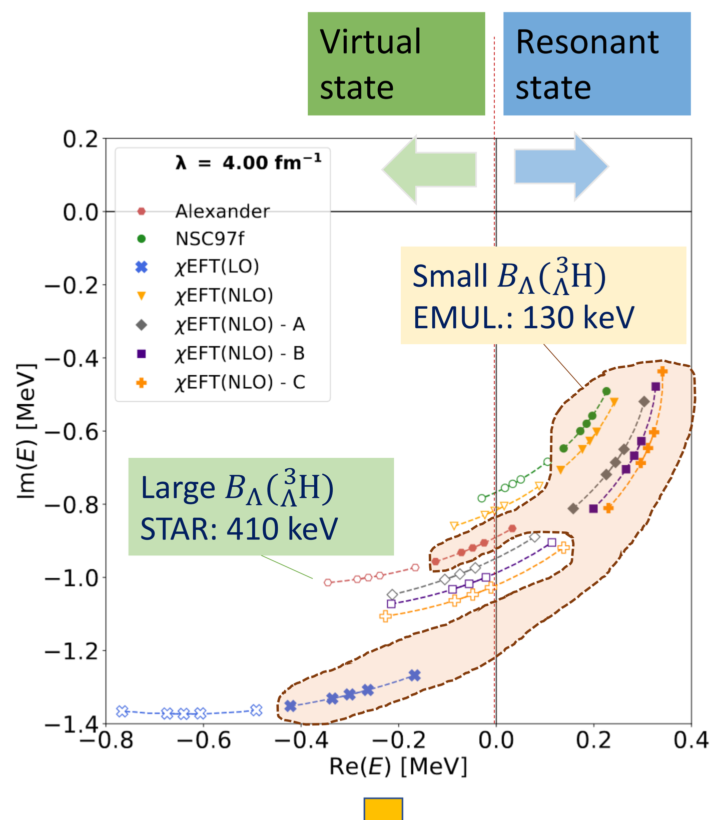
1. Introduction



The Λ binding energy of hypertriton ($^3_\Lambda$H) is small
→ The bound state is difficult to reproduce by theoretical calculations.

But, there found a peak that may be interpreted as the bound state of nnΛ by HypHI Collaboration.

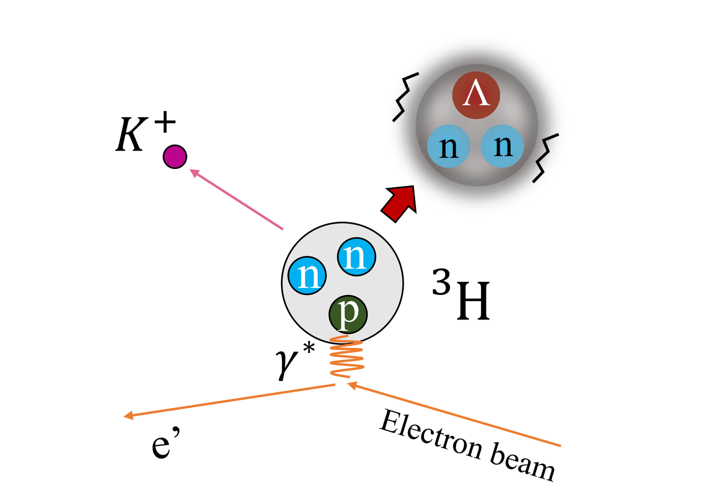
M. Schäfer et al., PRC 105, 015202 (2022)



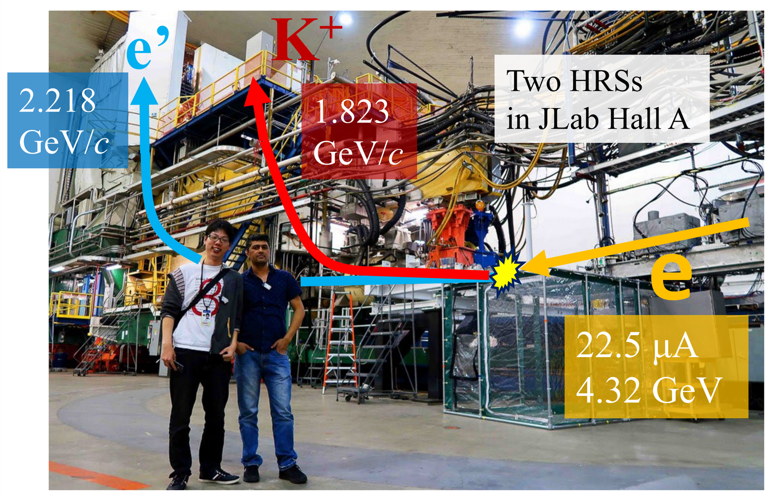
Resonant sate may exist

We tried investigating the Λnn state with a way which has a sensitivity to both resonant and bound states at JLab Hall A in 2018.

2. Experimental setup



- Tritium gas (T_2) gas target was used.
  → **Λnn production**
- Missing-mass method
  → **Sensitivity to both resonant and bound states.**
- High resolution spectrometers (HRSs) were used for e' (HRS-L) and K⁺ (HRS-R) measurements.
  → **~ 3.5 MeV (FWHM) for nnΛ**



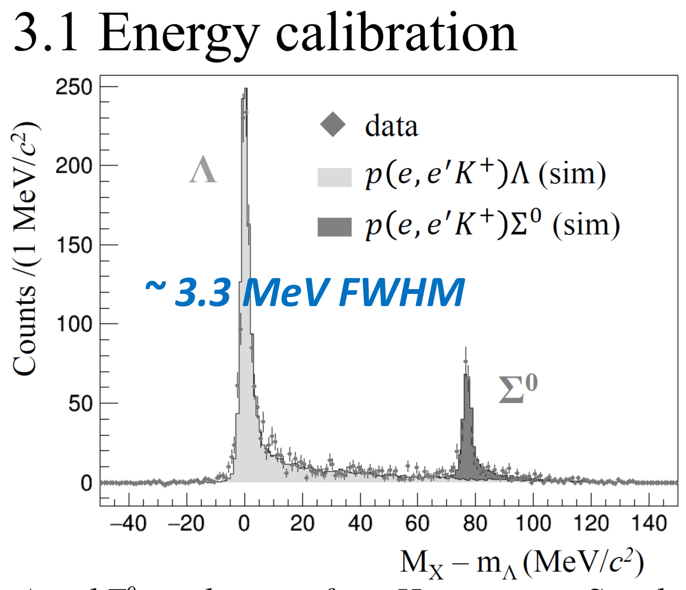
Photograph of HRS at JLab Hall A.

Table: Two momentum settings used for the experiment.

	Calibration mode ($M_{calib.}$)		Physics mode ($M_{phys.}$)
Reaction	$p(e, e'K^+)\Lambda/\Sigma^0$		$p(e, e'K^+)\Lambda$ $^3H(e, e'K^+)nn\Lambda$
$p_{e'}^{cent.}$ (GeV/c)	2.100		2.218
$p_K^{cent.}$ (GeV/c)		1.823	
Q^2 (GeV/c)^2	0.479		0.505
$\theta_{e\gamma}$ (deg)	11.9		13.2
q (GeV/c)	0.497		0.389
$\sqrt{s}$ (GeV)	2.13		2.07
ϵ	0.769		0.794
ϵ_L	0.075		0.092

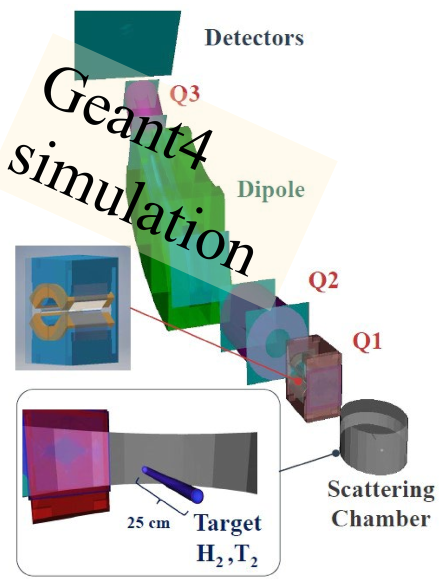
3. Analysis

3.1 Energy calibration



Λ and Σ⁰ productions from H gas target. Simulated spectra are superimposed for comparison.

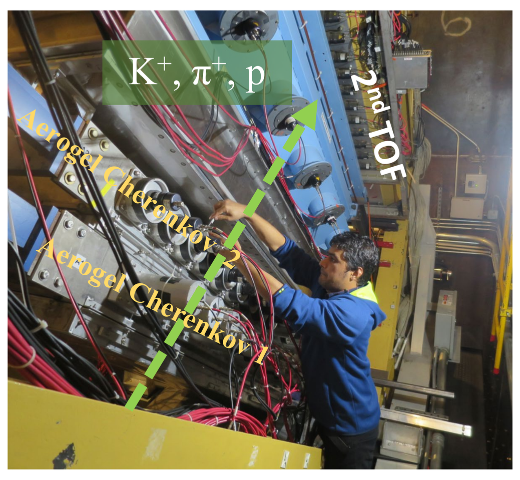
K.N. Suzuki, Ph.D. Thesis (2022)

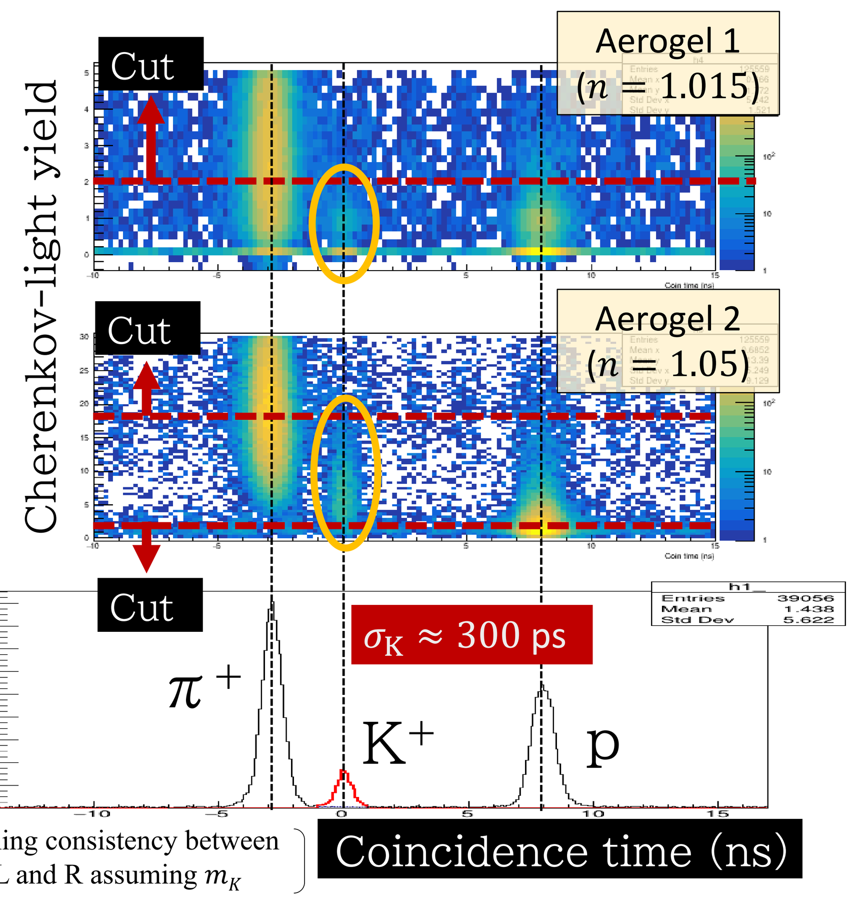


- The energy calibration was performed by using peaks of Λ and Σ⁰ for which the masses are well known.
  → High accuracy: < 0.4 MeV
- The peak shape of Geant4 MC simulation is consistent with the data → The response function (peak shape) is well understood.

3.2 K⁺ identification

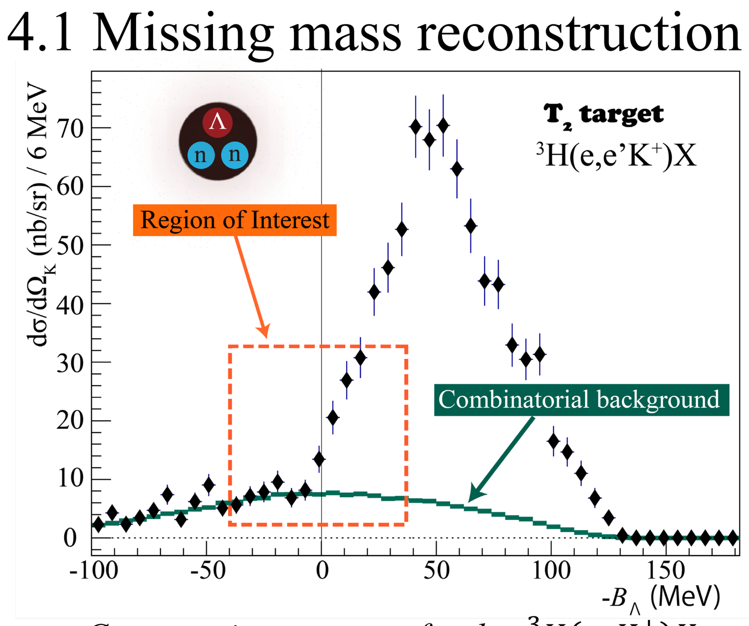
K⁺ needed to be identified from backgrounds in the hadron-arm spectrometer. Protons and pions were the major background sources, and they were rejected by using the analyses of a reaction time (coincidence time) and light yields in the aerogel-Cherenkov counters.





4. Result

4.1 Missing mass reconstruction



Cross section spectrum for the $^3H(\gamma,K^+)X$ reaction as a function of $-B_\Lambda$.

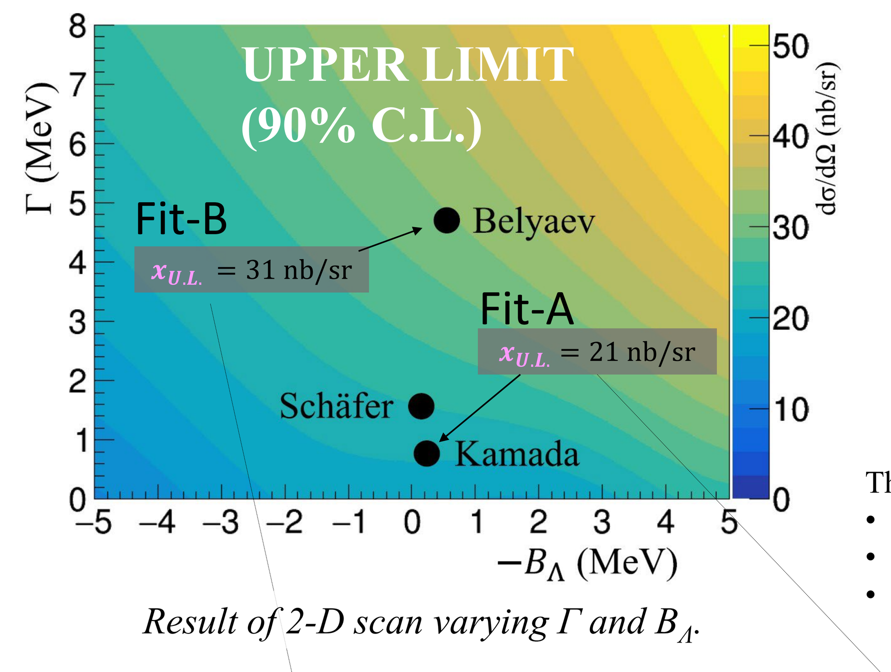
Fitting criteria:

Unbinned maximum likelihood fit
($-20 < B_\Lambda < 20$ MeV)

Probability density function (PDF):

1. Response function (RF)
   - Geant4 simulation
2. Decay width
   - Breit Wigner
3. QF shape ($-B_\Lambda > 0$)
   - Unknown
     → Linear function ⊗ RF
4. Combinatorial background
   - Data → the 4th order polynomial

4.2 Fitting result



Result of 2-D scan varying Γ and B_Λ.

Upper limit $x_{U.L.}$:

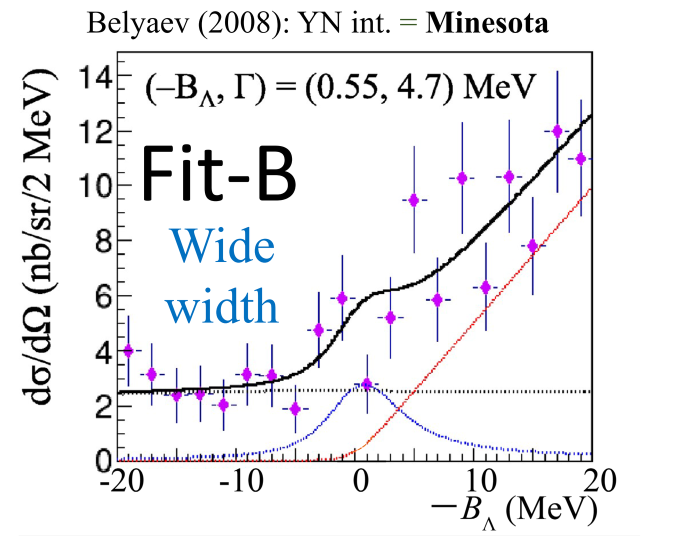
$$\frac{\int_0^{x_{U.L.}^{stat.}} g(x)dx}{\int_0^{\infty} g(x)dx} = 90\%$$

where, $g(x)$ is a Gaus.

$$x_{U.L.} = x_{U.L.}^{stat.} + sys.err.$$

Theoretical predictions (Γ, B_Λ) shown here:
- H. Kamada et al., EPJ Web Conf. 113, 07004 (2016)
- V. B. Belyaev et al., Nucl. Phys. A 803, 210–226 (2008).
- M. Schäfer et al., Phys. Rev. C 103, 025204 (2021).

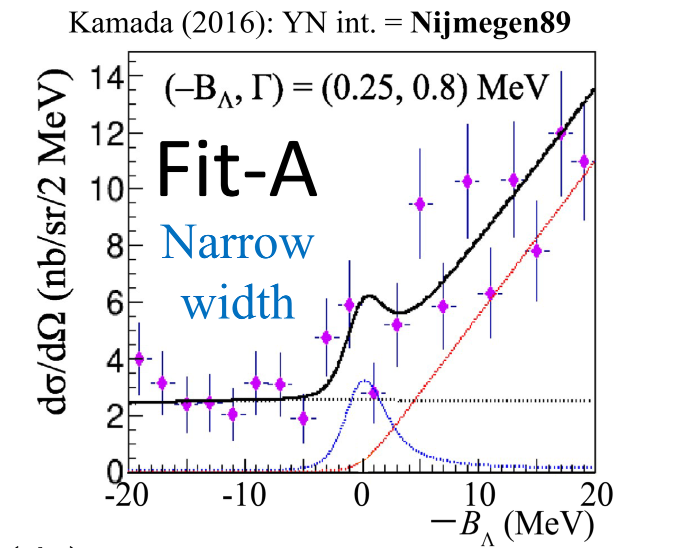
Belyaev (2008): YN int. = **Minesota**



$\left(\frac{d\sigma}{d\Omega_K}\right)_{Fit\,B}$ = **18.1** ± 6.8 (stat.)$^{+4.2}_{-2.9}$ (sys.) nb/sr

2.7 σ (only stat.)

Kamada (2016): YN int. = **Nijmegen89**



$\left(\frac{d\sigma}{d\Omega_K}\right)_{Fit\,A}$ = **11.2** ± 4.8 (stat.)$^{+4.1}_{-2.1}$ (sys.) nb/sr

2.3 σ (only stat.)

- ☐ Information on the reaction-cross section (upper limit) for the electro-production of Λnn was successfully obtained.
- ☐ There are remained events after the expected backgrounds were subtracted, although they are not significant.

5. Summary

- ☐ The Λnn state was investigated by the ^{3}H(e,e'K⁺)X reaction at JLab Hall A to pin down the existence of its bound state.
- ☐ Energy calibration was performed by using Λ and Σ⁰ productions from H_2-gas target.
- ☐ Spectrum of the reaction-production cross-section was successfully obtained
  - ✓ Unbinned MLF fitting → Upper limit for the nnΛ production was obtained.
  - ✓ Some events remained over the backgrounds, although its significance is not so large.
  - → Further study is necessary

Other work:
- Count-base analysis: **B. Pandey, L. Tang et al., Phys. Rev. C 105, L051001 (2022).**
- Final state interaction analysis to study the Λn interaction: **in progress**

Related talks ⇨
- Mon-II: Prof. L. Tang, "Newly completed JLab experiment (E12-17-003): Determine the unknown Λn interaction by investigating the possible Λnn resonance"
- Wed-IVb: B. Pandey, "Analysis of E12-17-003 Experiment"
- Thu-IIIa: Dr. K. Itabashi, "Study of Λ-n FSI with Lambda quasi-free productions on the ^{3}H(e,e'K⁺)X reaction at JLab"
- Thu-IIIa: K. Okuyama, "Study of the Λ/Σ⁰ electroproduction in the low-Q² region at JLab"

JLab E12-19-002 Experiment

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

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HYP 2022 PRAGUE

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T. Gogami [1], P. Achenbach[9], T. Akiyama[2], D. Androic[11], A. Asaturyan[10], E. Brash[14], M. H. Bukhari[18], A. Camsonne[7], S. Covrig Dusa[7], K. Ebata[1], M. A. Elaasar[13], Y. Fujii[8], T. Fujiwara[2], M. Furic[11], F. Garibaldi [3,4], P. Gueye[20], D. W. Higinbotham[7], T. Ishige[2], K. Itabashi[21], M. Kaneta[2], R. Kino[2], N. Lashley[3], P. Markowitz[5], D. Meekins[7], M. Mizuno[2], H. G. Mkrtchyan[10], A. H. Mkrtchyan[10], S. Nagano[2], S. Nagao[2], S. N. Nakamura[21], Y. R. Nakamura[2], G. Niculescu[16], I. Niculescu[16], K. Okuyama[2], B. Pandey[3], J. Pochodzalla[9], J. Reinhold[5], V. M. Rodriguez[12], C. Samanta[17], B. Sawatzky[7], M. H. Shabestari[19], A. Shahinyan[10], S.Sirca[15], K. N. Suzuki[1], K. Tachigana[2], L. Tang [6,7], Y. Toyama[22], K. Tsutsumi[1], K. Uehara[2], E. Umezaki[1], G. M. Urciuoli [3], D. Watanabe[2], and S. A. Wood[7]

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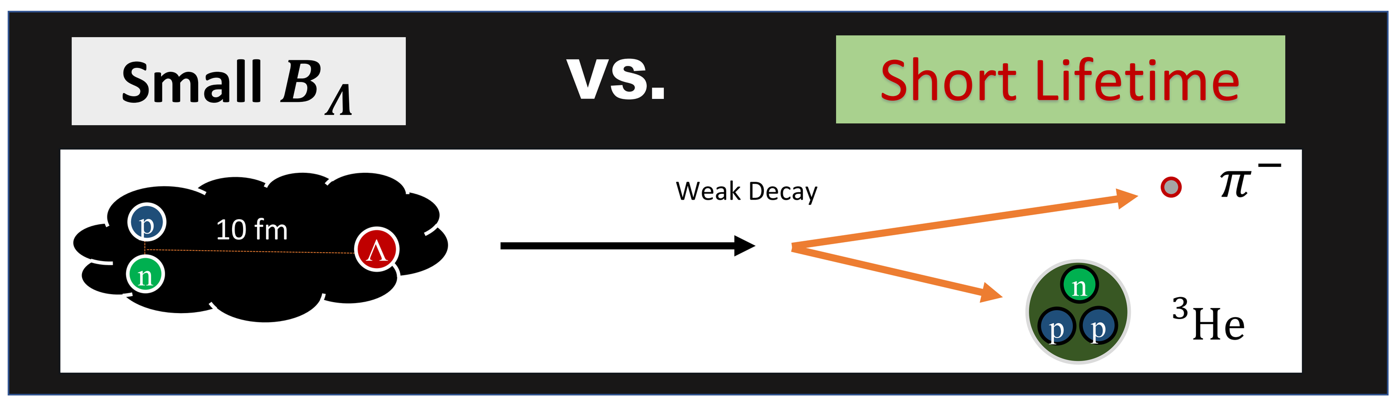
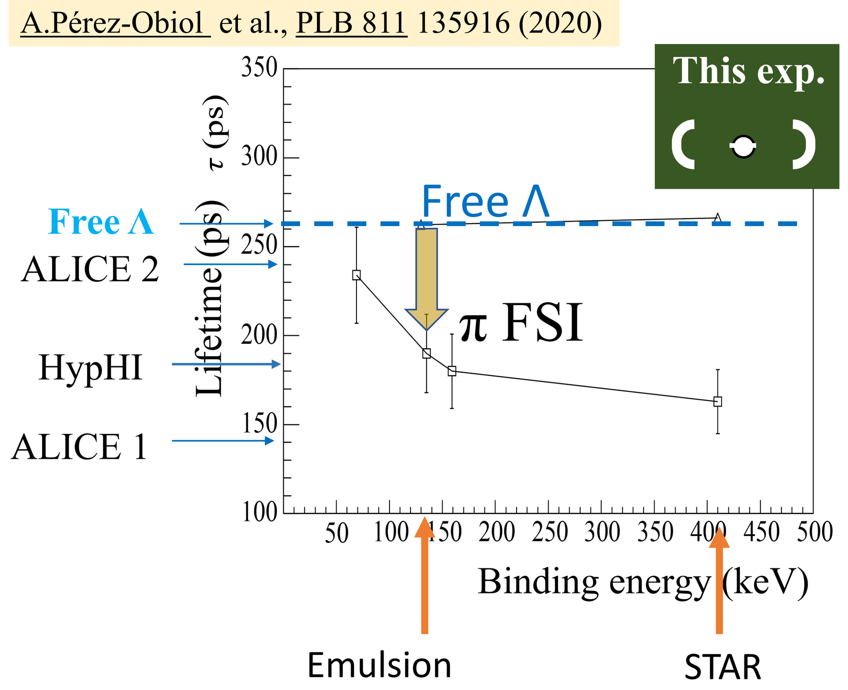
1. Introduction

1.1 Hypertriton ($^3_\Lambda$H) puzzle

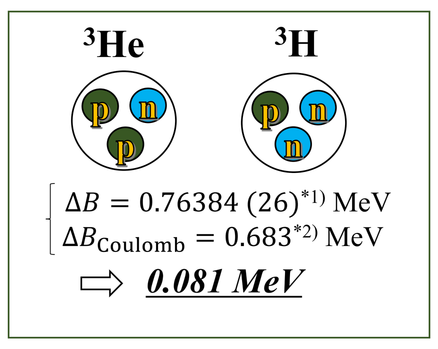


A.Pérez-Obiol et al., PLB 811 135916 (2020)



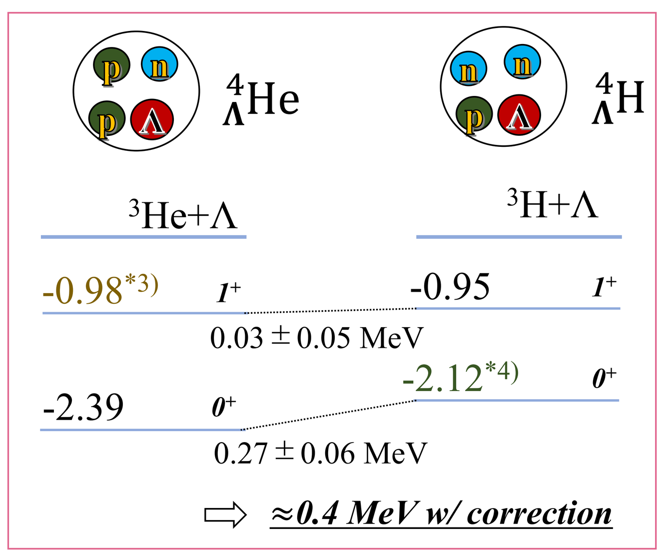
- The contradiction between small binding energy B_Λ and the short lifetime is called “Hypertriton Puzzle”
- Accurate data for both the binding energy and lifetime are being tried to be obtained in various experimental facilities

1.2 Charge Symmetry Breaking (CSB) in A = 4 system



*1) J.H.E.Mattauch et al., Nucl. Pys. 67, 1 (1965).

*2) R.A.Brandenburg, S.A.Coon et al., NPA294, 305 (1978).



- Five times larger effect
- Spin dependent

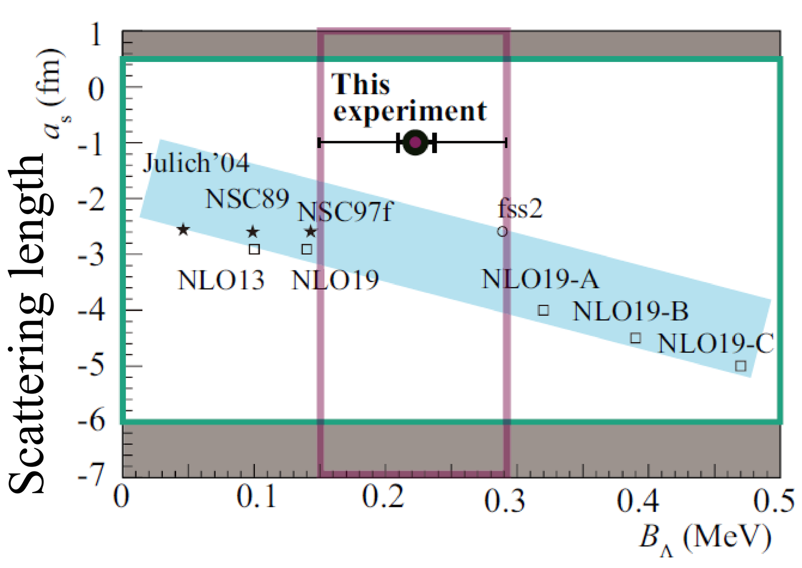
- The binding energies in the A = 4 system is a fundamental information for the CSB discussion.

*3) T. O. Yamamoto et al. (J-PARC E13 Collaboration), Phys. Rev. Lett. 115, 222501 (2015)

*4) A. Esser et al. (A1 Collaboration), Phys. Rev. Lett. 114, 232501 (2015).

2. Goal of the experiment

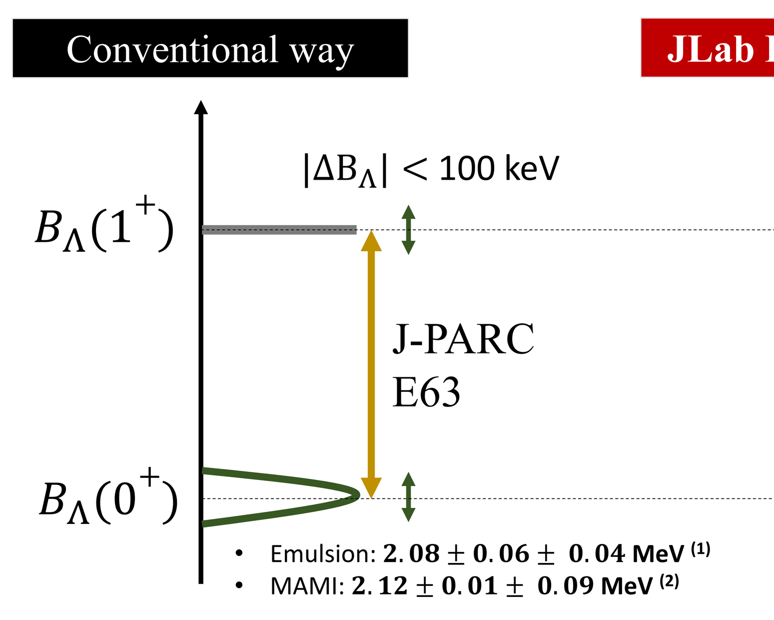
2.1 $B_\Lambda(^3_\Lambda\mathrm{H};\, 1/2^+\ \mathrm{or}\ 3/2^+)$ measurement



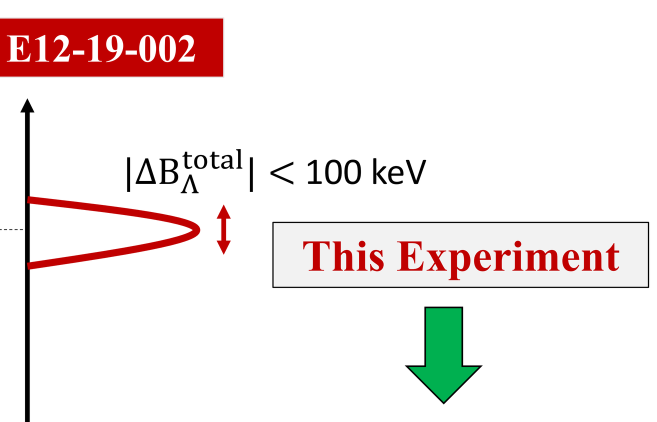
$|\Delta B_\Lambda^{total}| < 100$ keV

- The ground state 1/2+ measurement → ΛN spin singlet interaction / Hypertriton puzzle
- The first excited sate 3/2+ may be able to be determined if it exists (the cross section could be much larger) → ΛN spin triplet interaction.

2.2 $B_\Lambda(^4_\Lambda\mathrm{H};\ 1^+)$ measurement



(1) NPB 52, 1-30 (1973)
(2) PRL 114, 232501 (2015)



Absolute Energy Measurement:
- Very unique (direct meas.)
- Complementary with other data

3. Experimental setup

3.1 Magnetic spectrometers

References for HKS and HES spectrometers
- TG et al., NIMA 729, 816—824 (2013)
- Y. Fujii et al., NIMA 795, 351—363 (2015)
- TG et al., NIMA 900, 69—83 (2018)

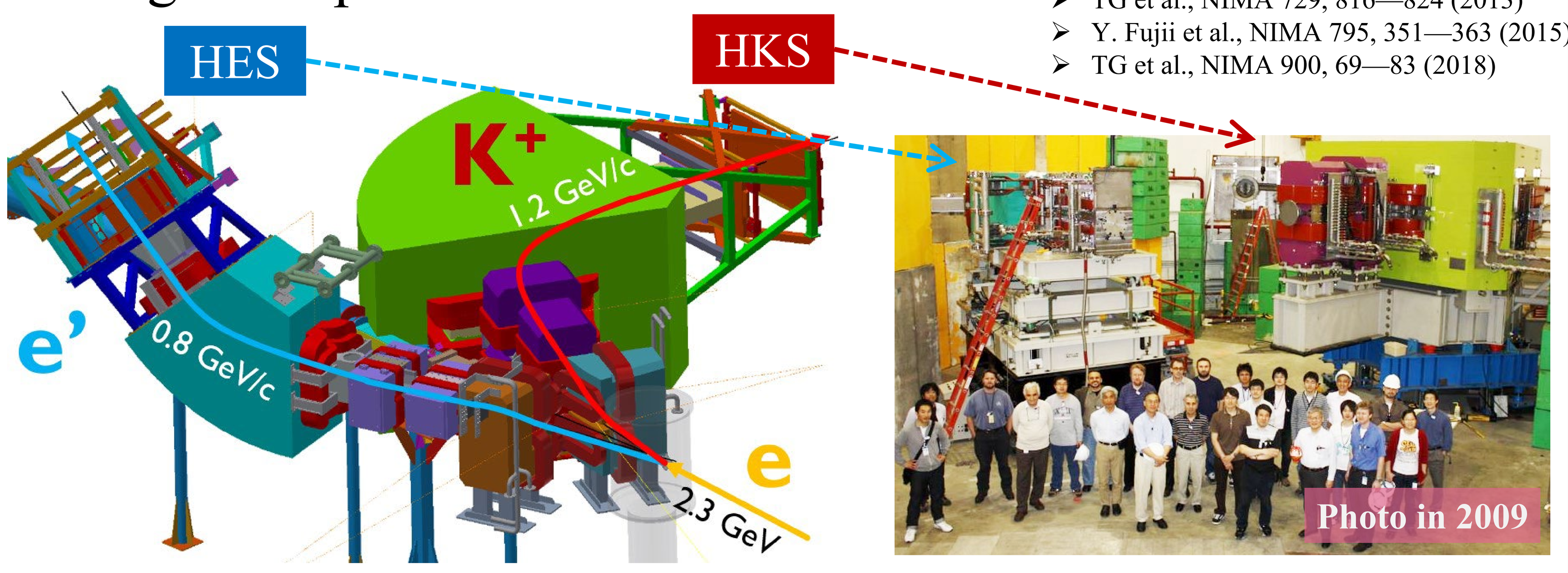
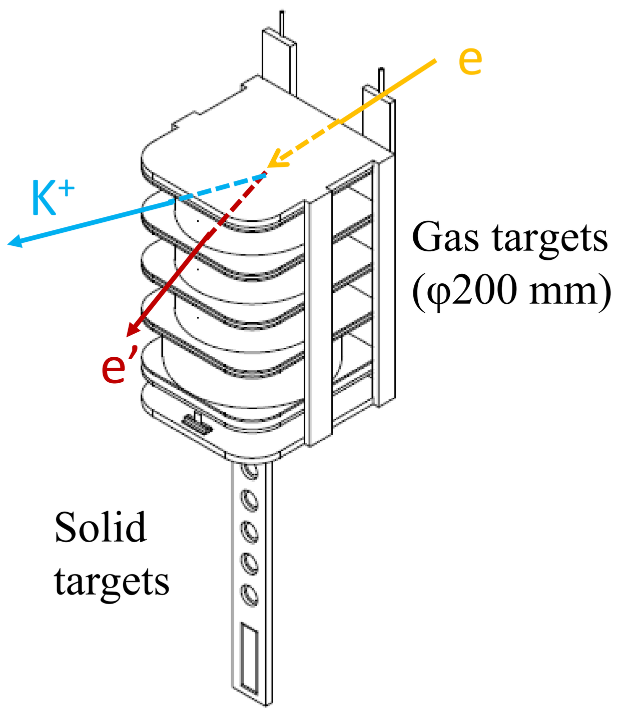
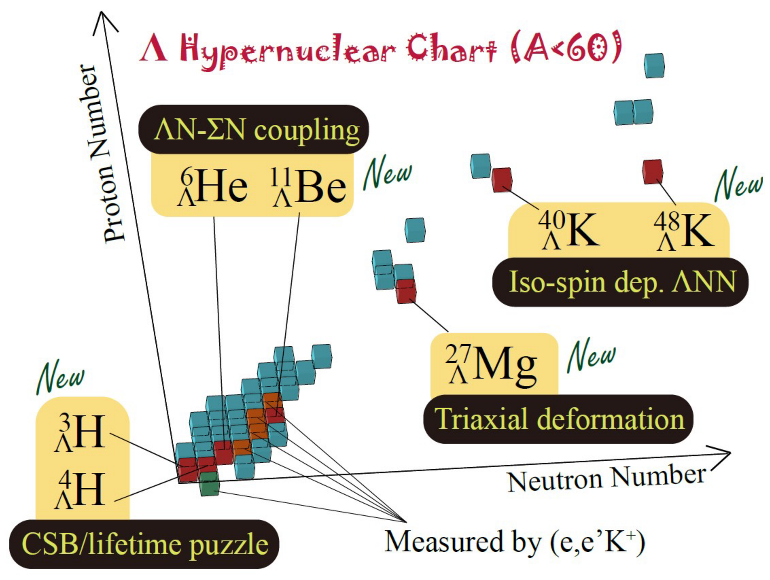


Fig. Experimental setup for the new experiment at JLab Hall C

Great energy resolution of 0.5 ~ 1 MeV FWHM thanks to HES and HKS

3.2 Experimental targets

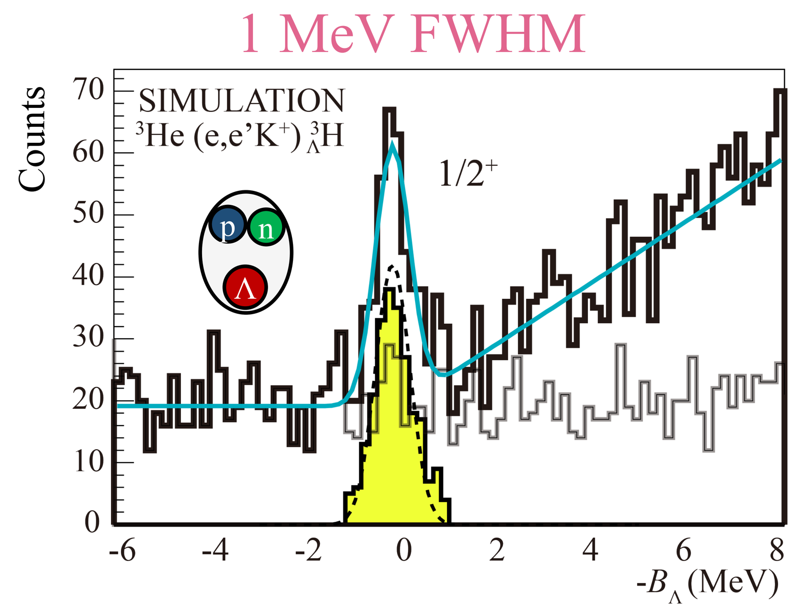


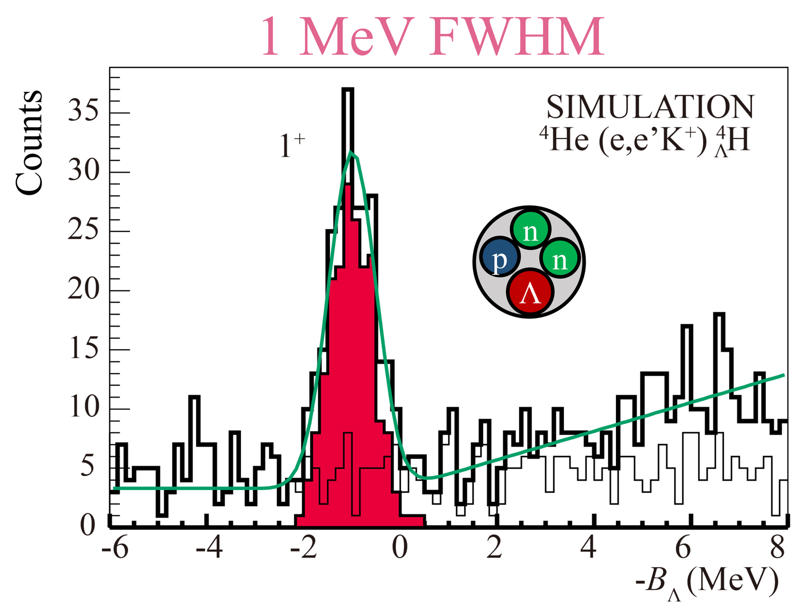


- Gas ($^1H_2$, ^{3,4}He) and solid targets (CH_2, ^{6}Li, ^{11}B, ^{12}C, ^{40,48}Ca, ^{208}Pb) will be used.
- For the gas target analysis, most of background events from Al cell would be omitted by a vertex cut.
- Beam current of about 20 μA is assumed.

4. Expected result

Hypernucleus	Target [/(mg/cm²)]	Beam time (/days)	Cross section [/(nb/sr)]	Gas density reduction	Yield
$^3_\Lambda$H	^{3}He (190)	20	5	0.5	230
$^4_\Lambda$H	^{4}He (262)	4	20		190





✓ $|\Delta B_\Lambda^{stat.}| \simeq 40$ keV
✓ $|\Delta B_\Lambda^{sys.}| \simeq 60$ keV
→ $|\Delta B_\Lambda^{total}| < 100$ keV

5. Summary

- HES (vertical) + HKS at JLab Hall C
  - ✓ Missing mass spectroscopy
  - ✓ 0.5 ~ 1 MeV FWHM resolution
  - ✓ < 100 keV accuracy
- Binding energies of $^3_\Lambda$H ($1/2^+$ or $3/2^+$) and $^4_\Lambda$H (1^+)
  - ✓ Hypertriton puzzle
  - ✓ Charge Symmetry breaking

→ We aim to perform the experiment in 2025

Related Presentations →
- Poster: T. Akiyama, “Missing mass spectroscopy of potassium hypernuclei at Jefferson Lab”
- Thu-IIb: F. Garibaldi, “Studying Λ interactions in nuclear matter with the $^{208}\mathrm{Pb}(e,e'K^+)^{208}_\Lambda\mathrm{Tl}$ reaction”