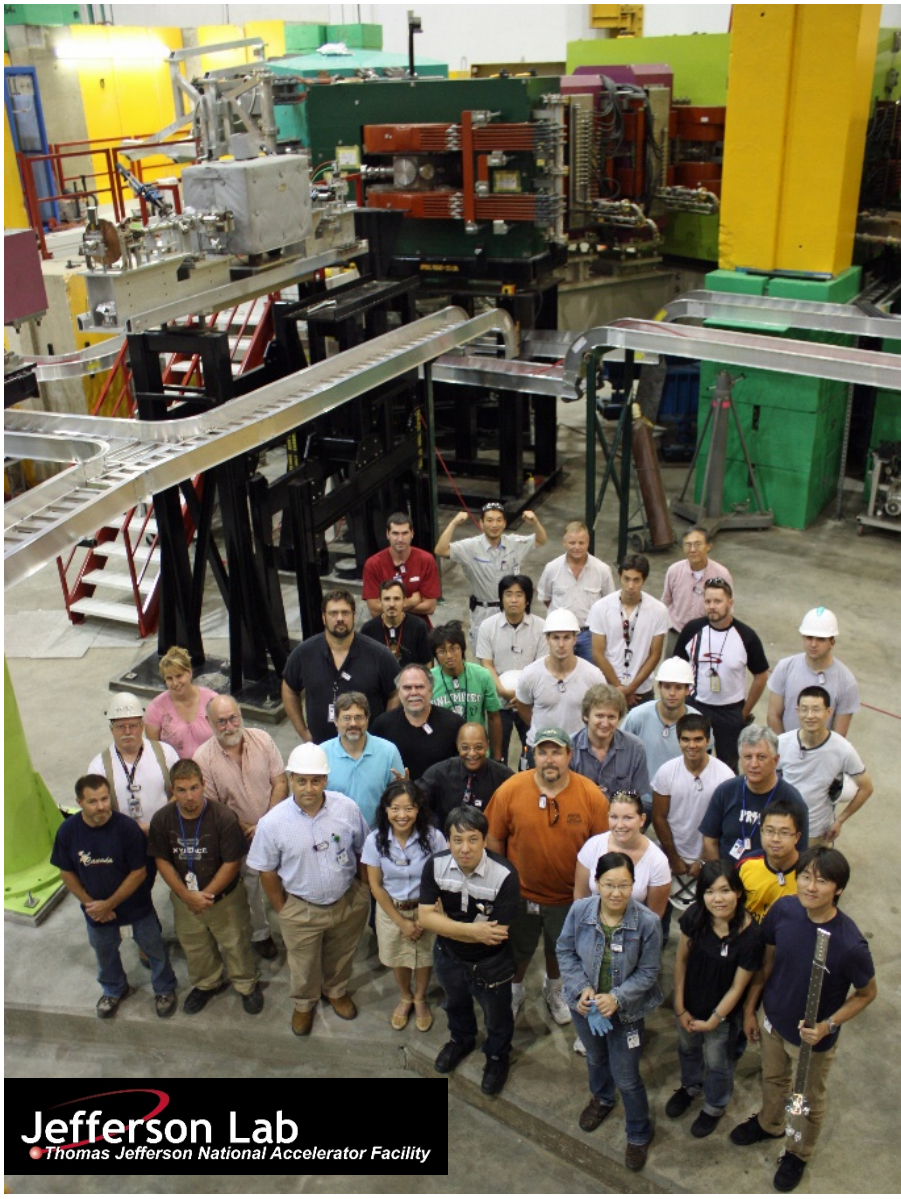
The 13th International Conference
on Hypernuclear and
Strange Particle Physics
(HYP2018)

Latest results from JLab on ${}^{7}_{\Lambda}$He and ${}^{10}_{\Lambda}$Be

Tohoku University
Toshiyuki Gogami
for the HKS (JLab E05-115) Collaboration
and the JLab Hypernuclear Collaboration
(June 25, 2018)



GPPU
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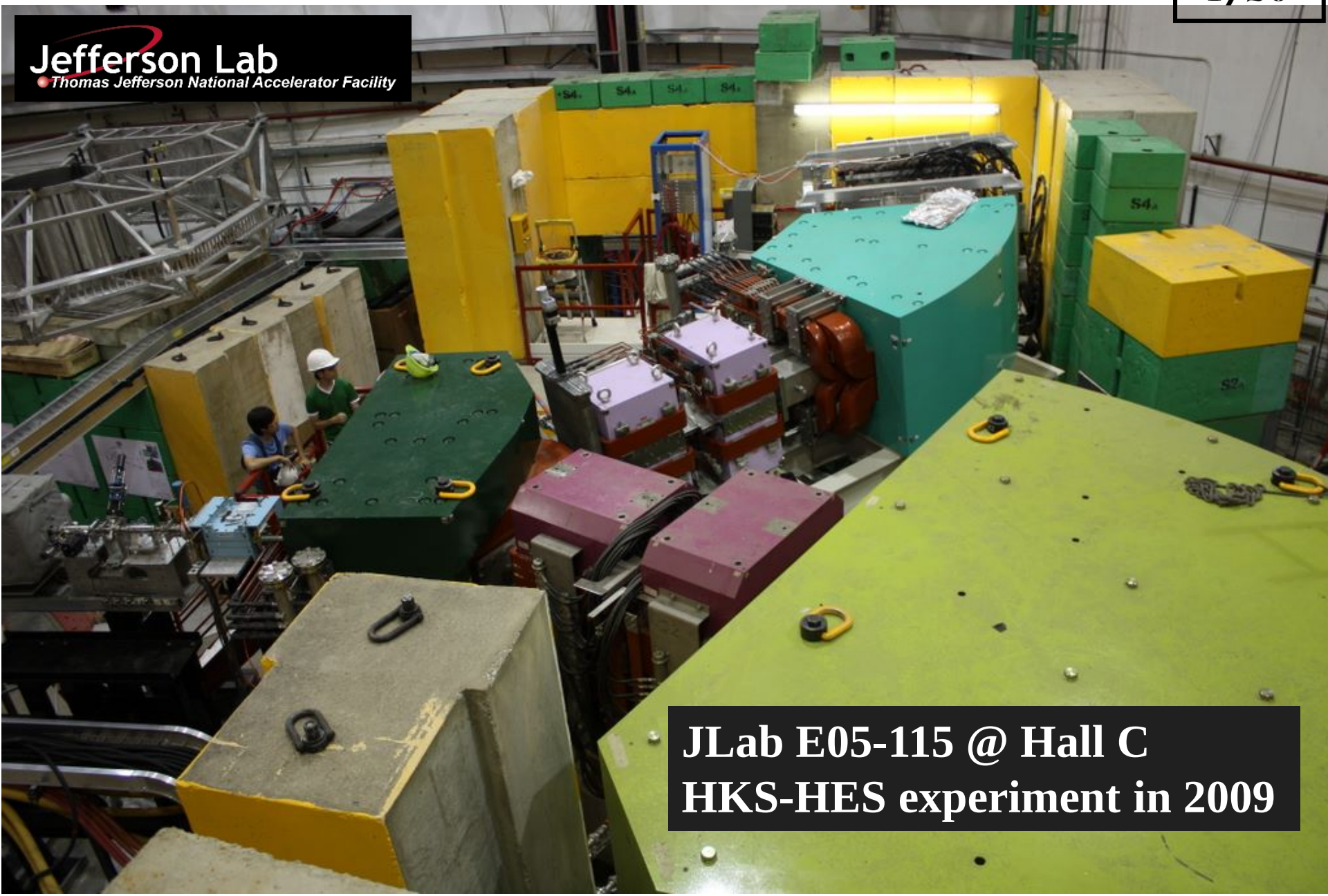
東北大学


Jefferson Lab
Thomas Jefferson National Accelerator Facility
JLab E05-115 @ Hall C
HKS-HES experiment in 2009

Contents

◎ Introduction

◎ Experimental results ($^{10}_{\Lambda}$Be, $^{7}_{\Lambda}$He and $^{9}_{\Lambda}$Li)

◎ Summary

Contents

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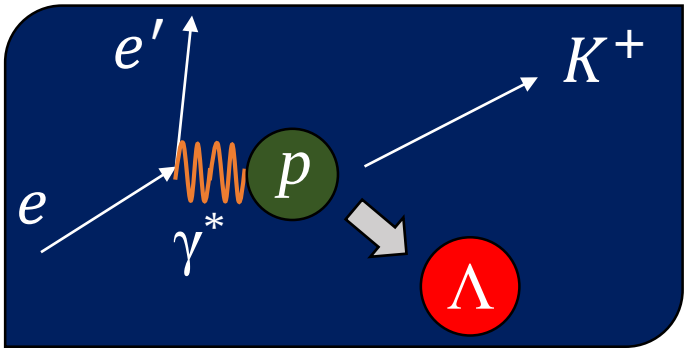
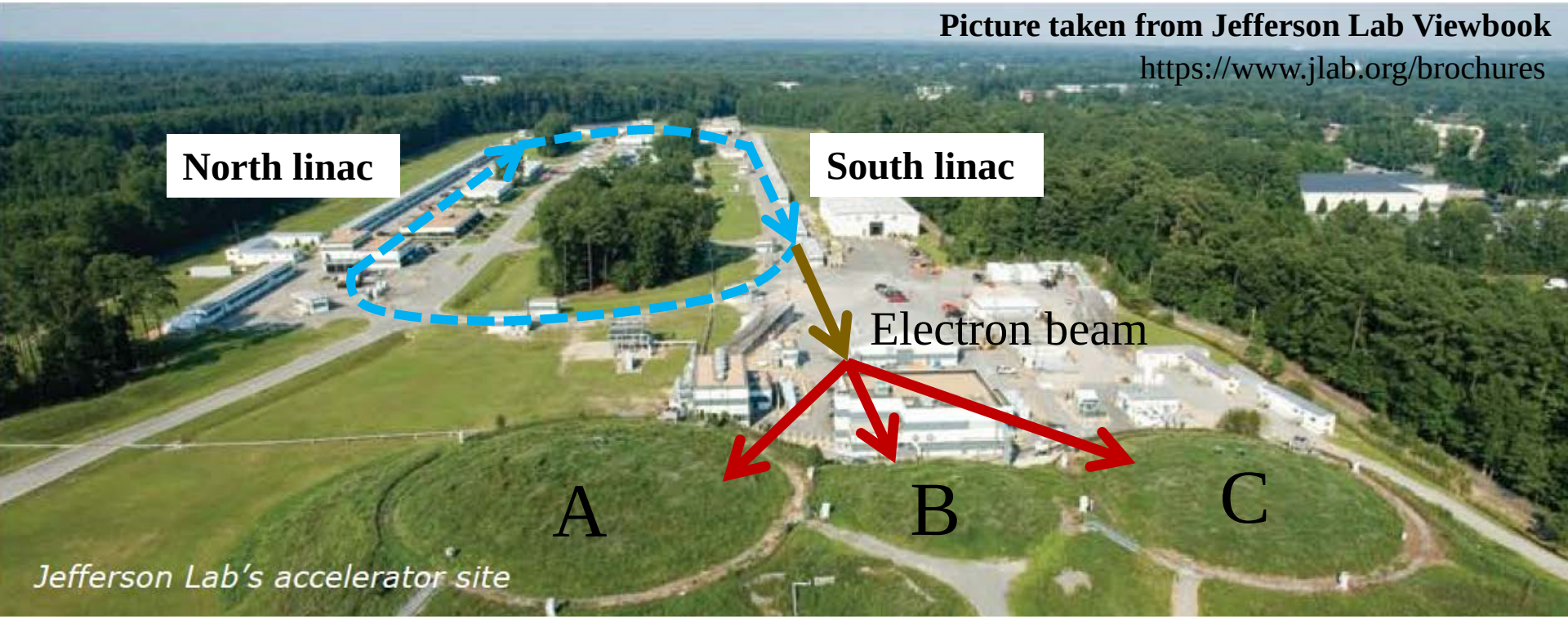
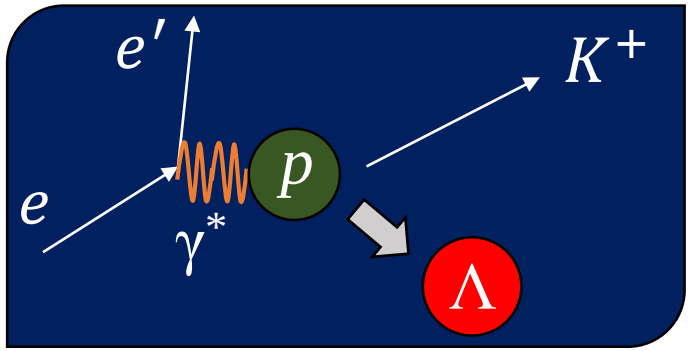


CEBAF at Newport News, VA, US



Continuous electron beam facility (CABAF)

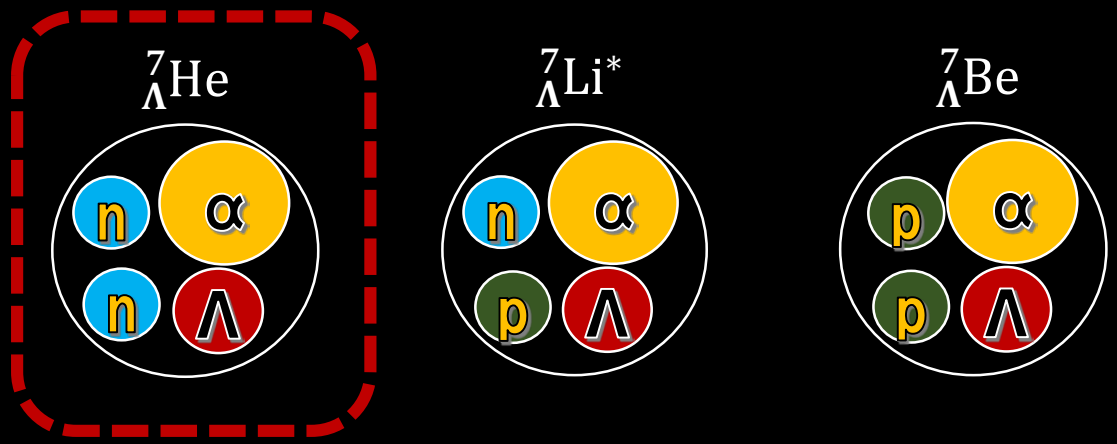
- ✓ 12 GeV at maximum
- ✓ 85 μA (> 500 THz)
- ✓ 2-ns interval bunches
- ✓ Emittance of 2 μm·mrad
- ✓ Energy spread ($^{\Delta E}/_{E} < 10^{-4}$)



Charge symmetry breaking (CSB)
in the p-Shell hypernuclei

emulsion + γ-ray

emulsion

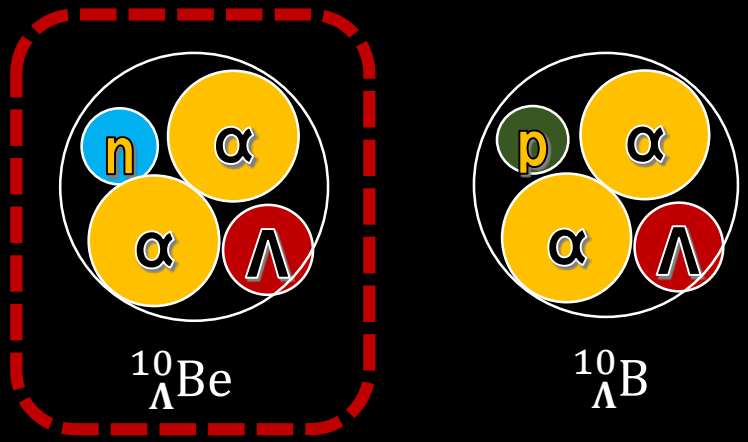


$A = 7, T = 1$

9.30 ± 0.26 MeV
8.91 ± 0.60 MeV
8.31 ± 0.61 MeV

↓

$B_{\Lambda}^{g.s.}(^{10}_{\Lambda}\mathrm{Be}) =$
9.11 ± 0.22 MeV



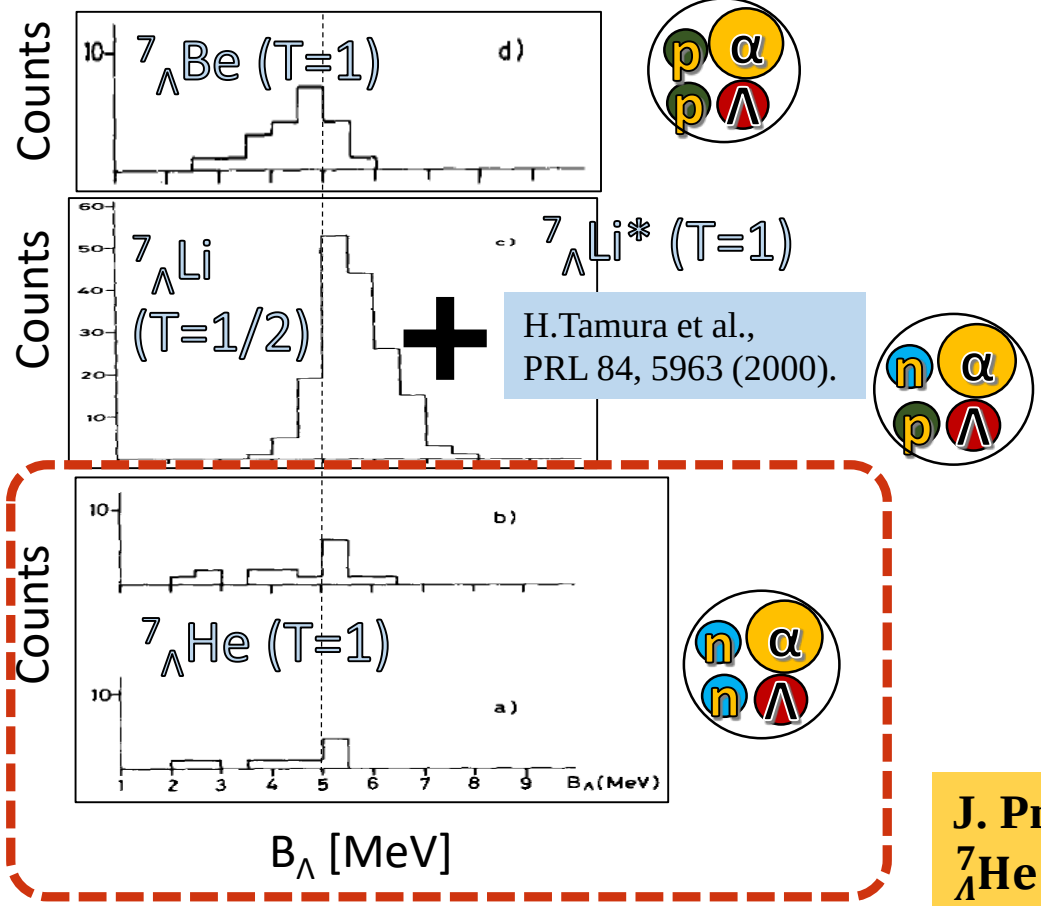
$^{10}_{\Lambda}$Be
emulsion
(3 events)

$^{10}_{\Lambda}$B
emulsion
(10 events)

$A = 10, T = 1/2$

The ΛN-CSB effect in the $A = 7$ iso-triplet ($T = 1$) hypernuclei

M.Juric et al., NPB52 (1973)



H.Tamura et al., PRL 84, 5963 (2000).

A.K. Wroblewski, Acta Physica Polonica B 35, 3 (2004).

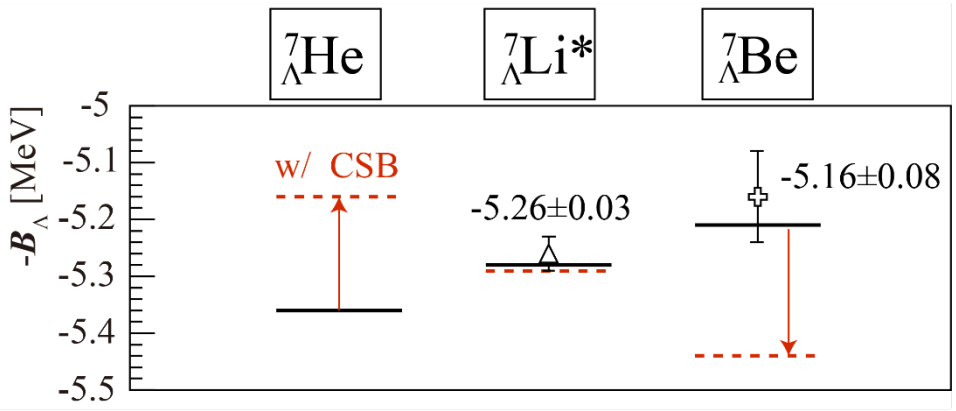
J. Pniewski and M. Danysz, "A note of the $^{7}_{\Lambda}$He hyperfragments", Phys. Lett. 1, 4 (1962).

The *p*-shell hypernuclear CSB

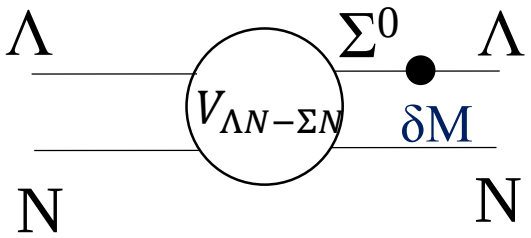
Phenomenological potential of the ΛN CSB interaction

E. Hiyama *et al.*, *Phys. Rev. C* **80**, 054321 (2009).

$$V_{\Lambda N}^{\rm CSB}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\rm even,CSB} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\rm even,CSB}\right)e^{-\beta_{\rm even}r^2} + \frac{1-P_r}{2}\left(v_0^{\rm odd,CSB} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\rm odd,CSB}\right)e^{-\beta_{\rm odd}r^2}\right]$$



Explicit inclusion of the ΛN ↔ΣN coupling



A. Gal, Phys. Lett. B 744, 352 (2015)

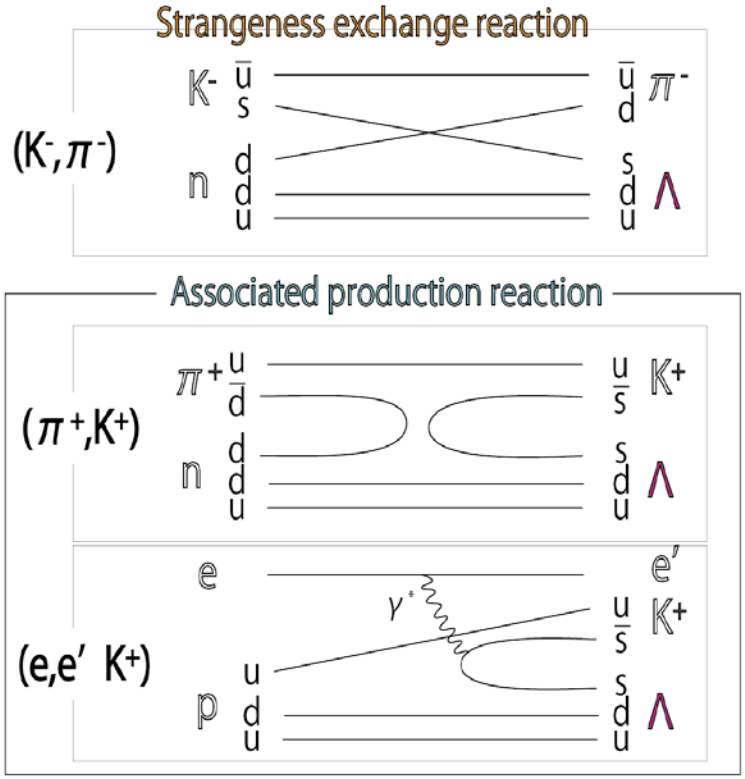
Isomultiplet	$\Delta B_\Lambda^{\rm exp}$ (MeV)	Prediction (MeV)
$^{4}_{\Lambda}$He − $^{4}_{\Lambda}$H (0^+)	270±60	+226
$^{4}_{\Lambda}$He − $^{4}_{\Lambda}$H (1^+)	30±50	+39
$^{7}_{\Lambda}$Li* − **$^{7}_{\Lambda}$He**	−420 ± 250	-28
$^{10}_{\Lambda}$B − **$^{10}_{\Lambda}$Be**	−220 ± 250	-136
$^{12}_{\Lambda}$C − **$^{12}_{\Lambda}$B**	~~−790 ± 190~~ −250 ± 190	-

$^{12}_{\Lambda}$B: L Tang et al., PRC 90, 0343320 (2014)
***B*$_\Lambda$($^{12}_{\Lambda}$C) correction** : TG et al., PRC 93, 034314 (2016); E. Botta et al., NPA 960, 165 (2017)

The characteristics of the $(e, e'K^+)$ reaction in Λ hypernuclear research

Missing mass spectroscopy of Λ hypernuclei via the $(e, e'K^+)$ reaction at JLab

- **High resolution** (sub-MeV — MeV FWHM)
- **High accuracy** (100-keV level systematic error on B_Λ)



Primary electron beam

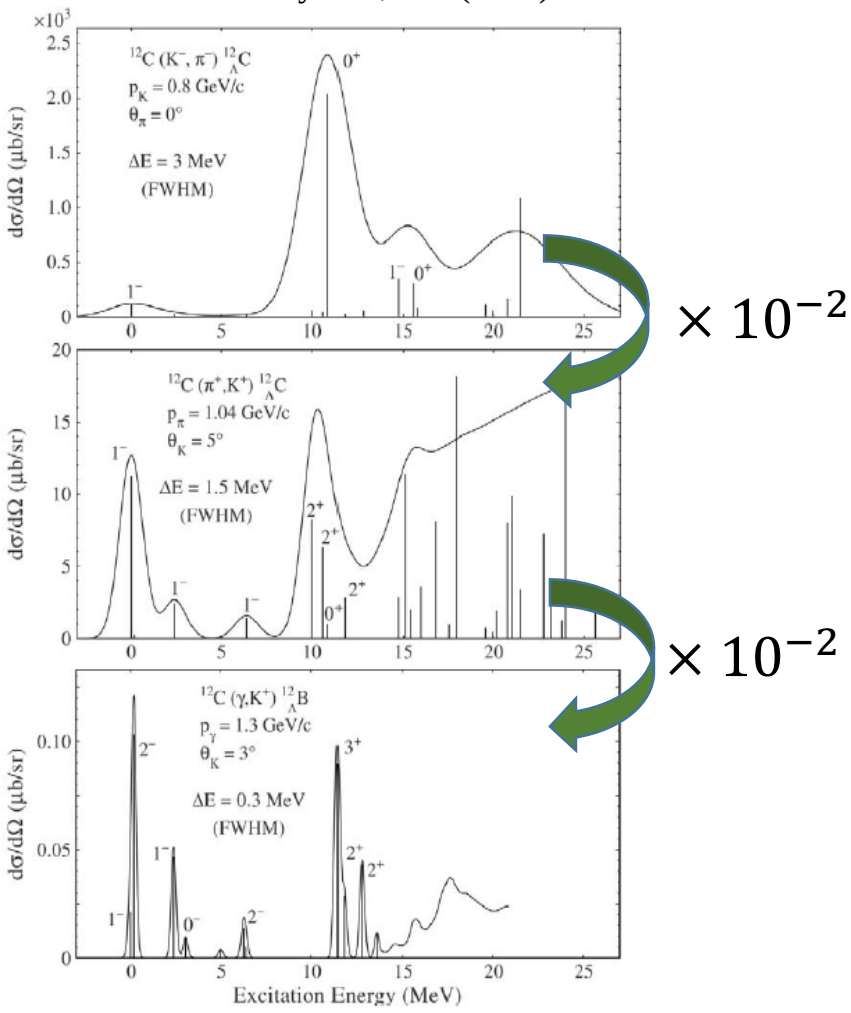
- High intensity (100 μA)
- Small energy spread ($^{\Delta E}/_{E} < 10^{-4}$)
- Small emittance (2 μm·mrad)

Proton to Λ [cf. $n \rightarrow \Lambda$ in (π^+, K^+)]

- Energy calibration with Λ and Σ^0 from hydrogen target → High precision
- Studying isotopic mirror hypernuclei of which partners were measured by mesic beam spectroscopy → ΛN CSB

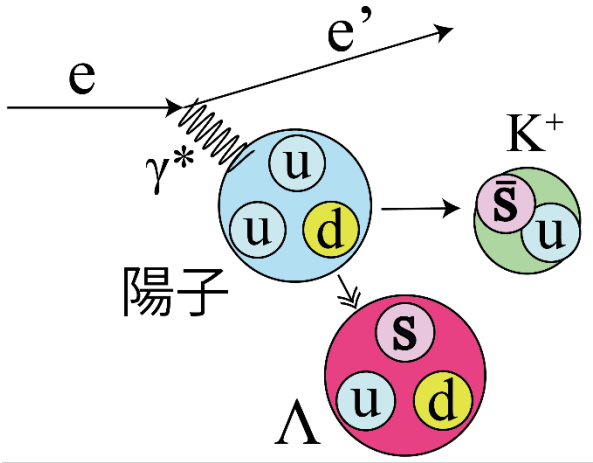
Experimental difficulty to be overcome

O. Hashimoto and H. Tamura, Prog. Par. Nucl. Phys. 57, 564 (2006)



$\times 10^{-2}$

$\times 10^{-2}$



- Small Cross section
- Small VP flux ($\Gamma \sim 10^{-5}$)
- EM backgrounds (Moller, Bremsstrahlung)
- High precision spectroscopy → $\Delta p/p \sim 10^{-4}$ for both e' and K^+

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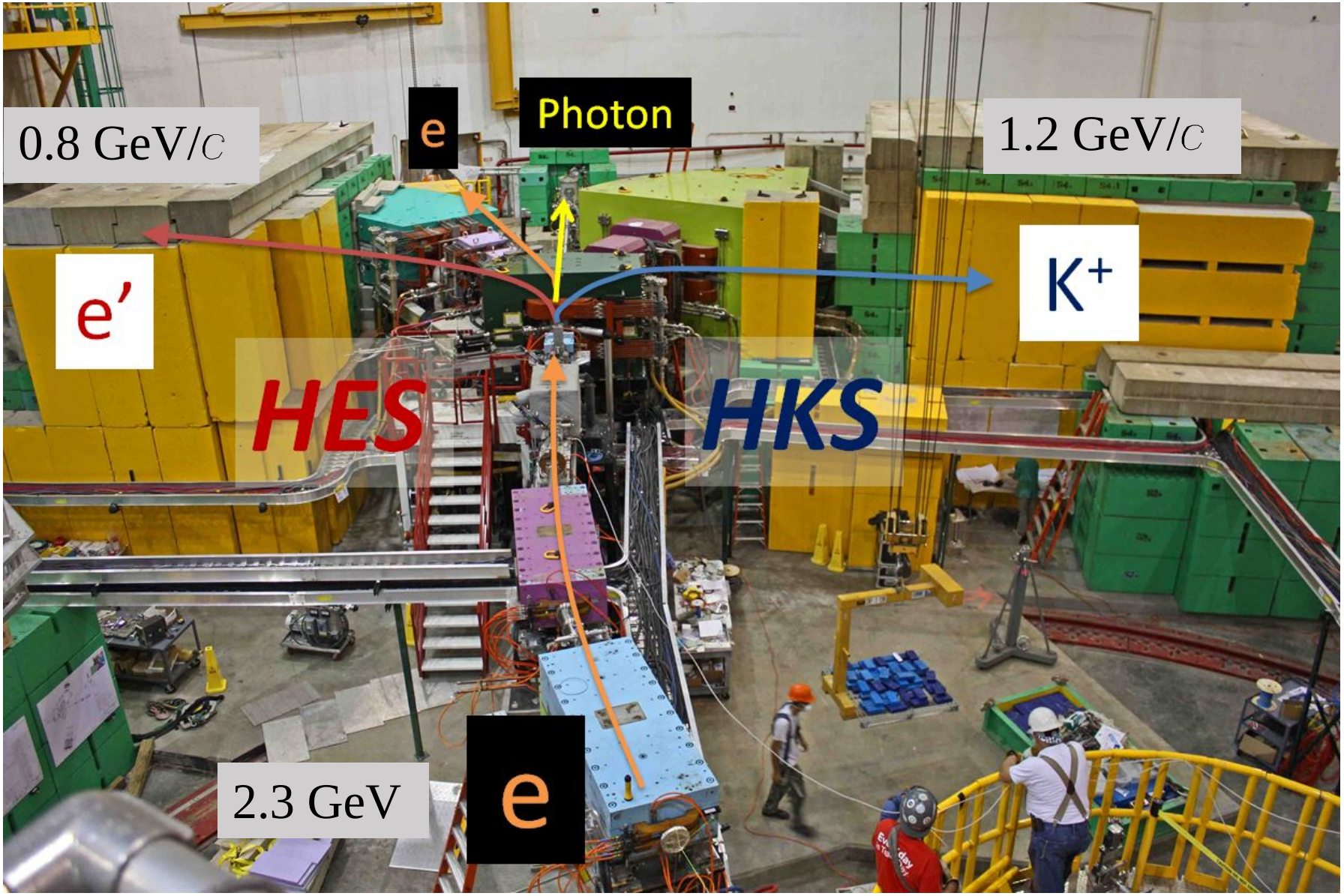
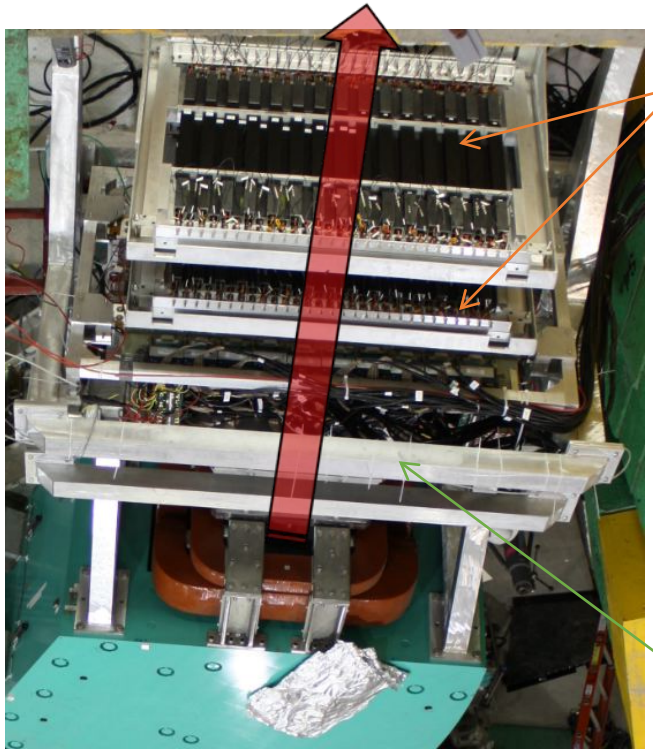
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Experimental setup for E05-115 (2009) at JLab Hall C



Particle Detectors & Trigger

e^-

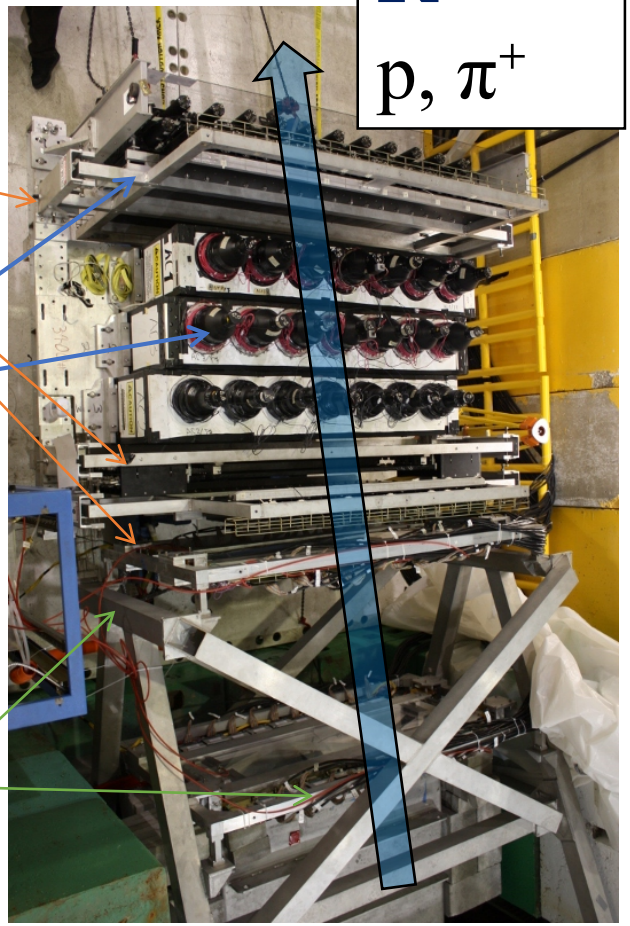


TOF walls
(Plastic scintillators)

Cherenkov detectors
- **Aerogel (n=1.05)**
- **Water (n=1.33)**

Drift chambers

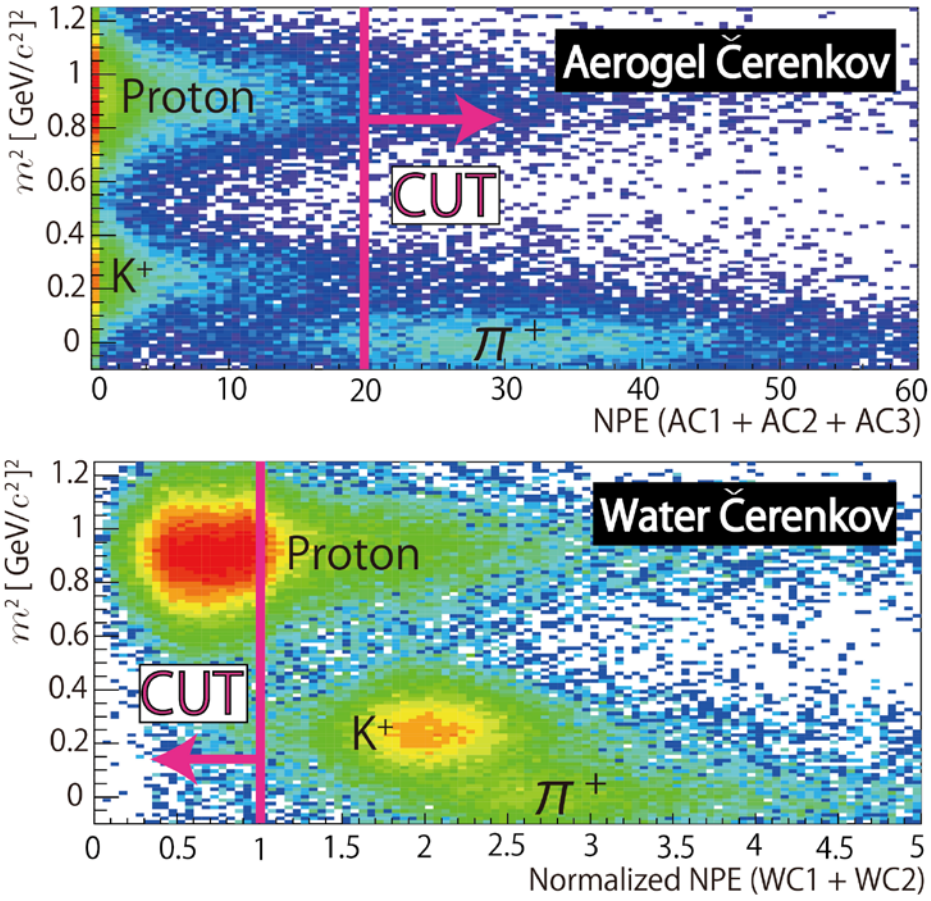
K^+
p, π^+

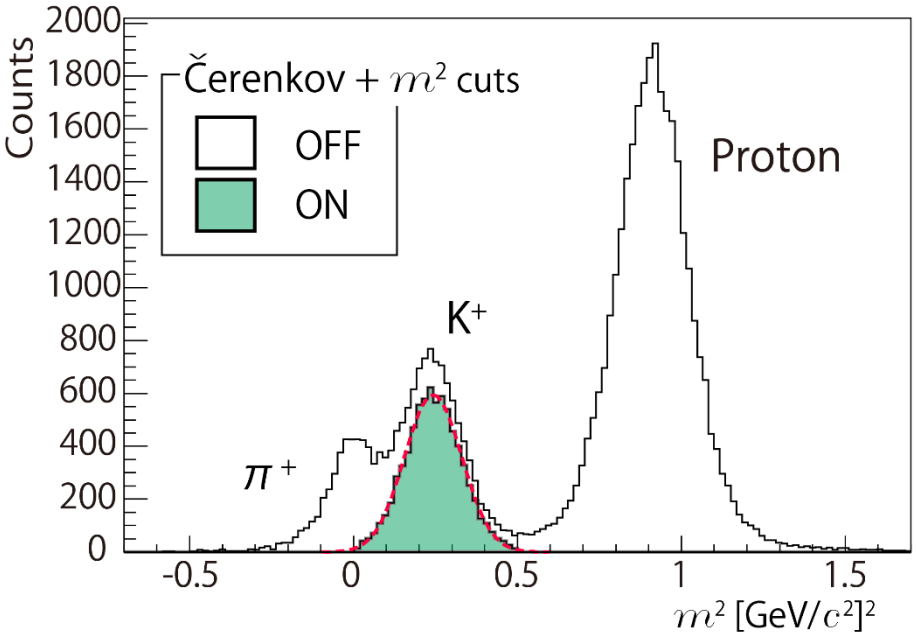


HES

HKS

Off-line K^+ identification



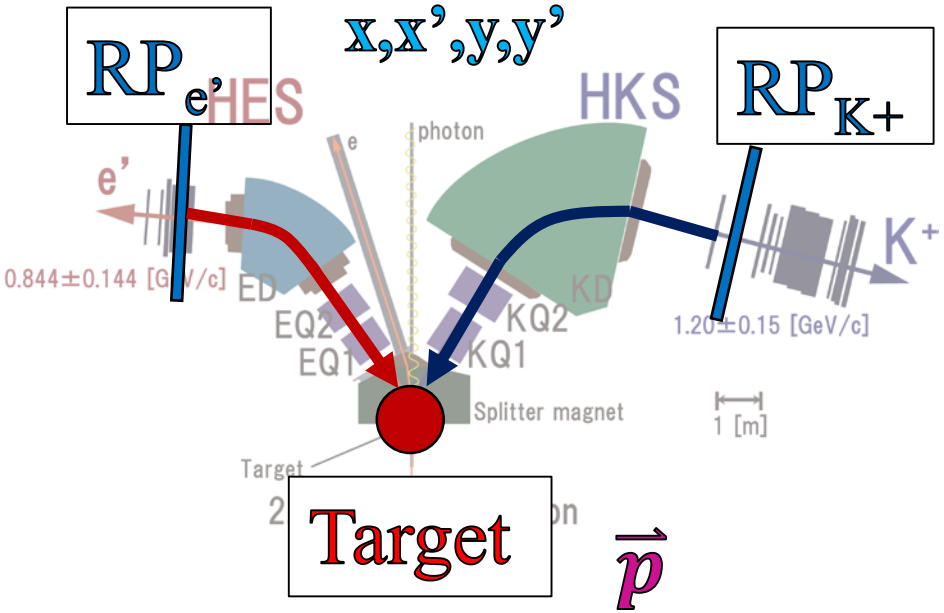


Survival ratios (on- and off-lines)

- ✓ K^+ : 83%
- ✓ π^+: 4.7×10^{-4}
- ✓ p : 1.9×10^{-4}

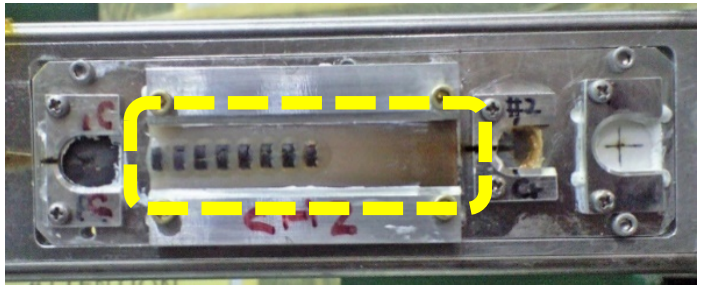
T. Gogami *et al.*, *Nucl. Instrum. Methods Phys. Res., A* **729**, 816–824 (2013).

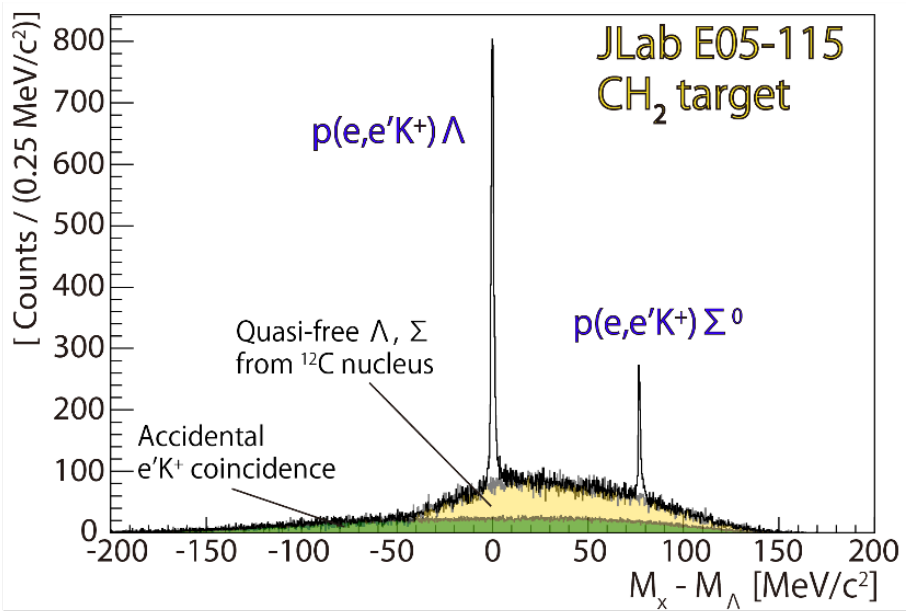
Missing-mass reconstruction and calibration with Λ and Σ^0



$$\begin{pmatrix} x_{\mathrm{T}} \\ x'_{\mathrm{T}} \\ y_{\mathrm{T}} \\ y'_{\mathrm{T}} \\ p \end{pmatrix} = M^{\mathrm{R2T}} \begin{pmatrix} x_{\mathrm{RP}} \\ x'_{\mathrm{RP}} \\ y_{\mathrm{RP}} \\ y'_{\mathrm{RP}} \\ x^2_{\mathrm{RP}} \\ x_{\mathrm{RP}} x'_{\mathrm{RP}} \\ \vdots \end{pmatrix}$$

Polyethylene target





T. Gogami *et al.*, *Nucl. Instrum. Methods Phys. Res., A* **900**, 69–83 (2018).

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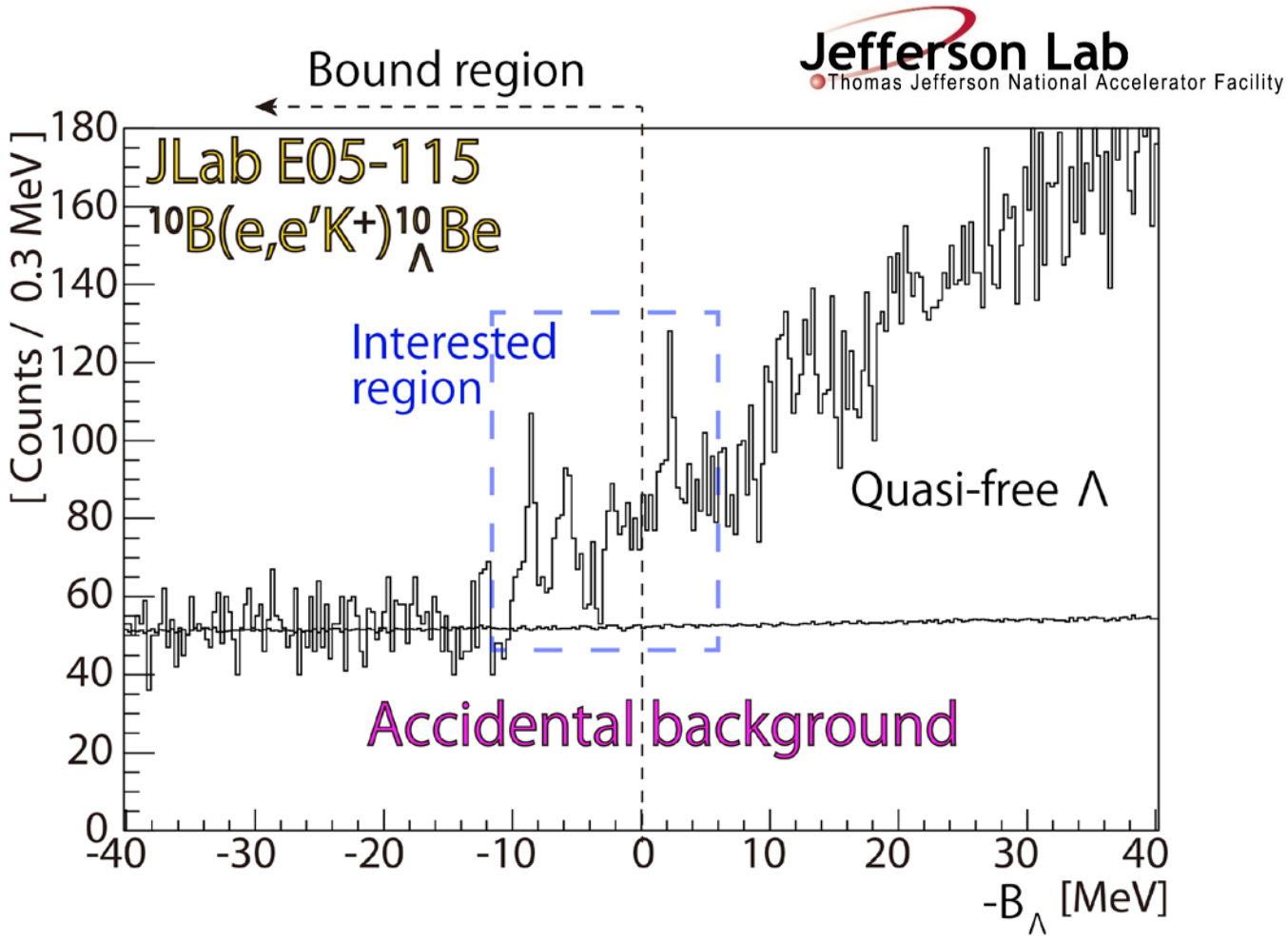
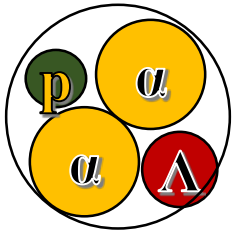
$^{10}\mathrm{B}(e,e'K^+)^{10}_{\Lambda}\mathrm{Be}$ Spectrum

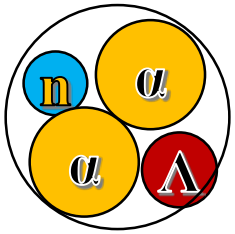


T. Gogami *et al.* (HKS(JLab E05-115) Collaboration), *Phys. Rev. C* ***93***, 034314 (2016)

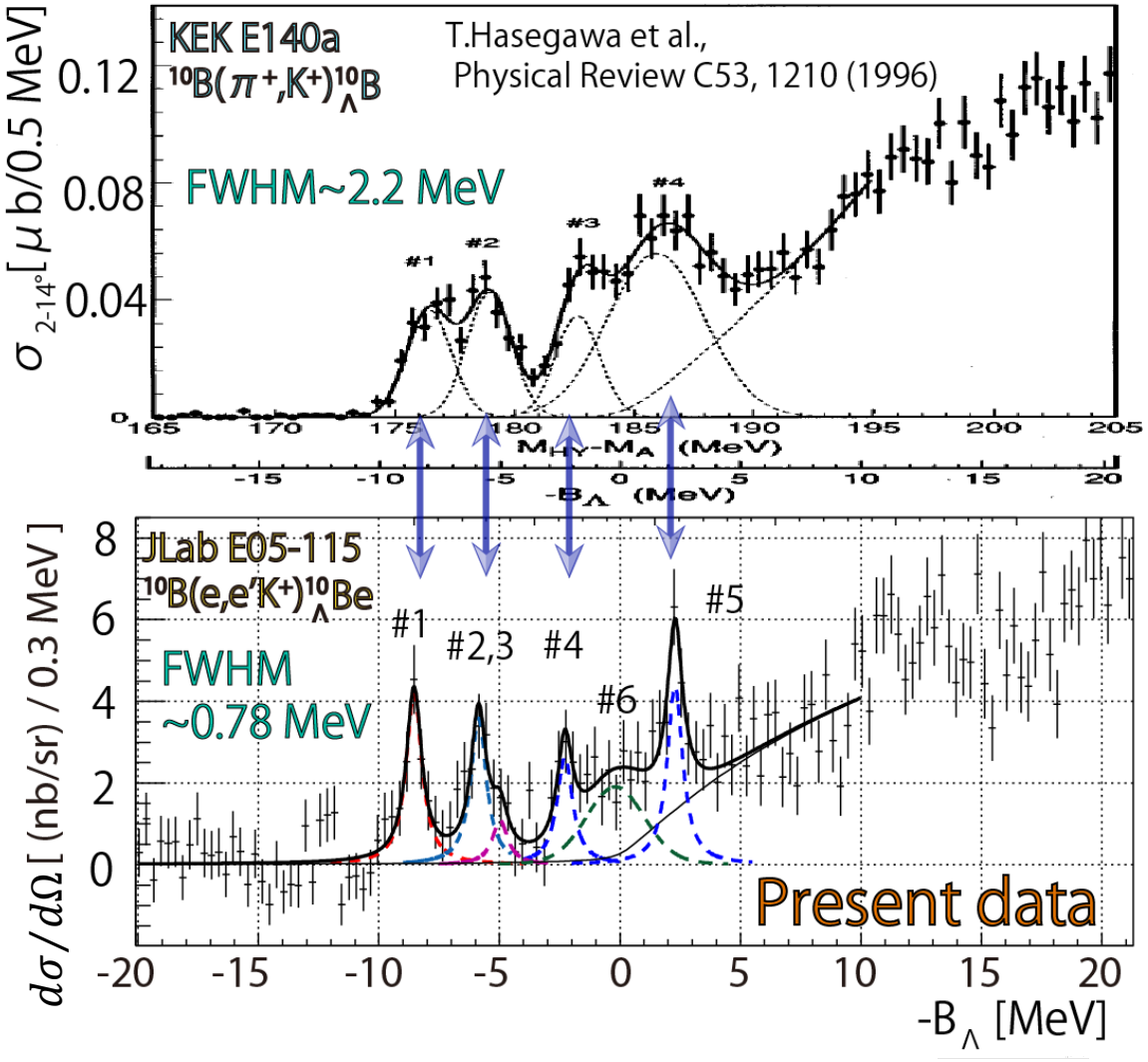
Comparison between $^{10}_{\Lambda}$B and $^{10}_{\Lambda}$Be



$^{10}_{\Lambda}$B

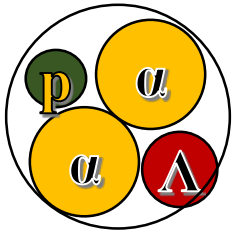


$^{10}_{\Lambda}$Be

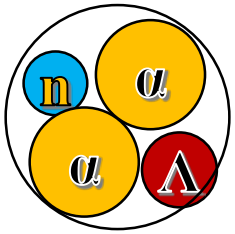


Compari…etween $^{10}_{\Lambda}$B and $^{10}_{\Lambda}$Be

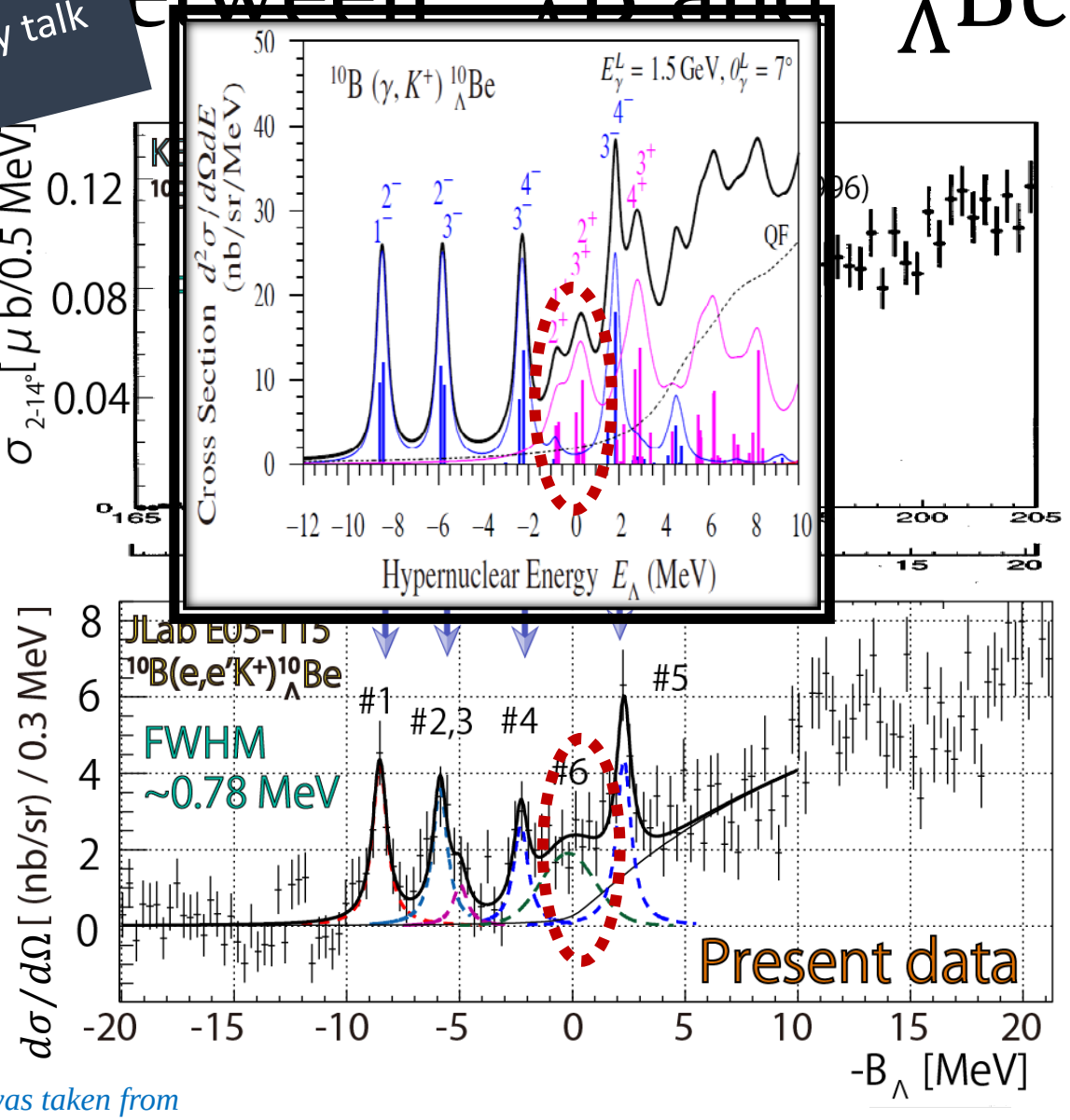
It will be talked about in tomorrow's plenary talk by T. Motoba



$^{10}_{\Lambda}$B



$^{10}_{\Lambda}$Be



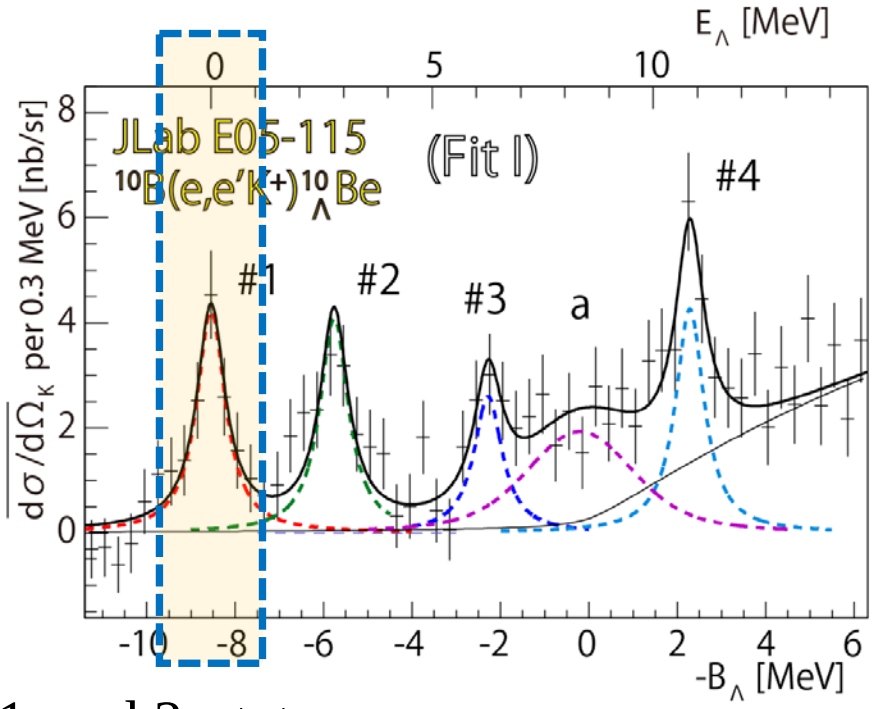
Theoretical calc. was taken from
"22aK309-8, A. Umeya, T. Motoba, K. Itonaga, JPS meeting, Mar 2018"

$^{10}_{\Lambda}$Be g.s. binding energy

Emulsion experiments:

A)	9.30 ± 0.26	MeV
B)	8.91 ± 0.60	MeV
C)	8.31 ± 0.61	MeV

$B_{\Lambda}^{g.s.}(^{10}_{\Lambda}\mathrm{Be}) =$
9.11 ± 0.22 MeV



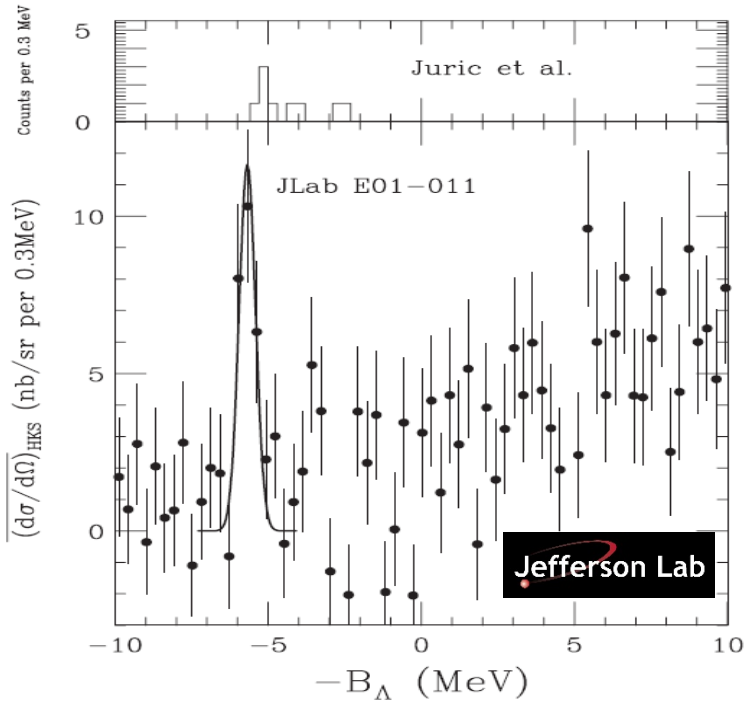
1^- and 2^- states
(^{9}Be[J^{π};E_x]$\otimes j^{\Lambda}$= [3/2$^-$; g.s.] $\otimes s_{\Lambda}$)

NEW

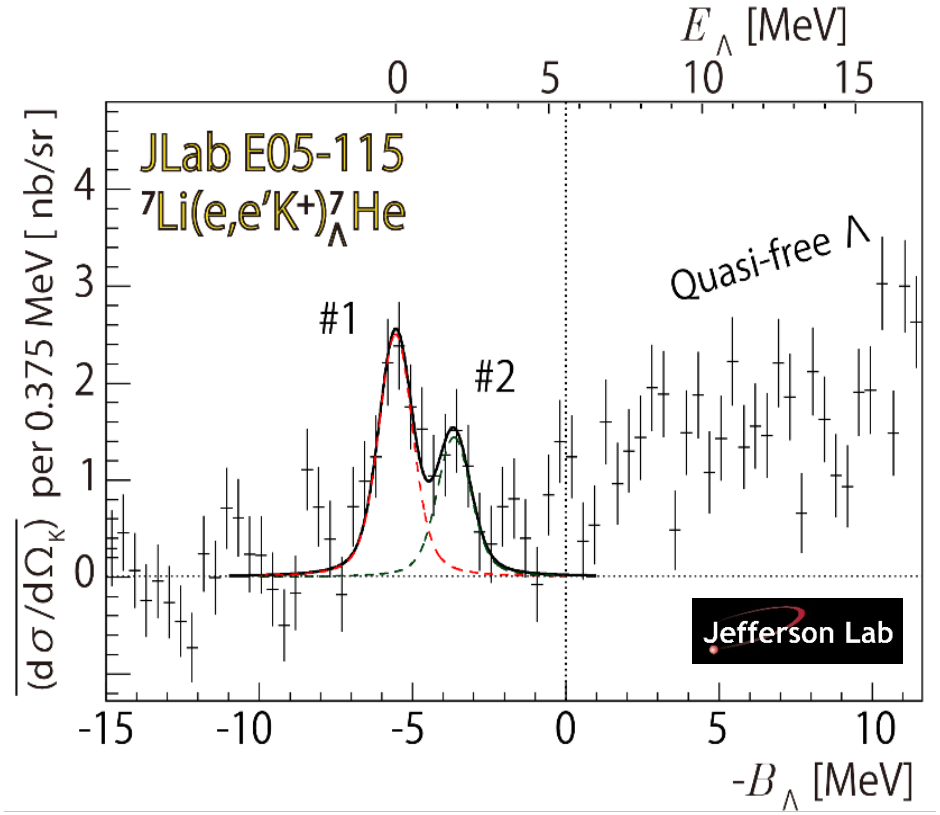
$B_{\Lambda}^{g.s.}(^{10}_{\Lambda}\mathrm{Be}) = 8.60 \pm 0.07^{stat.} \pm 0.16^{sys.}$ MeV

Assumption
Cross-section ratio: 0.5—1.5
State separation: 0.05—0.15 MeV

${}^{7}_{\Lambda}$He measurements at JLab

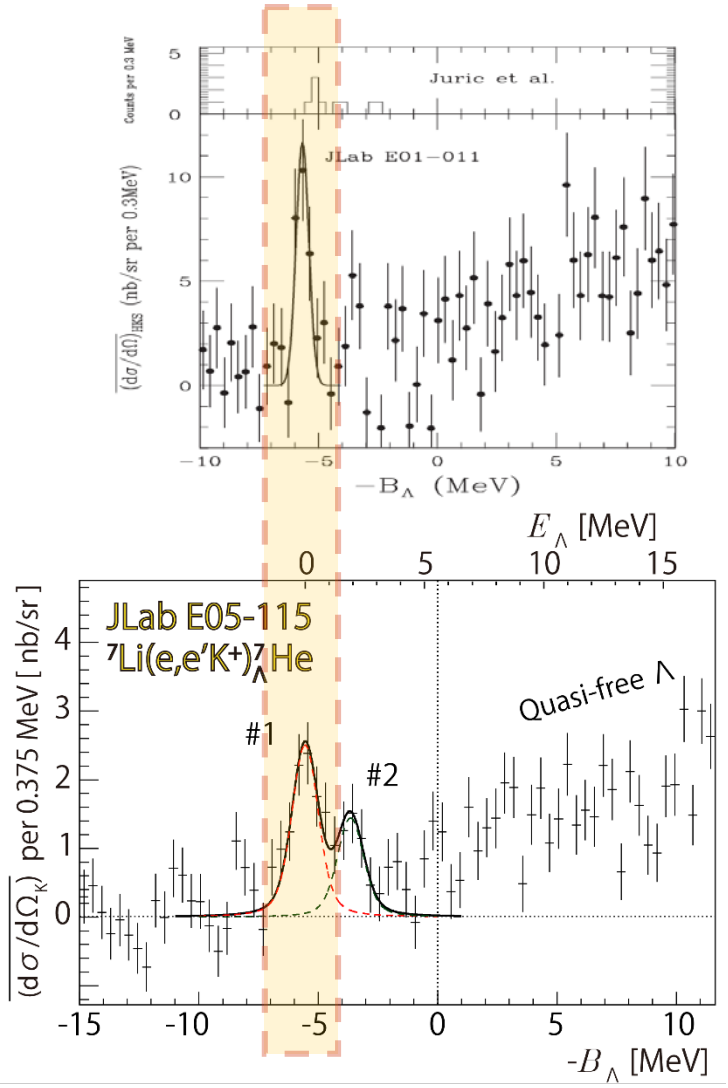


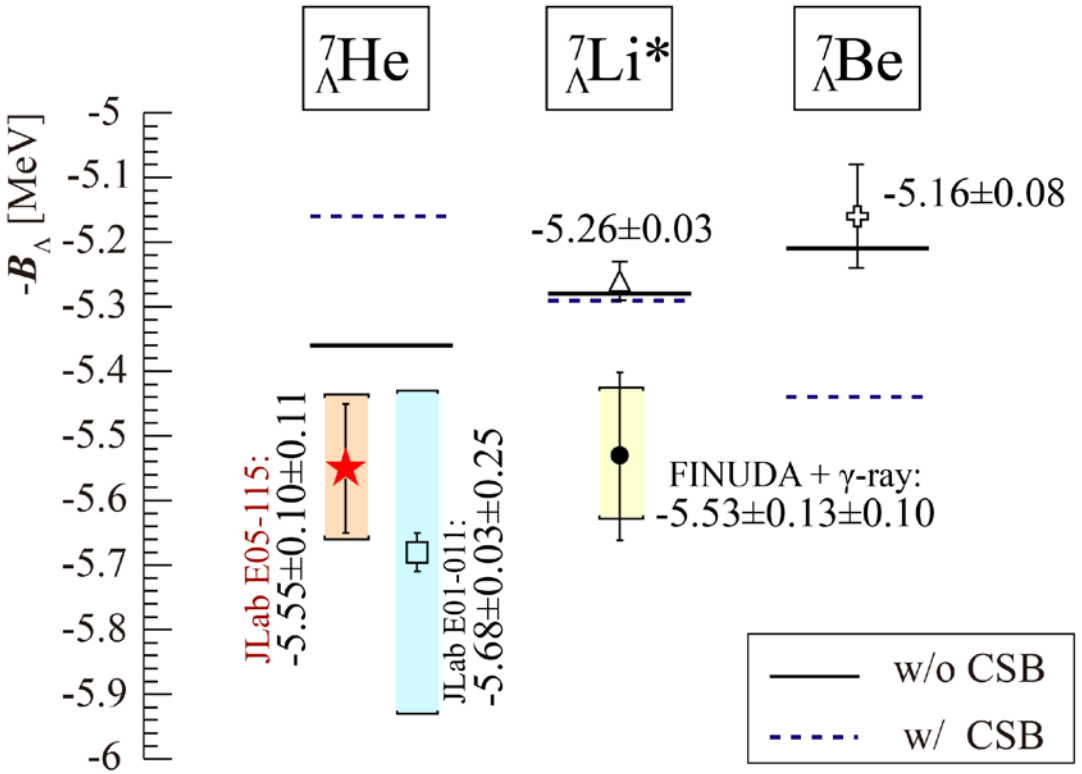
S. N. Nakamura *et al.*
(HKS(JLab **E01-011** Collaboration)),
Phys. Rev. Lett. **110**, 012502 (2013).



T. Gogami *et al.*
(HKS(JLab **E05-115** Collaboration)),
Phys. Rev. C **94**, 021302(R) (2016).

Phenomenological CSB test in the A=7, T=1 hypernuclei





E. Hiyama *et al.*, *Phys. Rev. C* **80**, 054321 (2009).

ΔB_Λ of isotopic mirror pairs (g.s.)

Mirror pairs	$\Delta B_\Lambda^{theor.}$ [keV]	Experiment	$\Delta B_\Lambda^{exp.}$ [keV]
${}^{7}_{\Lambda}\mathrm{Be} - {}^{7}_{\Lambda}\mathrm{Li}^{*}$	-17[1], -70[2]	Emul.(35 evts) – [Emul.(226)+γ]	-100 ± 90
		Emul.(35 evts) – (FINUDA+γ)	-370 ± 180
${}^{7}_{\Lambda}\mathrm{Li}^{*} - {}^{7}_{\Lambda}\mathrm{He}$	-80[2], -28[5]	(Emul.+γ) – JLab_2005	-420 ± 250
		(Emul.+γ) – ***JLab_2009***	-290 ± 140
		(FINUDA+γ) – ***JLab_2009***	-20 ± 220
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	$+49$[1]	Emul.(68 evts) – Emul. (787 evts)	$+40 \pm 60$
${}^{9}_{\Lambda}\mathrm{B} - {}^{9}_{\Lambda}\mathrm{Li}$	-54[1]	Emul.(3 evts) – Emul.(13 evts)	-210 ± 220
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	-136[1], -180[3]	Emul.(10 evts) – Emul. (3 evts)	-220 ± 250
		Emul. – ***JLab_2009***	$+290 \pm 220$
		(π^+, K^+) – ***JLab_2009*** + correction[4]	-40 ± 200
${}^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$		Emul. – Emul. + correction[4]	-70 ± 200
		Emul. – ***JLab_2009*** + correction[4]	-250 ± 190

[1] A.Gal, PLB 744, 352 (2015)
[2] E.Hiyama *et al.*, PRC 80, 054321 (2009), w/o CSB
[3] E.Hiyama and Y.Yamamoto., PTP 128, 1 (2012), w/o CSB
[4] T. Gogami et al., PRC 93, 034314 (2016); E. Botta et al., NPA 960, 165 (2017)
[5] A. Gal, JPS Conf. Proc. 17, 011006 (2017)

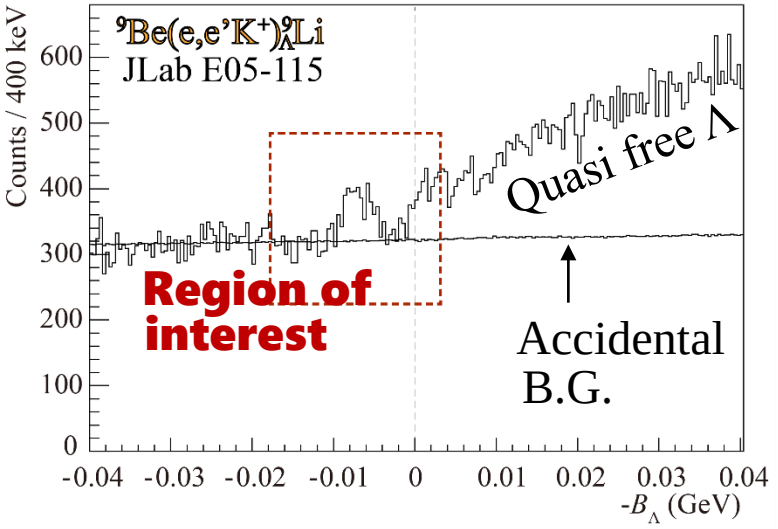
ΔB_Λ of isotopic mirror pairs (g.s.)

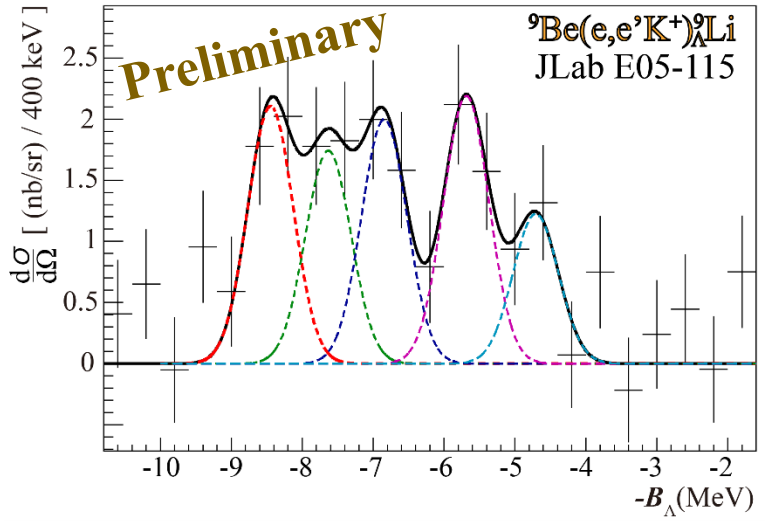
For A = 7, 10 and 12,
the ΛN CSB effect is consistently small (ΔB < a few 100 keV)

Mirror pairs	$\Delta B_\Lambda^{theor.}$ [keV]		
		(FINUDA+γ) – *JLab_2009*	−20 ± 220
$^{8}_{\Lambda}$Be − $^{8}_{\Lambda}$Li	+49[1]	Emul.(68 evts) – Emul. (787 evts)	+40 ± 60
$^{9}_{\Lambda}$B − $^{9}_{\Lambda}$Li	−54[1]	Emul.(3 evts) – Emul.(13 evts)	−210 ± 220
$^{10}_{\Lambda}$B − $^{10}_{\Lambda}$Be	−136[1], −180[3]	Emul.(10 evts) – Emul. (3 evts)	−220 ± 250
		Emul. – *JLab_2009*	+290 ± 220
		(π^+, K^+) – *JLab_2009* + correction[4]	−40 ± 200
$^{12}_{\Lambda}$C − $^{12}_{\Lambda}$B		Emul. – Emul. + correction[4]	−70 ± 200
		Emul. – *JLab_2009* + correction[4]	−250 ± 190

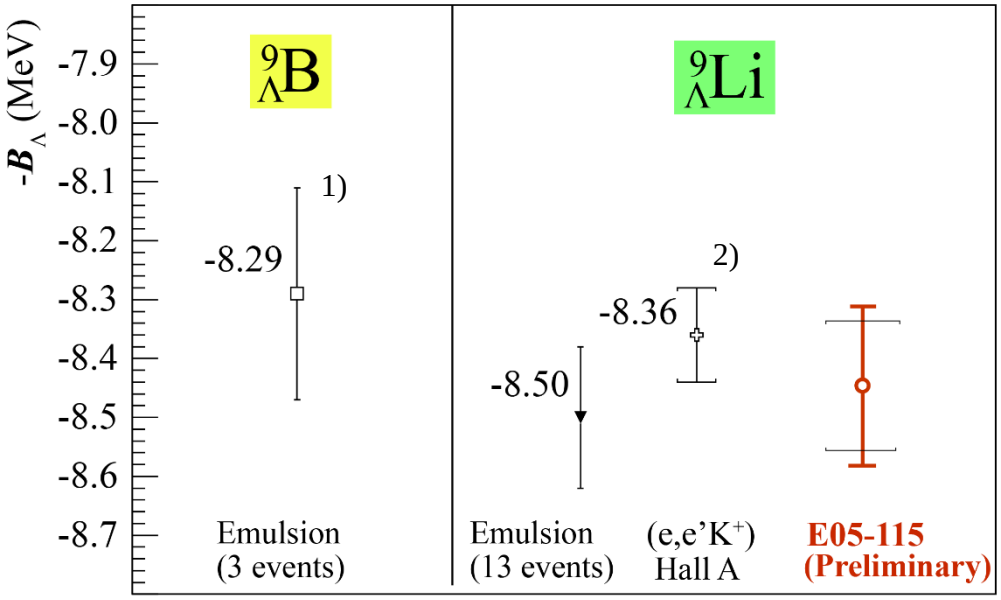
[1] A.Gal, PLB 744, 352 (2015)
[2] E.Hiyama *et al.*, PRC 80, 054321 (2009), w/o CSB
[3] E.Hiyama and Y.Yamamoto., PTP 128, 1 (2012), w/o CSB
[4] T. Gogami et al., PRC 93, 034314 (2016); E. Botta et al., NPA 960, 165 (2017)
[5] A. Gal, JPS Conf. Proc. 17, 011006 (2017)

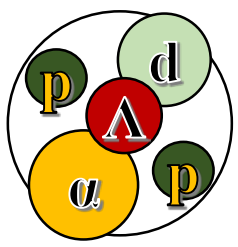
$^{9}\mathrm{Be}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Li}$ from E05-115

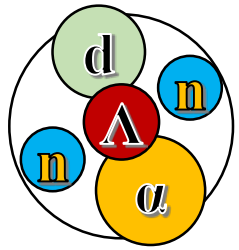




FWHM ≅ 760 keV







[1] J. Pniewski *et al.*, *Nucl. Phys. A* ***443*** (1985) 685.
[2] G.M. Urciuoli *et al.*, *Phys. Rev. C* ***91*** (2015) 034308.

Summary

References from HKS:

$^{7}_{\Lambda}$He: S.N. Nakamura et al., PRL 110, 012502 (2013)
$^{7}_{\Lambda}$He: T. Gogami et al., PRC 94, 021302(R) (2016)
$^{10}_{\Lambda}$Be: T. Gogami et al., PRC 93, 034314 (2016)
$^{12}_{\Lambda}$B: L. Tang et al., PRC 90, 0343320 (2014)

☆ Λ hypernuclear spectroscopy with the $(e, e'K^+)$ reaction at JLab

- ✓ High precision (sub MeV FWHM) and accuracy ($\Delta B_\Lambda = 100$ keV)
- ✓ E05-115 measured $^{7}_{\Lambda}$He, $^{10}_{\Lambda}$Be, $^{12}_{\Lambda}$B with better accuracy
- ✓ New result of $^{9}_{\Lambda}$Li which is consistent with emulsion and Hall A results
- ✓($^{12}_{\Lambda}$C needs about 500 keV correction)
  - → The ΛN CSB in A = 7—12 seems to be small (< a few 100 keV)

☆ For further study in the ΛN CSB

- ✓ Higher accuracy measurement at JLab
- ✓ More statistics for p-shell Λ hypernuclei in emulsion experiment
  - J-PARC E07
- ✓ Confirmation of A = 4 data (1^+)
  - J-PARC E63 (gamma ray spectroscopy) → $^{4}_{\Lambda}$H (1^+)
  - ^{4}He$(e, e'K^+)$ $^{4}_{\Lambda}$H at JLab

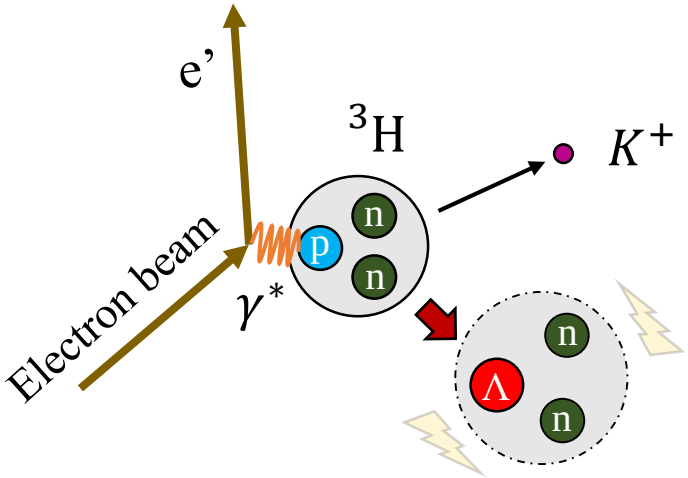
Future hypernuclear projects at JLab

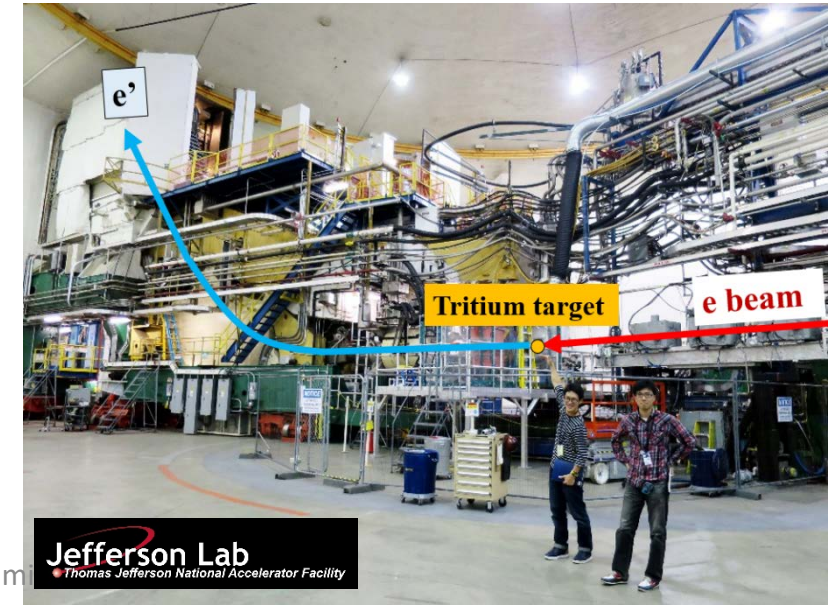
☆ $^{3}\mathrm{H}(e,e'K^{+})nn\Lambda$ (E12-17-003; Oct—Nov 2018)
→ Investigation of the unknkown $n\Lambda$ interaction

☆ $^{3,4}\mathrm{He}(e,e'K^{+})^{3,4}_{\Lambda}\mathrm{H}$ (TG *et al.*, *LOI to PAC46*)
→ Λ hypertriton puzzle, ΛN CSB

☆ $^{40,48}\mathrm{Ca}(e,e'K^{+})^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008)
→ Isospin dependence of the ΛN/ΛNN interaction
(+ $^{6,7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{10,11}_{\Lambda}$Be, $^{12}_{\Lambda}$B)

☆ $^{208}_{\Lambda}\mathrm{Pb}(e,e'K^{+})^{208}_{\Lambda}\mathrm{Tl}$ (O. Benhar *et al.*, *Proposal to PAC46*)
✓ Detailed spectroscopy of heavy hypernucleus





Backup

ΔB_Λ of isotopic mirror pairs (g.s.)

Mirror pairs	$\Delta B_\Lambda^{theor.}$ [keV]	Experiment	$\Delta B_\Lambda^{exp.}$ [keV]
${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$	$+226$[1]	Emul.(279 evts) – Emul.(155 evts)	$+350 \pm 60$
		Emul. – MAMI	$+270 \pm 100$
${}^{7}_{\Lambda}\mathrm{Be} - {}^{7}_{\Lambda}\mathrm{Li}^{*}$	-17[1], -70[2]	Emul.(35 evts) – [Emul.(226)+γ]	-100 ± 90
${}^{7}_{\Lambda}\mathrm{Li}^{*} - {}^{7}_{\Lambda}\mathrm{He}$	-80[2], -28[5]	(Emul.+γ) – JLab_2005	-420 ± 250
		(Emul.+γ) – ***JLab_2009***	-290 ± 140
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	$+49$[1]	Emul.(68 evts) – Emul. (787 evts)	$+40 \pm 60$
${}^{9}_{\Lambda}\mathrm{B} - {}^{9}_{\Lambda}\mathrm{Li}$	-54[1]	Emul.(3 evts) – Emul.(13 evts)	-210 ± 220
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	-136[1], -180[3]	Emul.(10 evts) – Emul. (3 evts)	-220 ± 250
		Emul. – ***JLab_2009***	$+290 \pm 220$
${}^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$		Emul. – Emul. + correction[4]	-70 ± 200
		Emul. – ***JLab_2009*** + correction	-250 ± 190

[1] A.Gal, PLB 744, 352 (2015)
[2] E.Hiyama *et al.*, PRC 80, 054321 (2009), w/o CSB
[3] E.Hiyama and Y.Yamamoto., PTP 128, 1 (2012), w/o CSB
[4] T. Gogami et al., PRC 93, 034314 (2016)
[5] A. Gal, JPS Conf. Proc. 17, 011006 (2017)

Future hypernuclear projects at JLab

☆ $^{3}\mathrm{H}(e,e'K^{+})\mathrm{nn}\Lambda$ (2018 Nov-Dec)

→ Investigation of the unknkown **nΛ** interaction

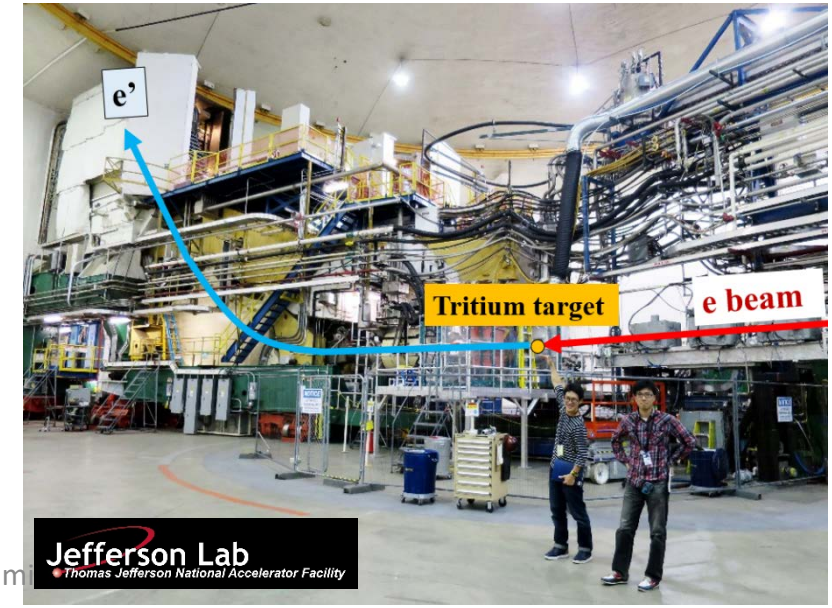
☆ $^{40,48}\mathrm{Ca}(e,e'K^{+})\,^{40,48}_{\Lambda}\mathrm{K}$ (2020-)

→ Isospin dependence of the ΛN/ΛNN interaction

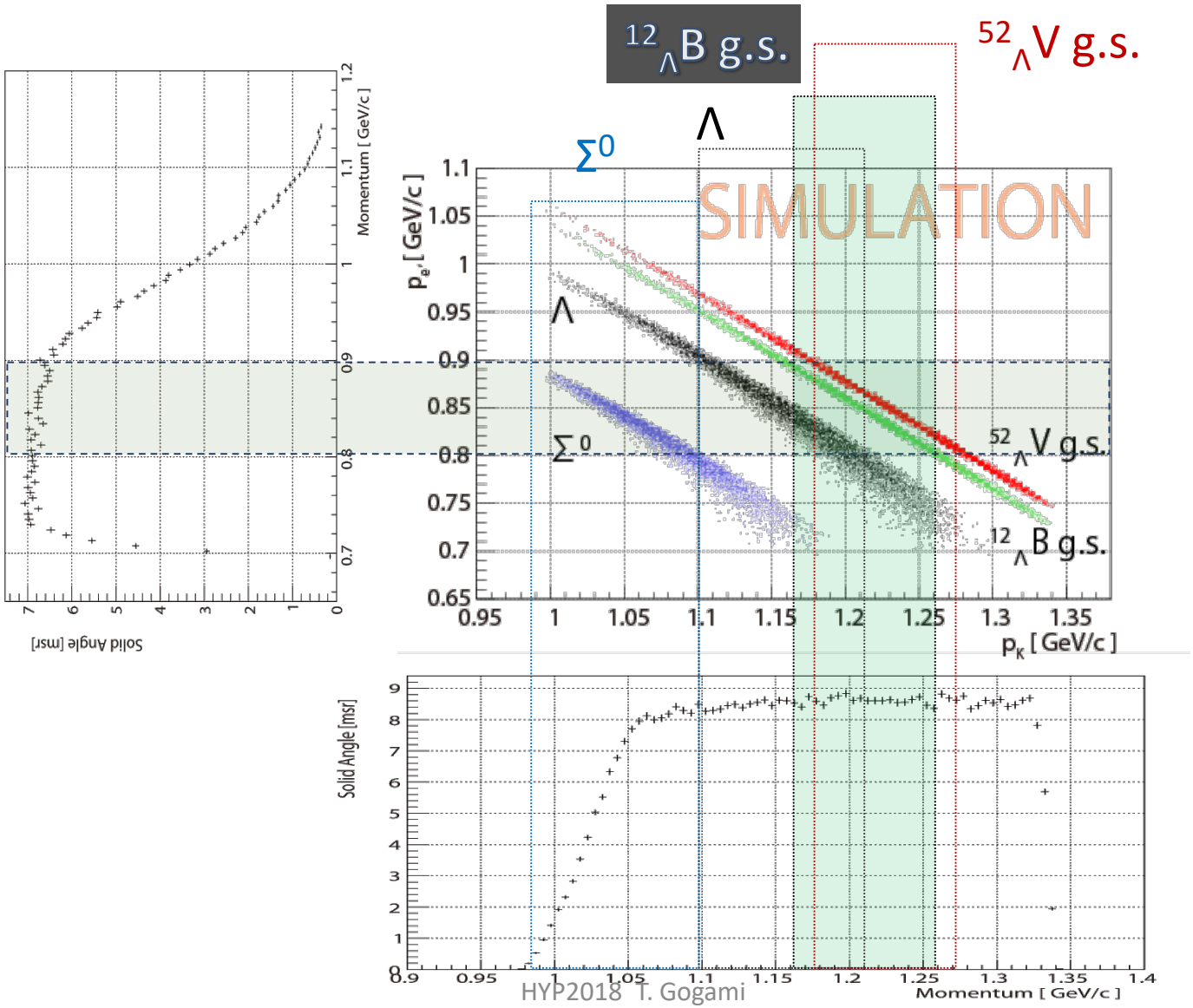
(+ $^{6,7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{10,11}_{\Lambda}$Be, $^{12}_{\Lambda}$B)

☆ $^{208}_{\Lambda}\mathrm{Pb}(e,e'K^{+})\,^{208}_{\Lambda}\mathrm{Tl}$ (LOI submitted)

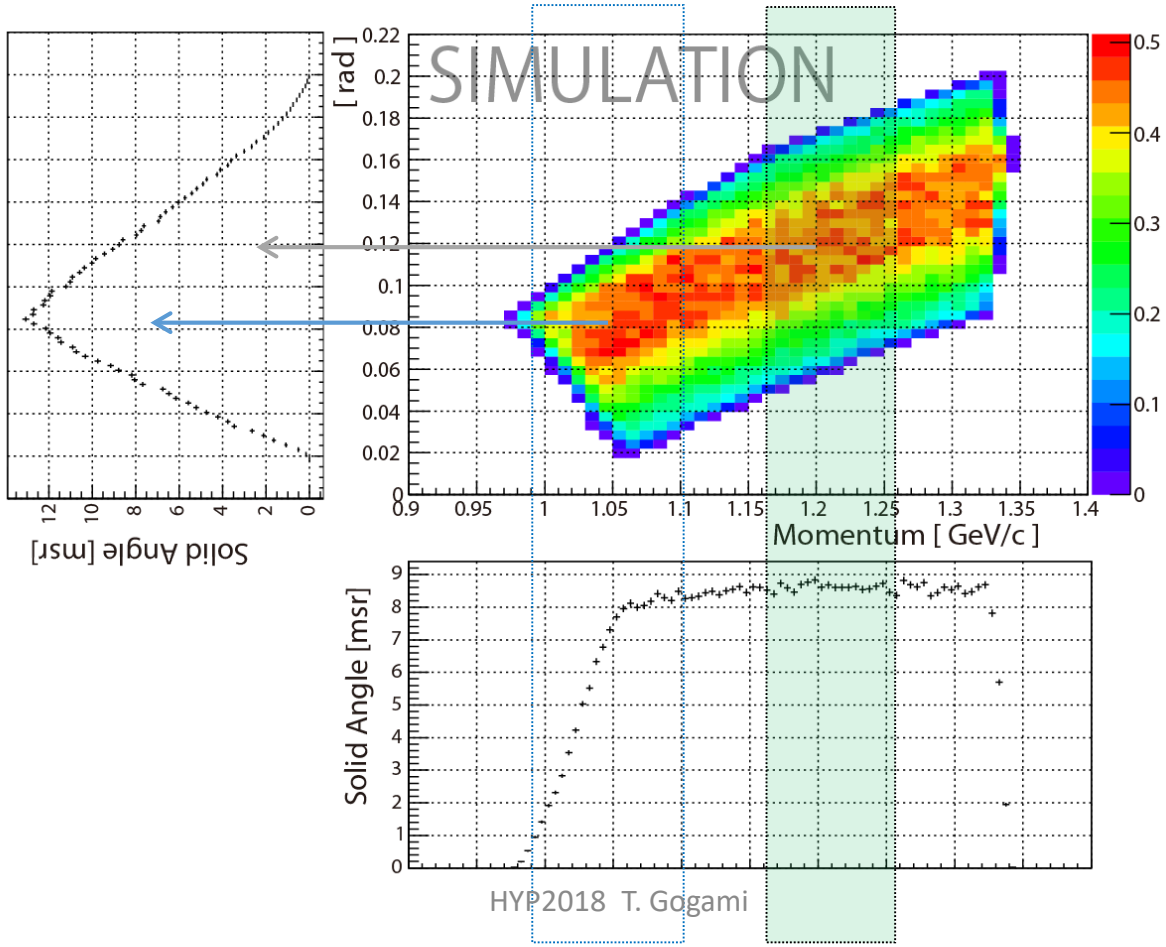
✓ Detailed spectroscopy of heavy hypernucleus



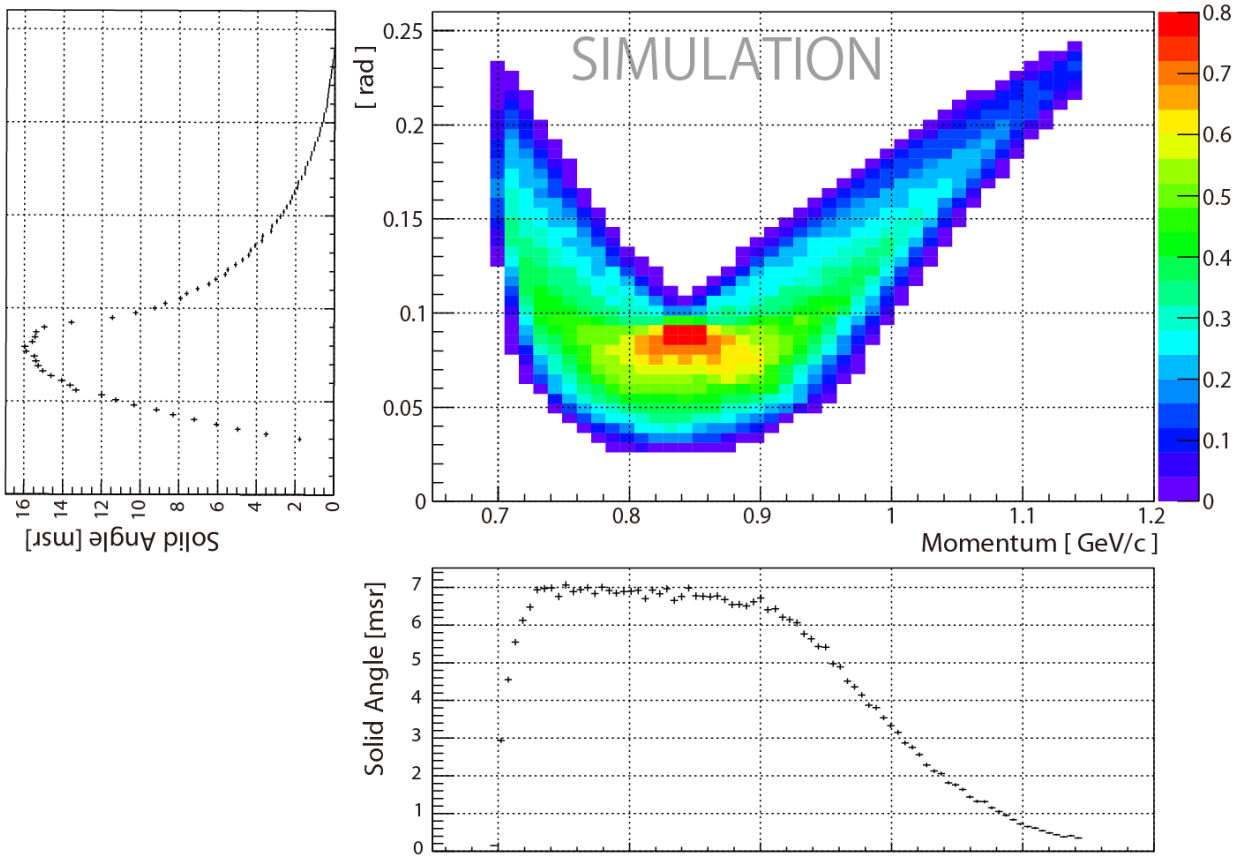
Concern 1 (HES HKS matching)



Concern 2
Different momentum region
→ different angular region



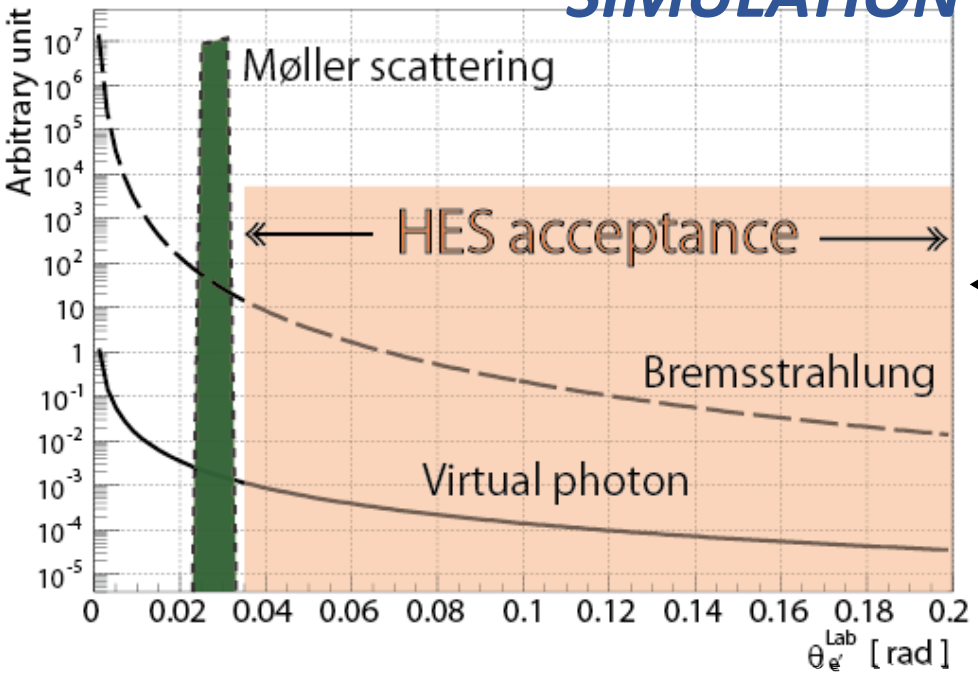
HES solid angle



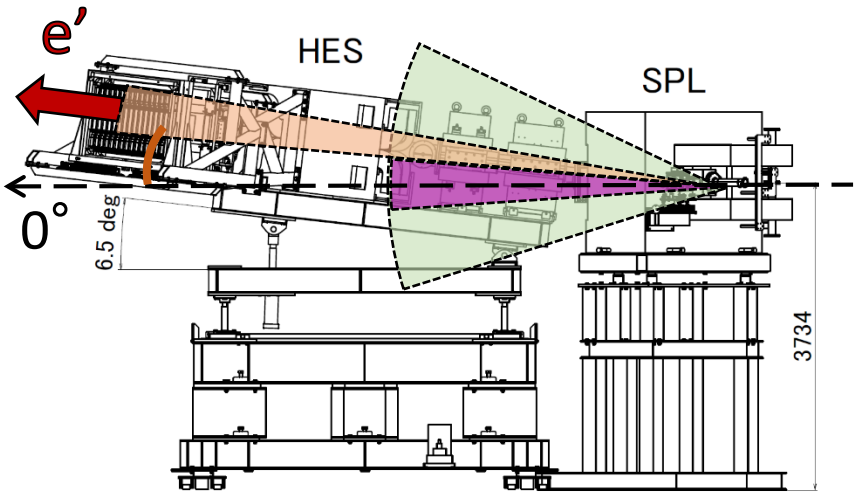
Background electrons in HES

E89-009 → E01-011
e' rate: 1/200
Luminosity: ×200

SIMULATION



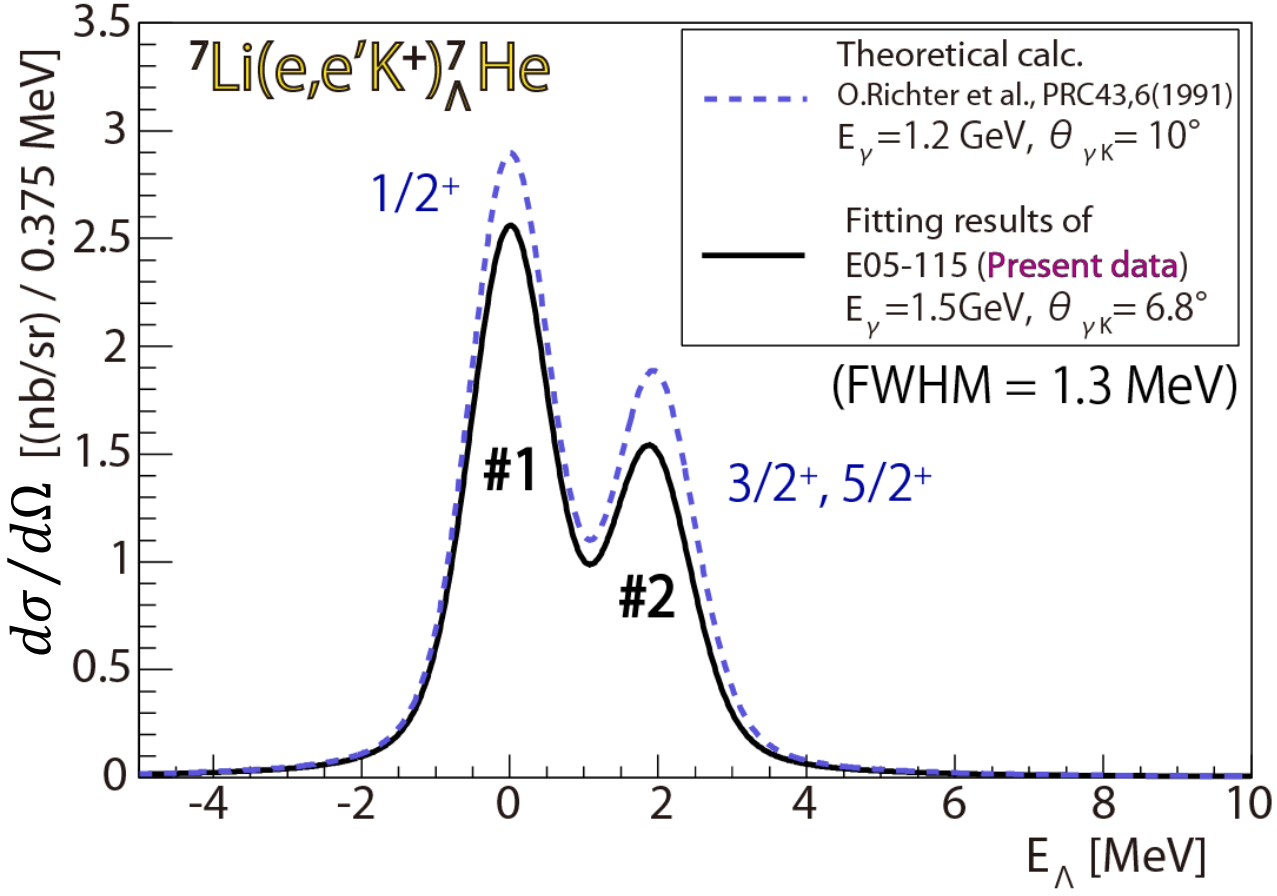
Tilt method



E_e = 2.344
$p_{e'}$ = 0.844 MeV/c
$\Delta p_{e'}$ = ±150 MeV/c

Optimized tilt angle = **6.5 deg**
(S/N and Yield)

Comparison with theoretical prediction of the differential cross section



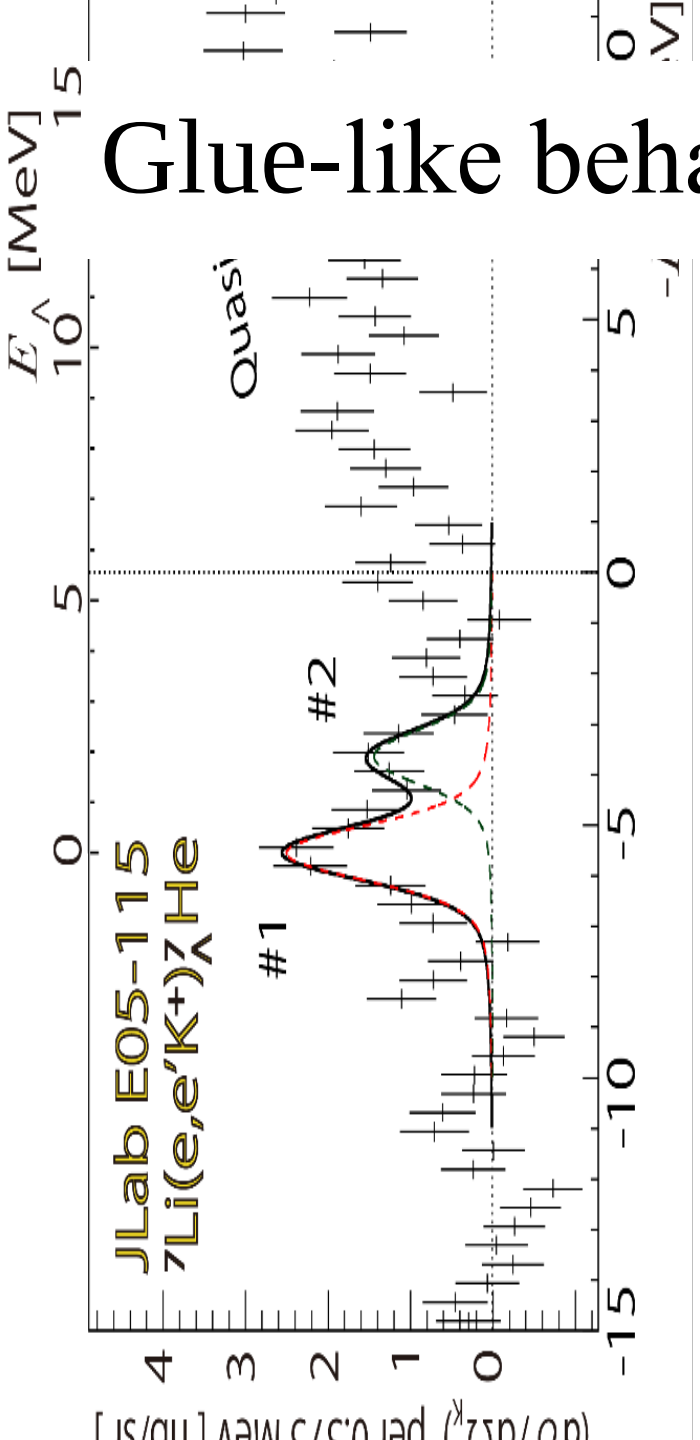
Theoretical Prediction

$1/2^+:(3/2^+,5/2^+)$ = 0.63

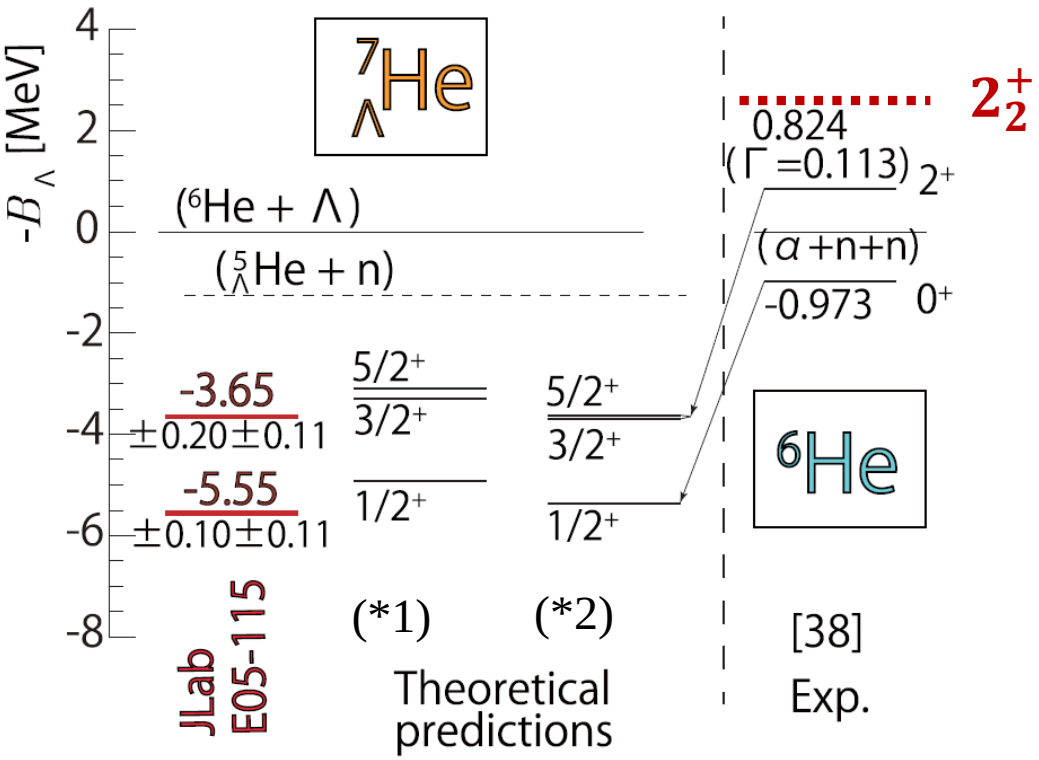
JLab E05-115

#1 : #2 $= 0.61 \pm 0.08$

Glue-like behavior of Λ in a nucleus



T. Gogami *et al.*, *Phys. Rev. C* **94**, 021302(R) (2016).



(*1) O. Richter *et al.*, *Phys. Rev. C* **43**, 2753 (1991).
(*2) E. Hiyama *et al.*, *Phys. Rev. C* **91**, 054316 (2015).

ΔB_Λ of isotopic mirror pairs (g.s.)

Mirror pairs	$\Delta B_\Lambda^{theor.}$ [MeV]	Experiment	$\Delta B_\Lambda^{exp.}$ [MeV]
${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$	$+0.226$[1]	Emul. - Emul.	$+0.35 \pm 0.06$
		Emul. - MAMI	$+0.27 \pm 0.10$
${}^{7}_{\Lambda}\mathrm{Be} - {}^{7}_{\Lambda}\mathrm{Li}^{*}$	-0.017[1], -0.070[2]	Emul. - (Emul.+ γ)	-0.10 ± 0.09
${}^{7}_{\Lambda}\mathrm{Li}^{*} - {}^{7}_{\Lambda}\mathrm{He}$	-0.080[2]	(Emul.+ γ) - JLab_2005	-0.42 ± 0.04
		(Emul.+ γ) - *JLab_2009*	-0.29 ± 0.14
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	$+0.049$[1]	Emul. - Emul.	$+0.04 \pm 0.06$
${}^{9}_{\Lambda}\mathrm{B} - {}^{9}_{\Lambda}\mathrm{Li}$	-0.054[1]	Emul. - Emul.	-0.21 ± 0.22
		Emul. - JLab_A	-0.07 ± 0.20
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	-0.136[1], -0.180[3]	Emul. - Emul.	-0.22 ± 0.25
		Emul. - *JLab_2009*	$+0.29 \pm 0.14$
${}^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$		Emul. - Emul.	~~-0.61 ± 0.20~~ -0.07 ± 0.20
		Emul. - Other_(e,e'K^+)	Consistent with above
		Emul. - *JLab_2009*	~~-0.79 ± 0.19~~ -0.25 ± 0.19

[1] A.Gal, PLB 744, 352 (2015)

[2] E.Hiyama *et al.*, PRC 80, 054321 (2009), w/o CSB

[3] E.Hiyama and Y.Yamamoto., PTP 128, 1 (2012), w/o CSB

JLab E05-115
$^{10}_{\Lambda}$Be
(Fit I)
#1
#2
#3
#4
a
E_Λ [MeV]
$d\sigma/d\Omega_K$ per 0.3 MeV [nb/sr]
^{9}Be
$^{10}_{\Lambda}$Be
$^{10}_{\Lambda}$B
E_x [MeV]
Exp.
Exp.
Theoretical calculations
Exp.
11.28 7/2⁻
6.76 7/2⁻
2.78 1/2⁻
2.43 5/2⁻
1.68 1/2⁺
0.0 3/2⁻
10.83
8.34
6.26
2.78
0.0
4⁻
3⁻, 4⁻
3⁻, 4⁻
2⁻, 3⁻
1⁻, 0⁻
0⁺, 1⁺
0⁺, 1⁺
2⁻, 3⁻
2⁻, 3⁻
2⁻, 3⁻
1⁻, 2⁻
1⁻, 2⁻
1⁻, 2⁻
1⁻, 2⁻
9.5
6.2
2.5
0.0
[35]
[32]
[33]
[23]
[34]
[31]
JLab E05-115 (Present data)
EXCITATION ENERGY Ex
2^- 1^- 3^- 2^- 4^- 3^- 4^-

Particle Detectors & Trigger

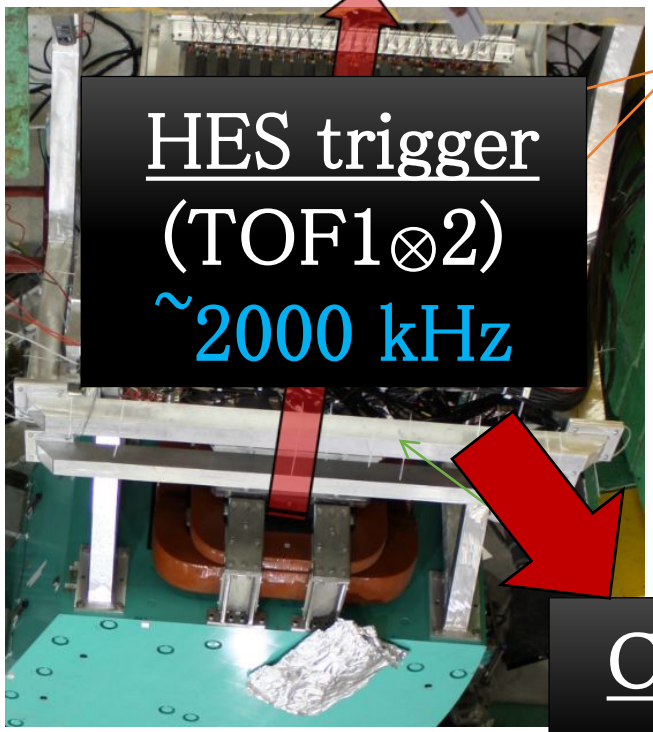
HES

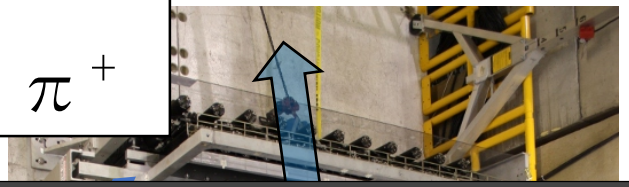
e^-

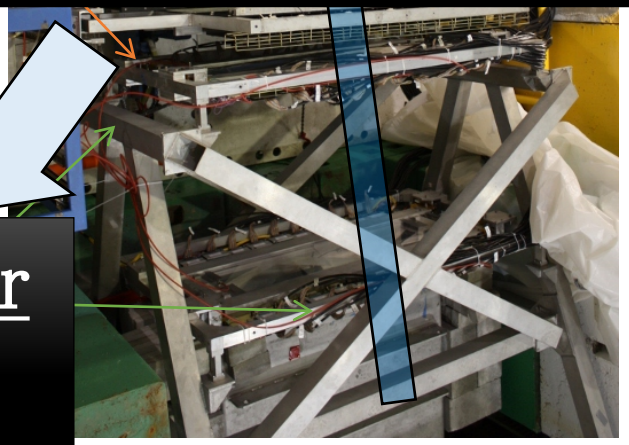
HKS

K^+

$p,\ \pi^+$







TOF walls
(Plastic scintil

Cherenkov de
- **Aerogel (n=1.05)**
- **Water (n=1.33)**

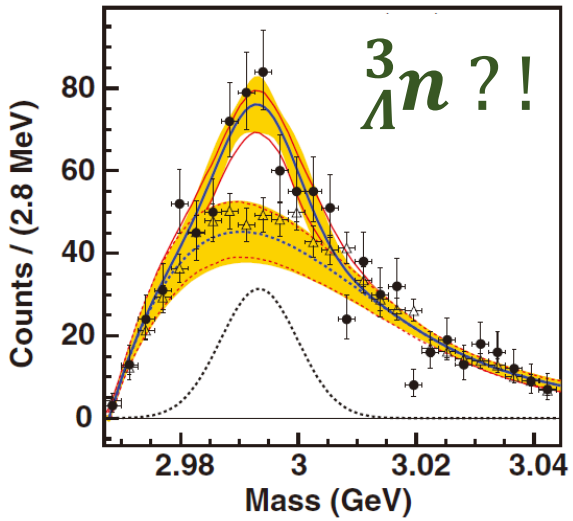
HES trigger
(TOF1⊗2)
~2000 kHz

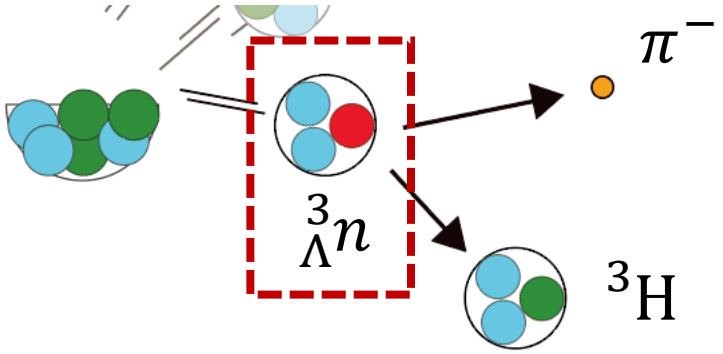
HKS trigger
(TOF1 ⊗ 2 ⊗ 3) ⊗ Cherenkov
~10 kHz

Coincidence trigger
HES ⊗ HKS
< 2 kHz

Bound $nn\Lambda$ state exists?

C. Rappold et al. (HypHI Collaboration), Phys. Rev. C 88, 041001(R) (2013).



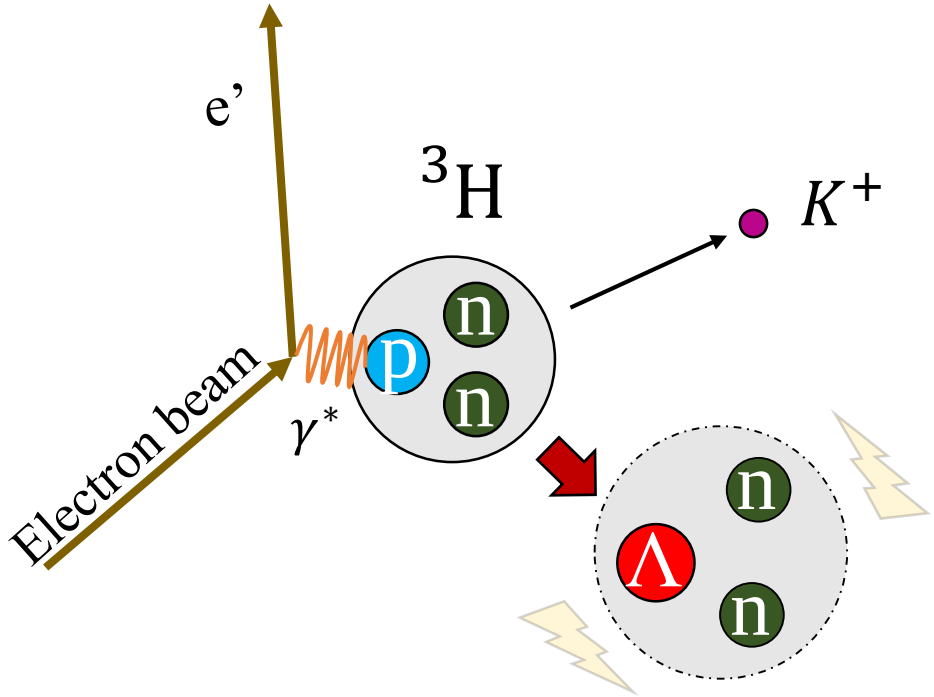


Bound $^{3}_{\Lambda}n$ cannot be reproduced:

E. Hiyama et al., Phys. Rev. C 89, 061302(R) (2014)
A. Gal et al., Phys. Lett. B 736, 93–97 (2014)

Resonance $nn\Lambda$ state might exist:

I.R.Afnan et al., PRC 92, 054608 (2015)
H. Kamada et al., EPJ Web Conf. 113, 07004 (2016)



A tritium target is available
at JLab Hall A for only one year !

→ **^{3}H(e, e′K$^+$)$nn\Lambda$ experiment**

(E12-07-003; approved with A$^-$, high impact)

The nnΛ experiment at JLab (E12-17-003)

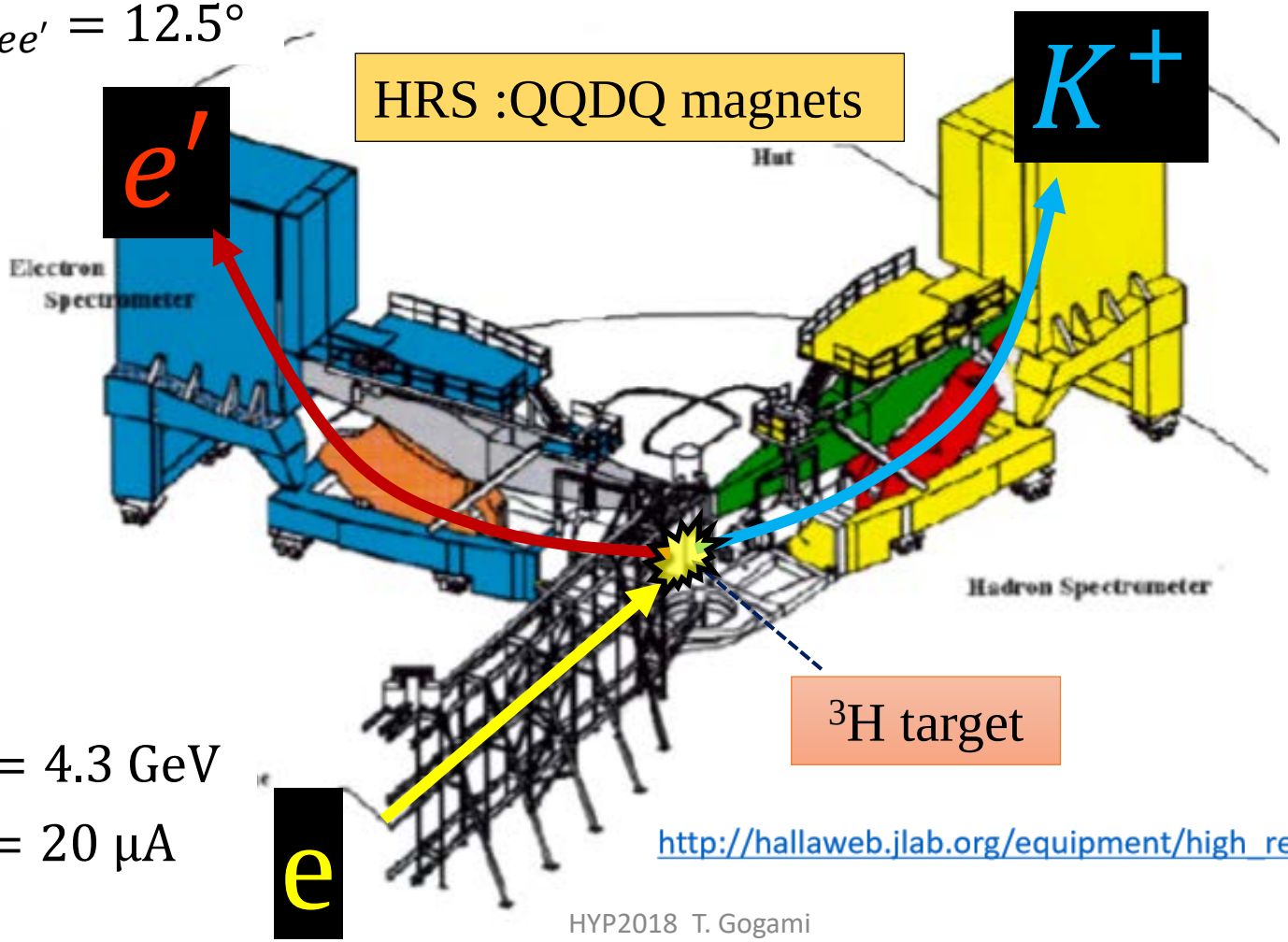
[It starts in October, 2018 !!]

$p_{e'} = 2.18\ \mathrm{GeV}/c \pm 4.5\%$

$\theta_{ee'} = 12.5°$

$p_K = 1.80\ \mathrm{GeV}/c \pm 4.5\%$

$\theta_{eK} = 17.5°$



$E_e = 4.3\ \mathrm{GeV}$

$I_e = 20\ \mu\mathrm{A}$

http://hallaweb.jlab.org/equipment/high_resol.html

Target cell of tritium gas

Cell material:
Al alloy (ASTM B209 AL 7075-T651)

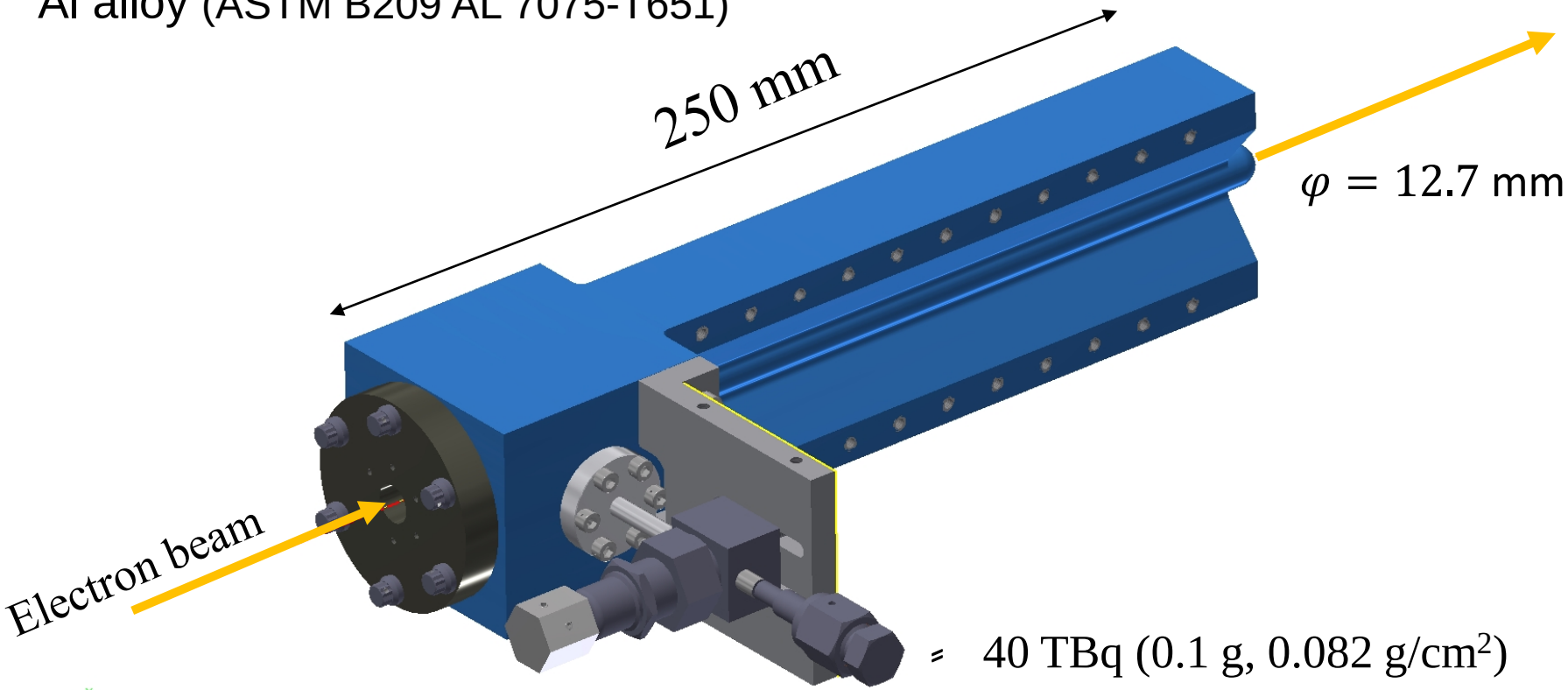
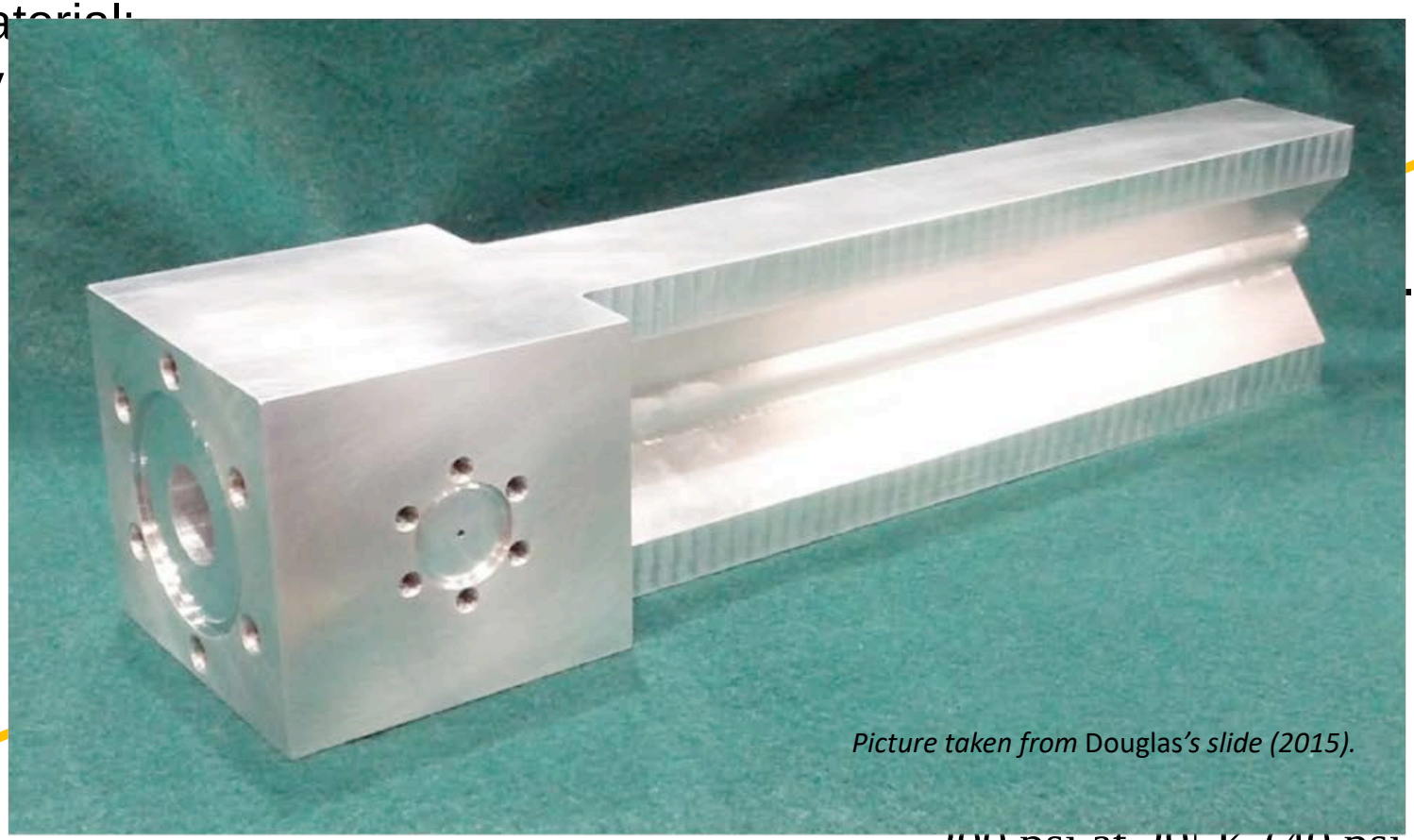


Figure taken from Dave's slide (2015).

- ≒ 40 TBq (0.1 g, 0.082 g/cm^2)
- ≒ 1.4 MPa at 295K (0.3 MPa at 40K)
- ≒ 34 cc

Target cell of tritium gas

Cell material:
Al alloy



Picture taken from Douglas*'s slide (2015).*

.7 mm

- 200 psi at 295K (40 psi at 40K)
- 34 cc

Assumptions for a simple simulation

Quasi-free Λ by SIMC

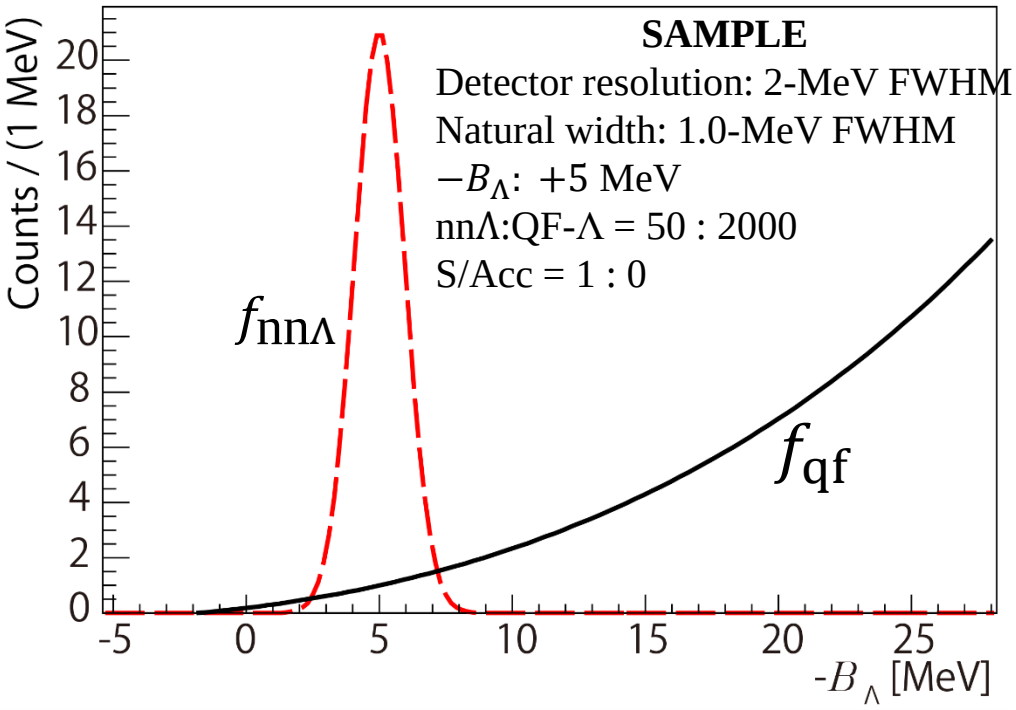
- Number of QF events = 4000
- Distribution is estimated from E91-016 data

nnΛ state

- $N_{nn\Lambda}$ = 60, 120
- Assumed $B_\Lambda = 0, -0.5$ MeV
- Detector resolution = 2 MeV FWHM
- Natural width = 0.5, 1.0 MeV FWHM
- Gaussian distribution

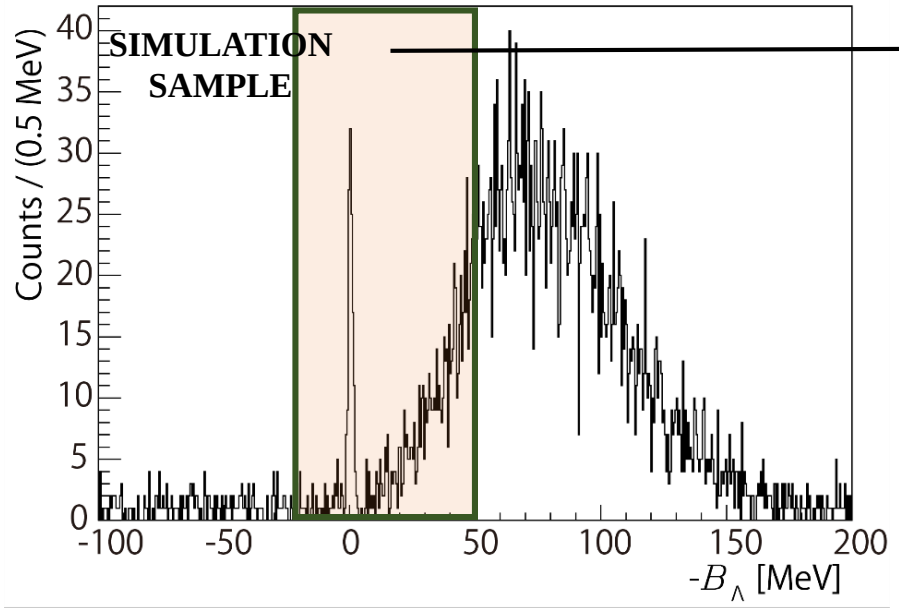
Acidental e’ K^+ events

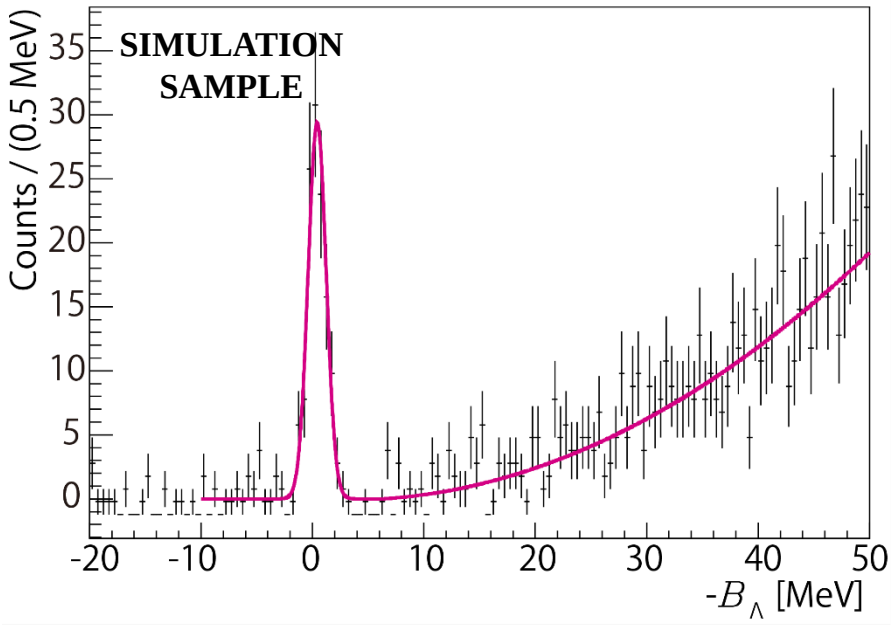
- Estimated by using results of E91-016
- Flat distribution



Simulation results

Detector resolution: 2-MeV FWHM
Natural width: 0.5-MeV FWHM
$-B_\Lambda$: +0.5 MeV
nnΛ:QF-Λ = 120 : 4000

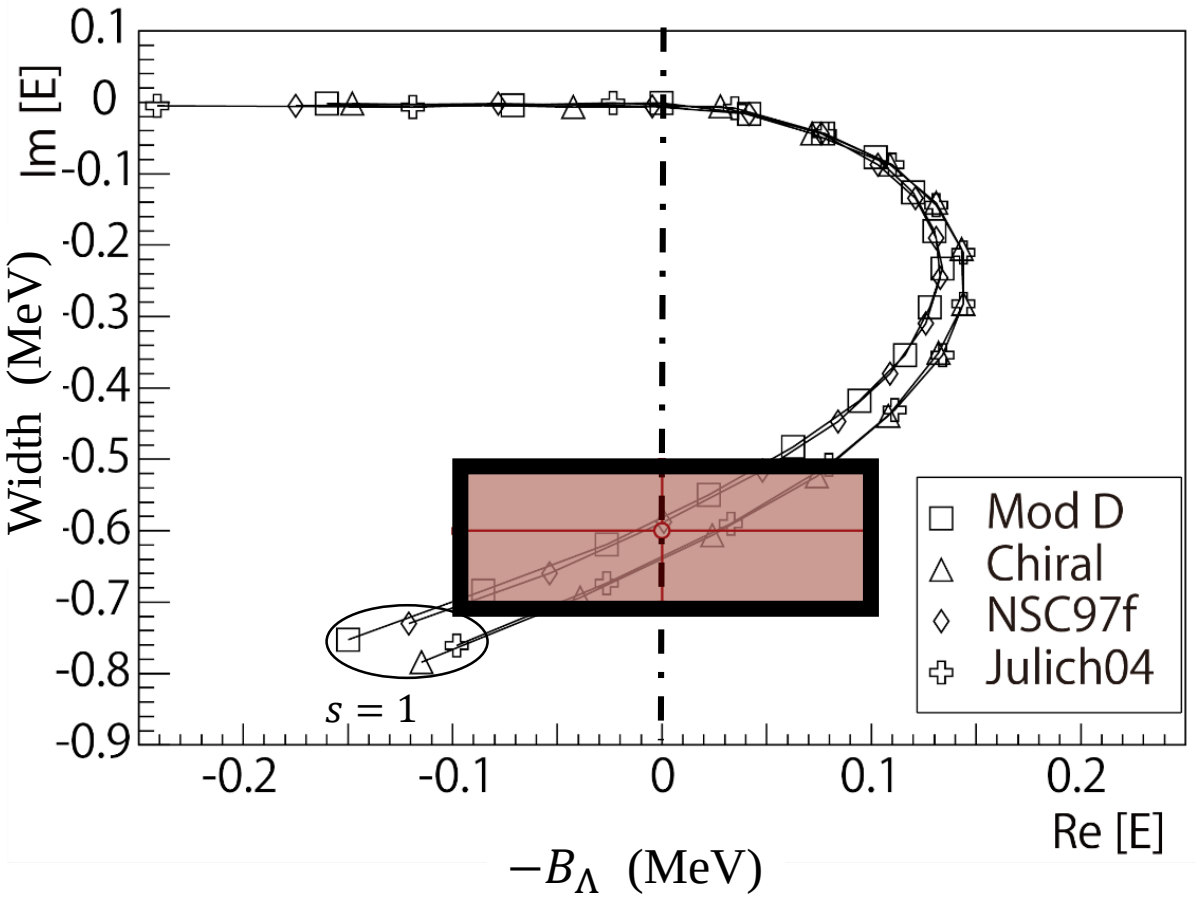




Peak width and binding energy are expected to be measured with a statistical uncertainty of ≈100 keV

Expected accuracy of the experiment

I.R. Afnan and B.F. Gibson, Physical Review C 92, 054608 (2015).



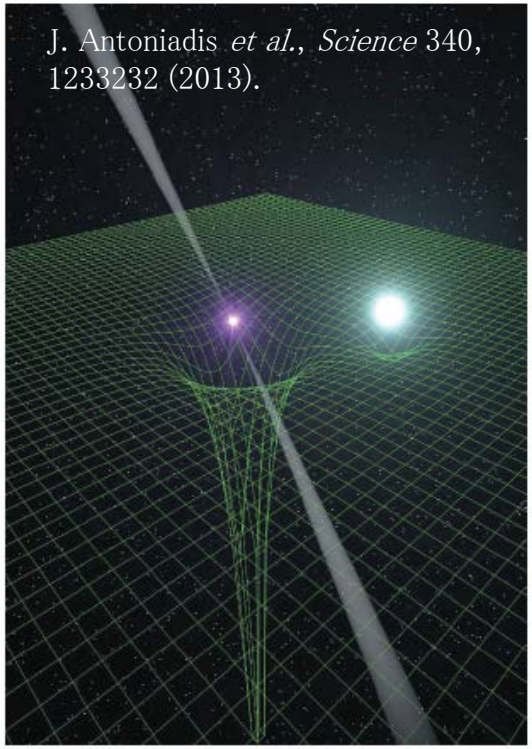
- ✓ The n-n interaction is fixed.
- ✓ A scale factor on the Λ-n int.: **s**
- ✓ $\Delta s = +2.5\%$ for each model

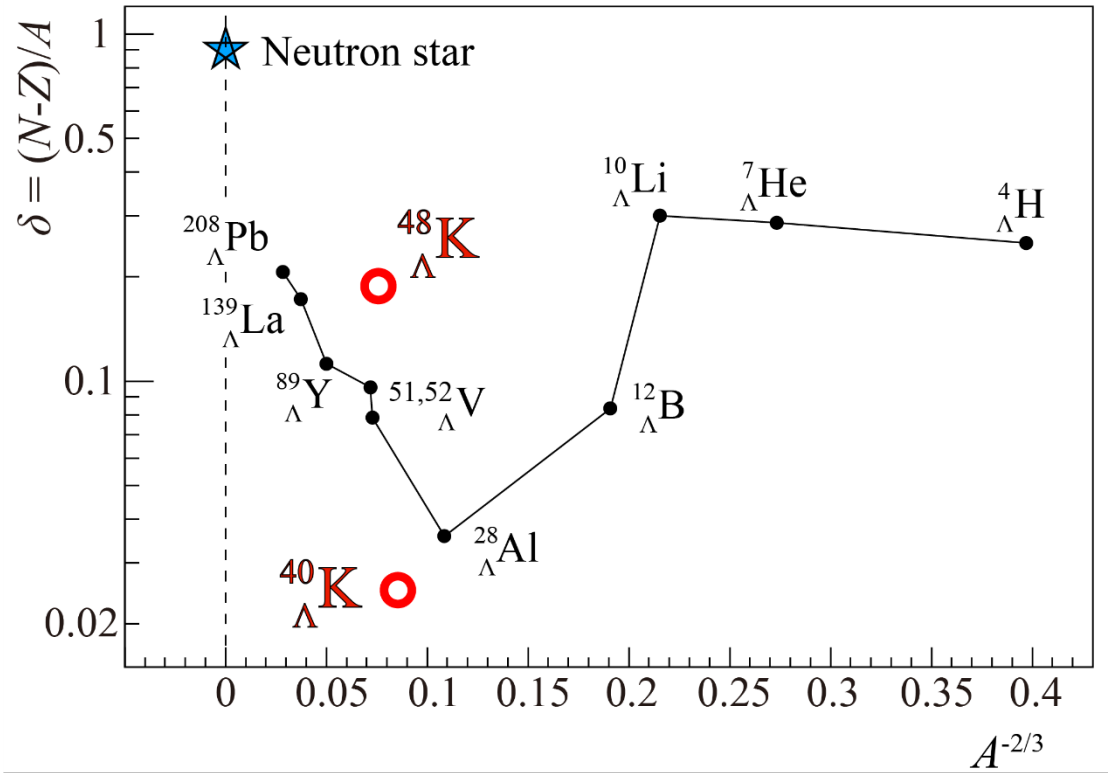
The nnΛ search exp. at JLab (E12-17-003)
→ Unknown Λ-n interaction

New experiment at JLab Hall A (E12-15-008)

$^{40}_{\Lambda}\mathrm{K}$, $^{48}_{\Lambda}\mathrm{K}$

Study of isospin dependence through precise measurement of $^{40,48}\mathrm{Ca}(e,e'K^+)^{40,48}_{\Lambda}\mathrm{K}$





$B_{\Lambda}(^{40,48}_{\Lambda}\mathrm{K})$ with high precision

Neutron star:

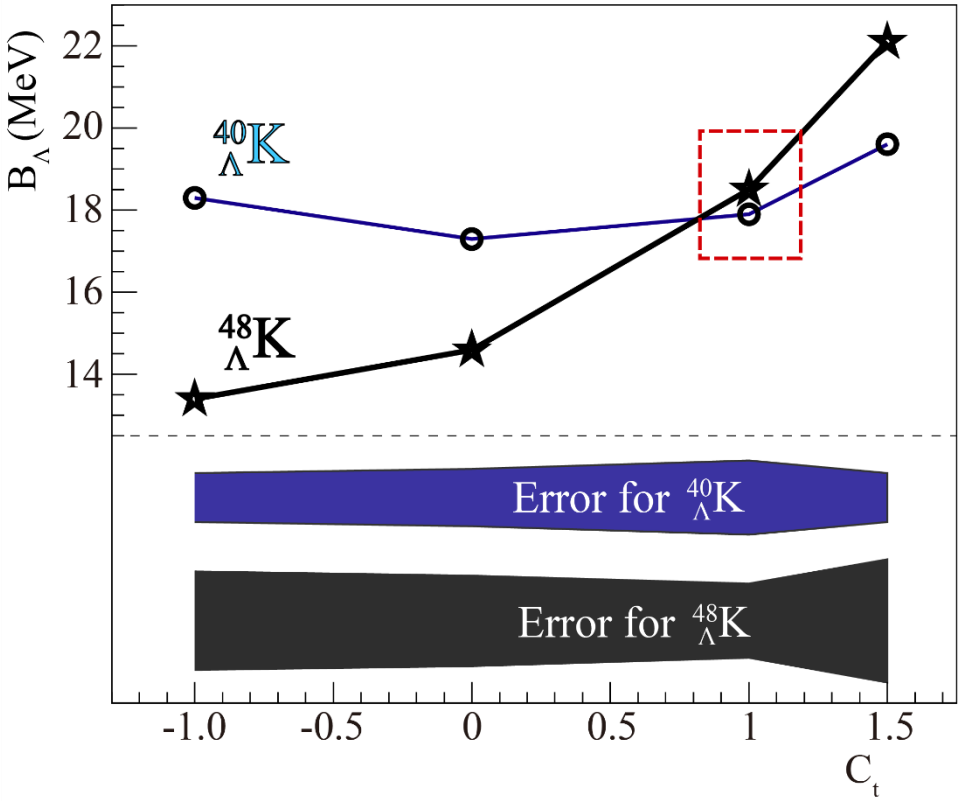
- ✓ Very dense nuclear matter ($\delta = \frac{N-Z}{A} \sim 0.9$)
- ✓ $\leq 2M_{\odot}$ ⇔ Λ inclusion (hyperon puzzle)

Isospin dependence of the *NNΛ* interaction

$B_\Lambda\left({}^{40,48}_{\Lambda}\mathrm{K}\right)$ as a function of isospin triplet strength

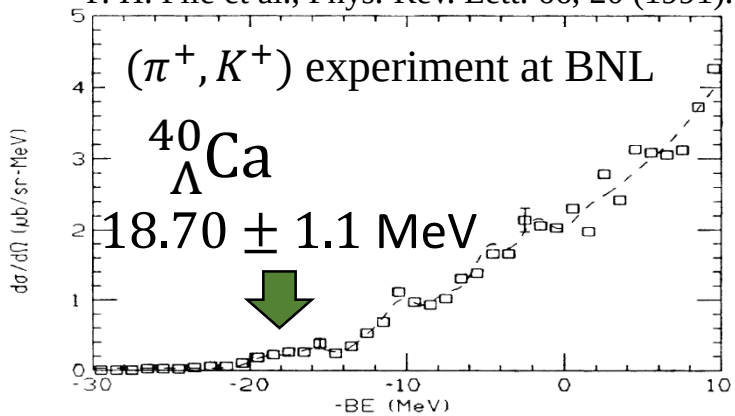
AFDMC calculation

(F. Paderiva et al., arXiv:1506.04042v1 (2015))

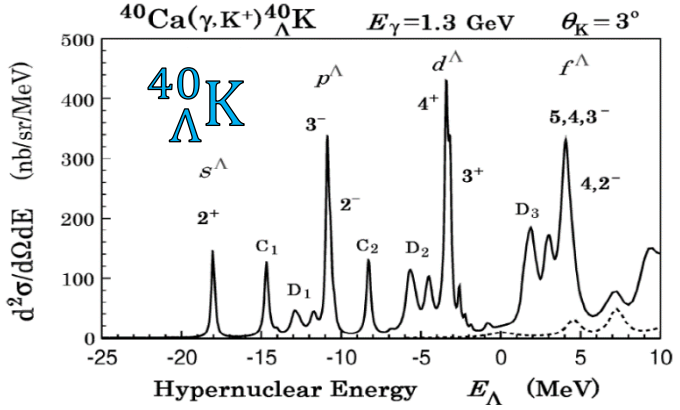


C_t: Strength factor for the isospin triplet term

P. H. Pile et al., Phys. Rev. Lett. 66, 20 (1991).



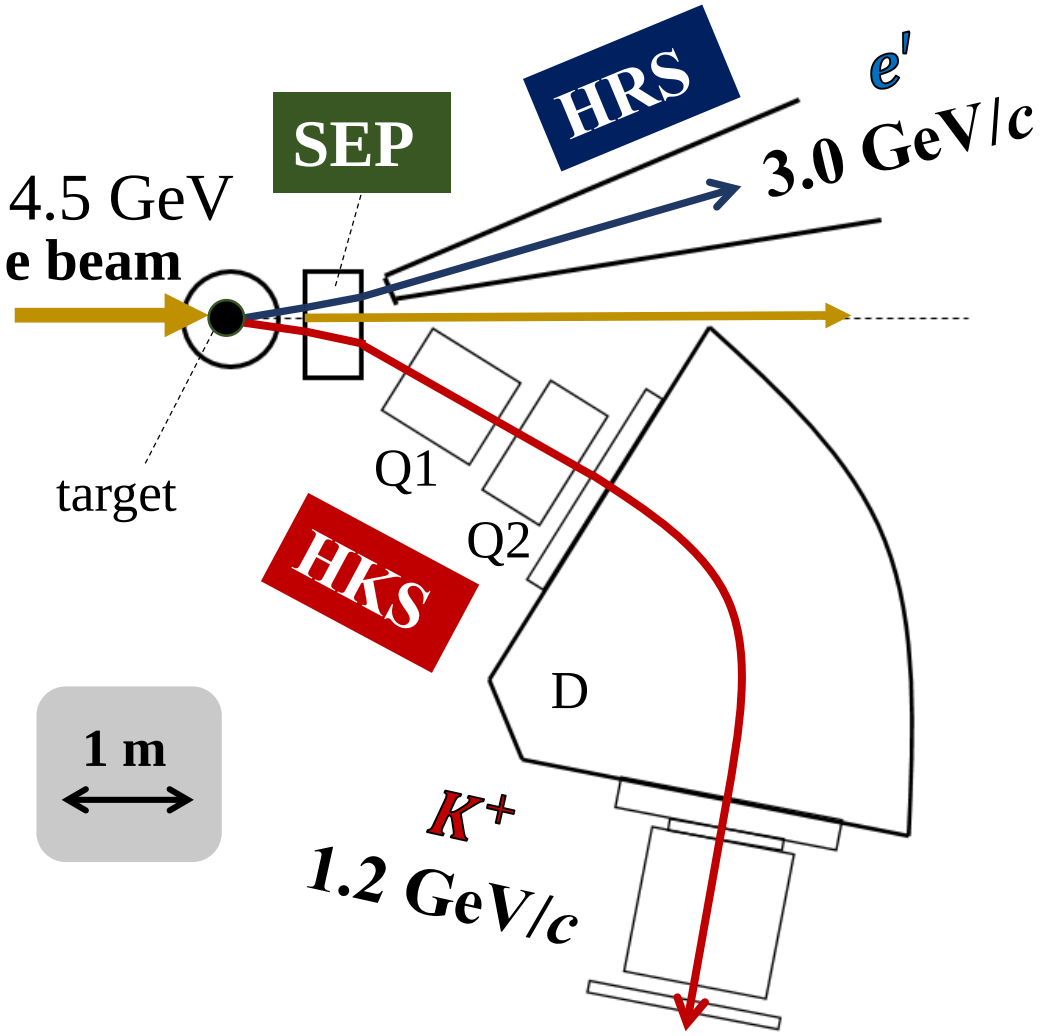
T. Motoba et al., Prog. Theor. Phys. Suppl., 185, 224 (2010).

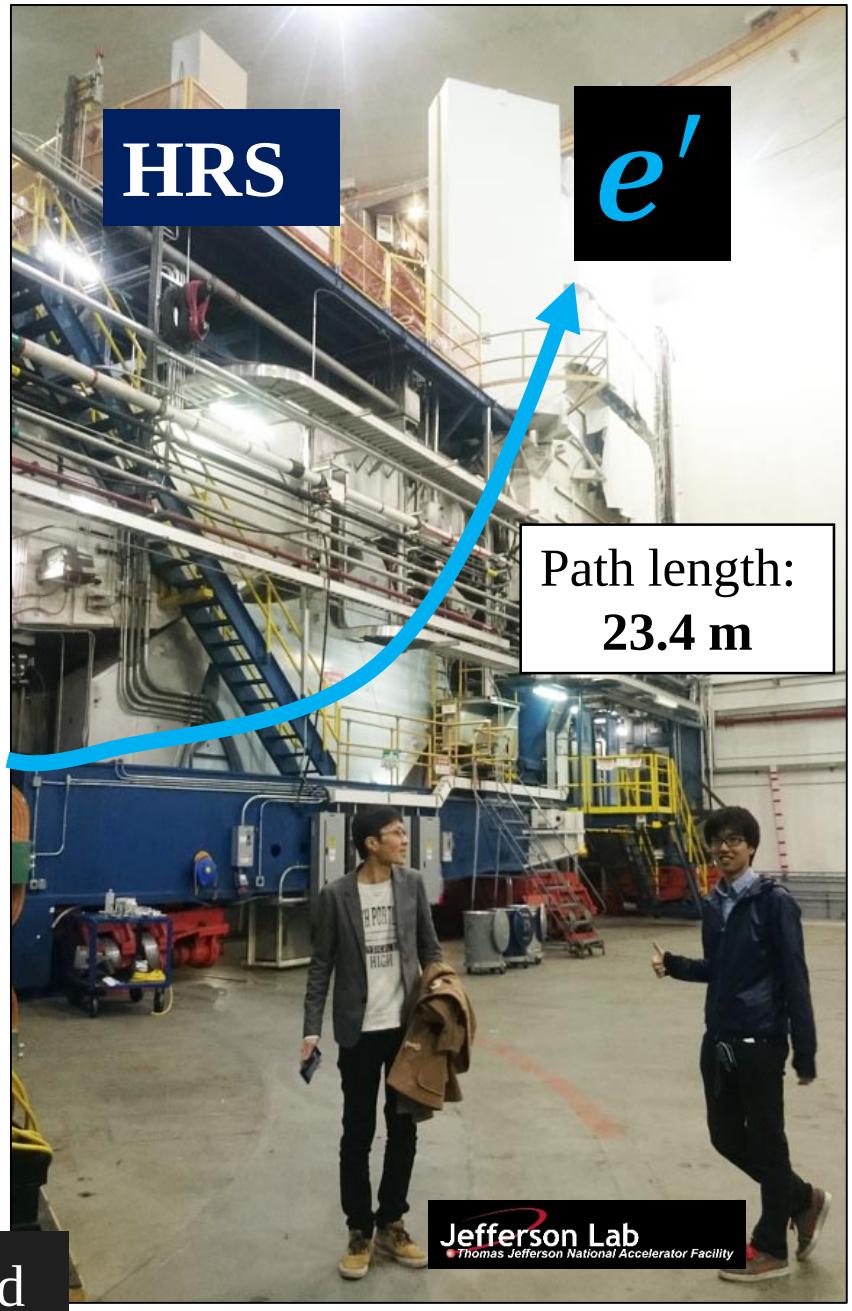


$B_\Lambda\left({}^{40}_{\Lambda}\mathrm{K}\right) - B_\Lambda\left({}^{48}_{\Lambda}\mathrm{K}\right)$ with $<$ **100 keV accuracy**

→ Insights for the isospin dependence of ΛNN force

Experimental setup





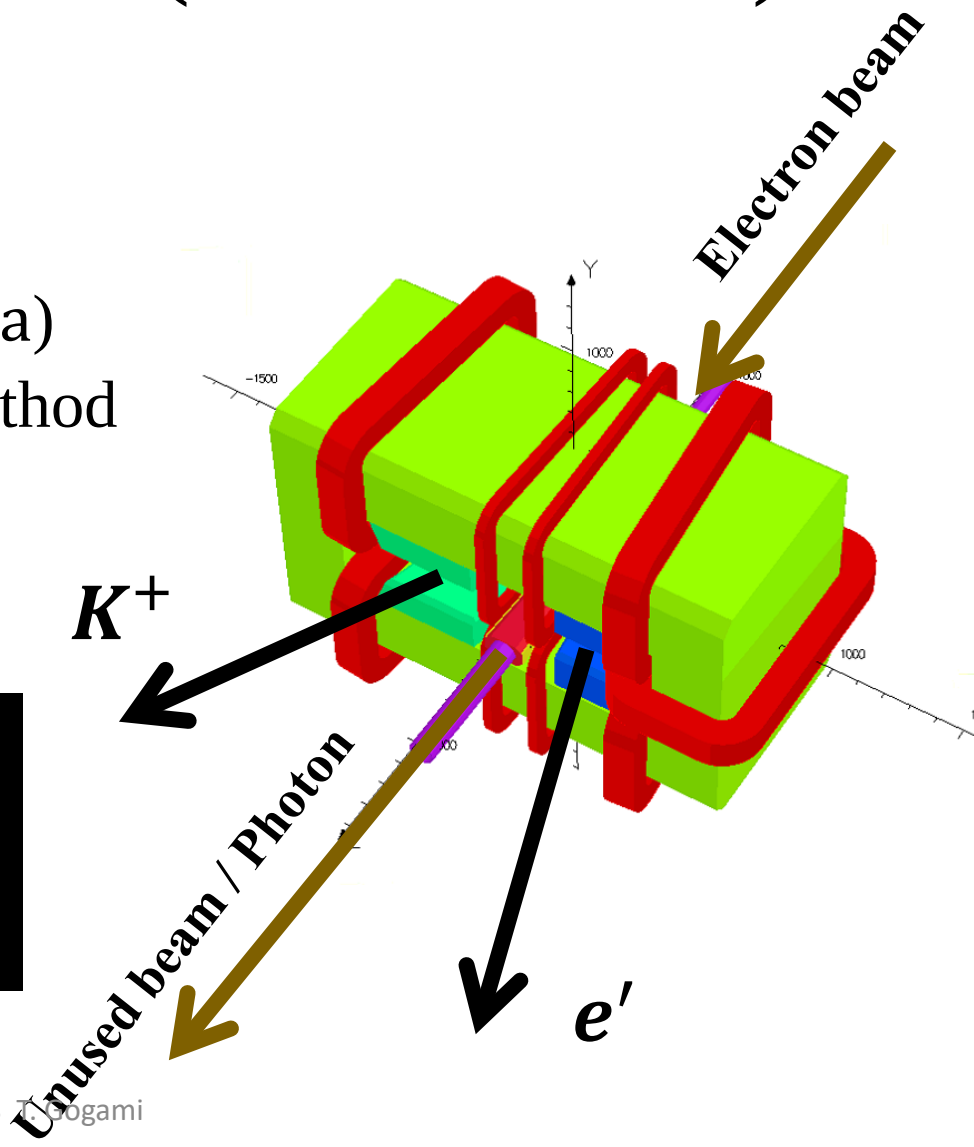
$\Delta p/p = 2 \times 10^{-4}$ + our calibration method

→ ΔE_Λ = 600 keV FWHM, $\Delta B_\Lambda \leq$ 100 keV

What to do for the experiment for *A*=40, 48 hypernuclei (E12-15-008)

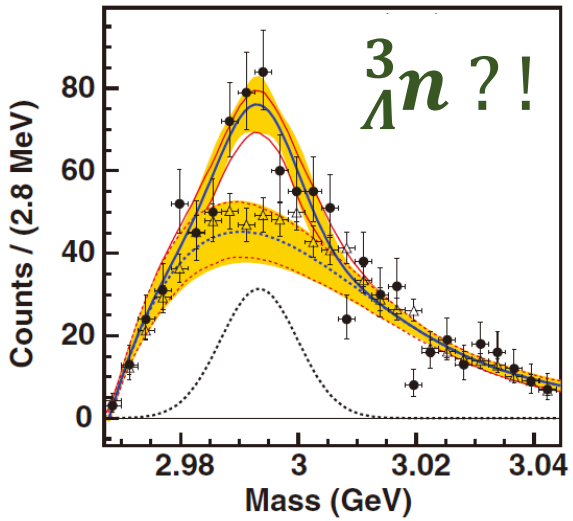
- ☆Design of septum magnet
- ☆Design of target system (^{40,48}Ca)
- ☆Development of calibration method
- ☆Detector commissioning
- ☆Spectrometer installation

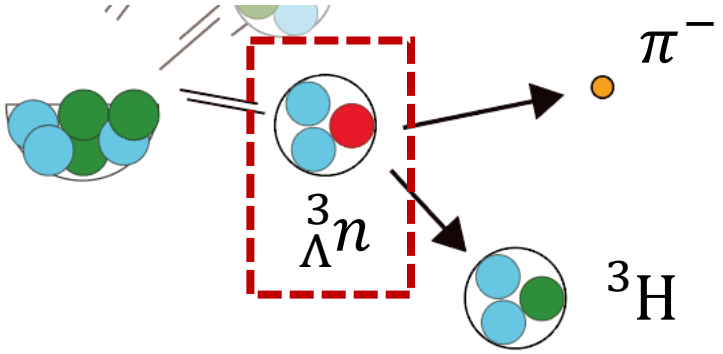
We are now preparing for the experiment, aiming to perform it in 2020 !



Bound $nn\Lambda$ state exists?

C. Rappold et al. (HypHI Collaboration), Phys. Rev. C 88, 041001(R) (2013).



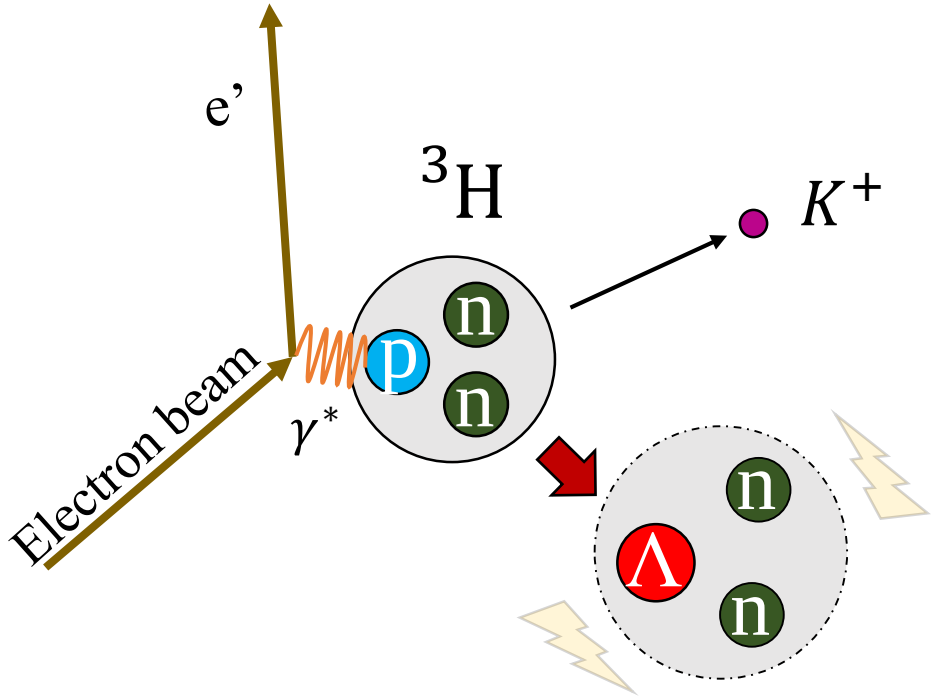


Bound $^{3}_{\Lambda}n$ cannot be reproduced:

E. Hiyama et al., Phys. Rev. C 89, 061302(R) (2014)
A. Gal et al., Phys. Lett. B 736, 93–97 (2014)

Resonance $nn\Lambda$ state might exist:

I.R.Afnan et al., PRC 92, 054608 (2015)
H. Kamada et al., EPJ Web Conf. 113, 07004 (2016)



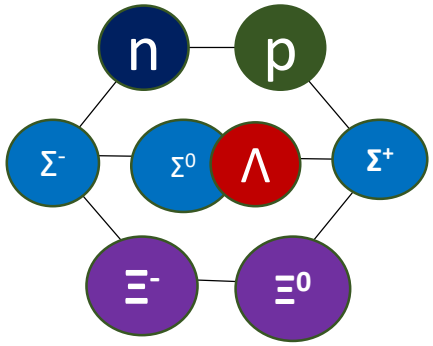
A tritium target is available
at JLab Hall A for only one year !

→ **^{3}H(e, e′K$^+$)$nn\Lambda$ experiment**

(E12-07-003; approved with A$^-$, high impact)

Significance of Λ hypernuclear investigation

① **Baryon-Baryon interaction in SU(3) symmetry**



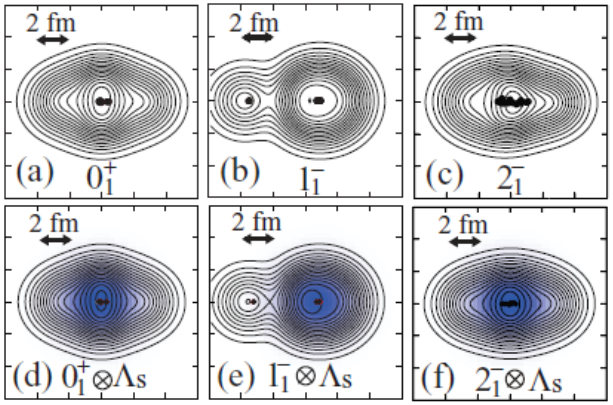
② **Investigation of deeply inside nucleus**

No Pauli blocking from nucleons

③ **Impurity effects**

✓ Shrinkage

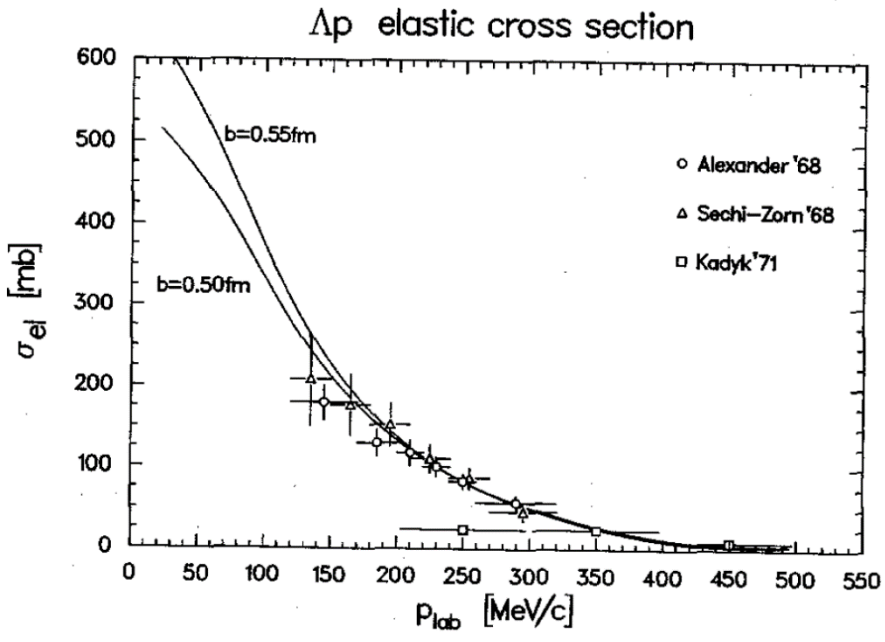
✓ Deformation



M.Isaka et al., Phys. Rev. C 83, 054304 (2011).

Study in the ΛN interaction

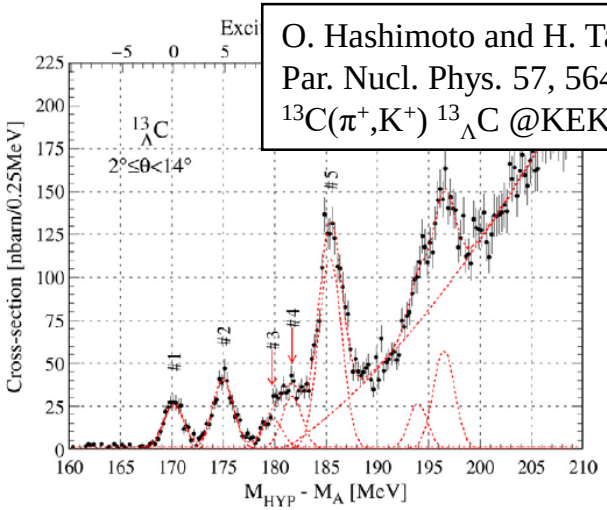
Scarce data for ΛN scattering



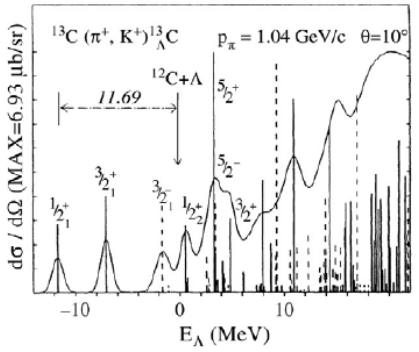
A. Faessler et al., Phys. Lett. B 183, 1 (1987).

J-PARC E40 experiment:
Σp scattering experiment

Hypernuclear structure → ΛN interaction



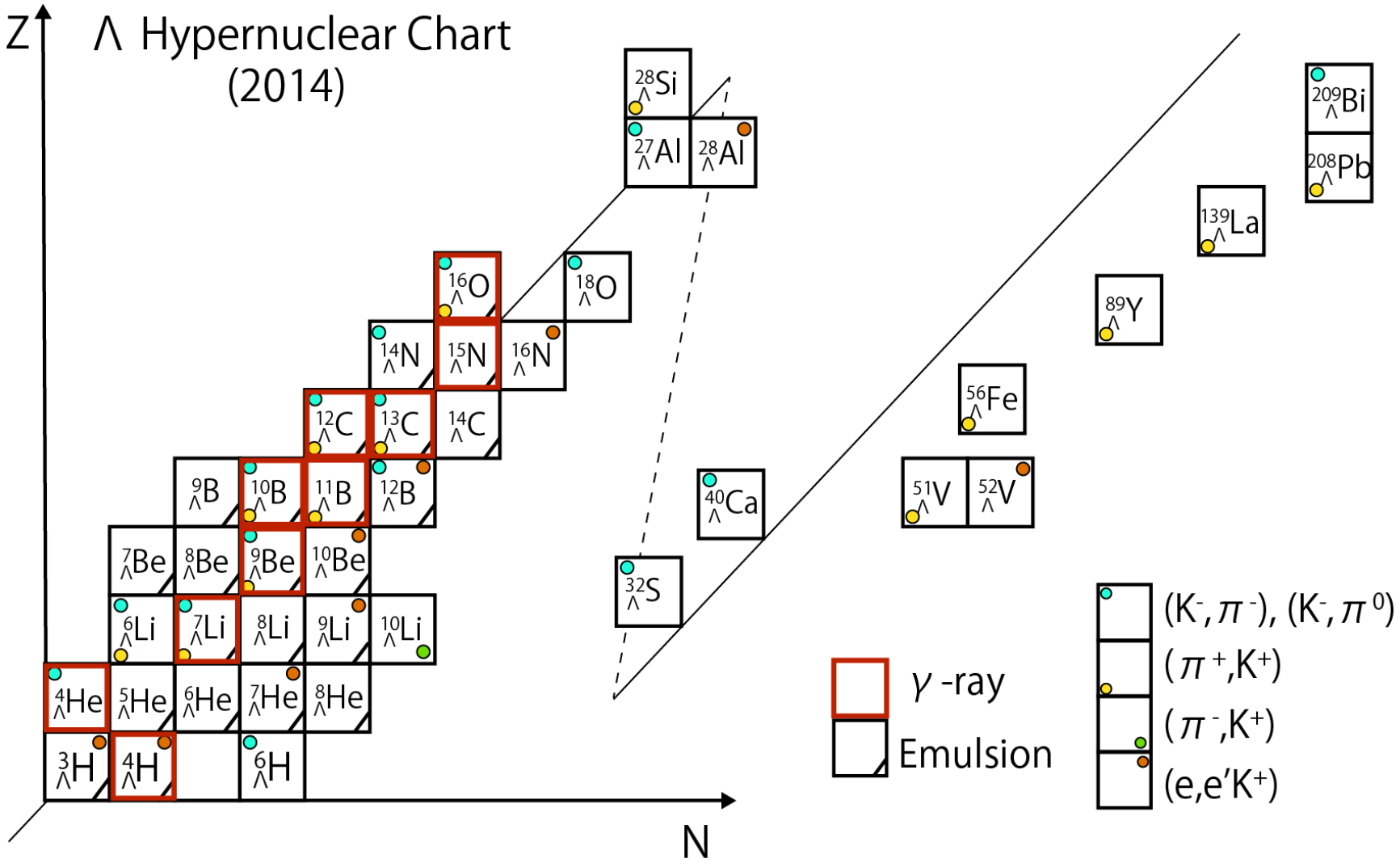
O. Hashimoto and H. Tamura, Prog. Par. Nucl. Phys. 57, 564 (2006);
^{13}C(π^+,K^+) $^{13}_{\Lambda}$C @KEK E336



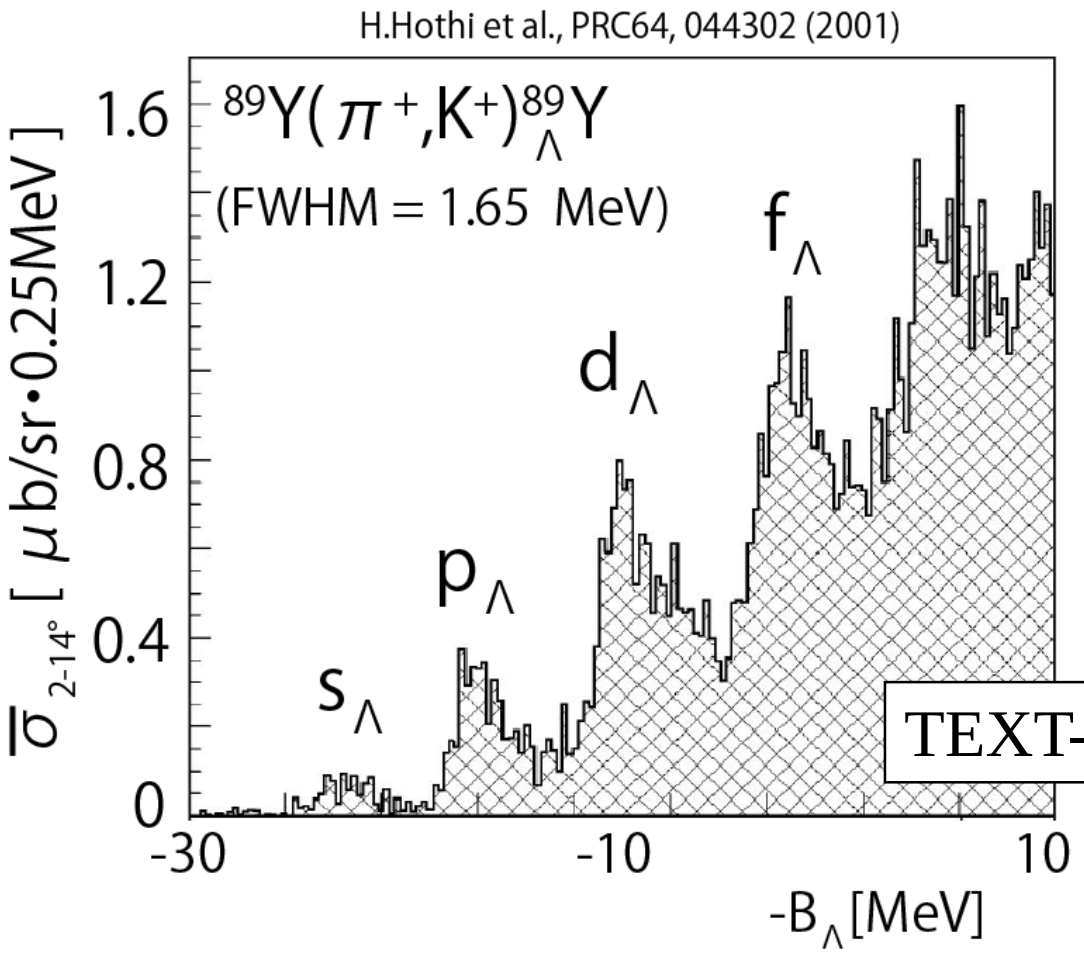
K. Itonaga, T. Motoba, O. Richter, M. Sotona, Phys. Rev. C 49 (1994) 1045.

22aK309-1 (藤岡徳菜 他)

Systematic study of Λ hypernuclei



Shell structure exists deeply inside of nucleus



$$^{89}_{\Lambda}\mathrm{Y} = {}^{88}\mathrm{Y} + \Lambda$$

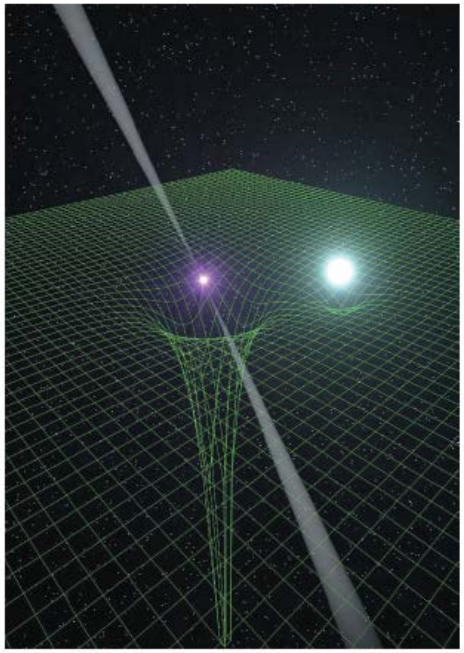
$$(^{A}_{\Lambda}Z = {}^{A-1}Z + \Lambda)$$

TEXT-BOOK LIKE

Λ binding energy: $B_\Lambda\left(^{A}_{\Lambda}Z\right) = M\left(^{A-1}Z\right) + M(\Lambda) - M\left(^{A}_{\Lambda}Z\right)$

Hyperon puzzle in neutron stars

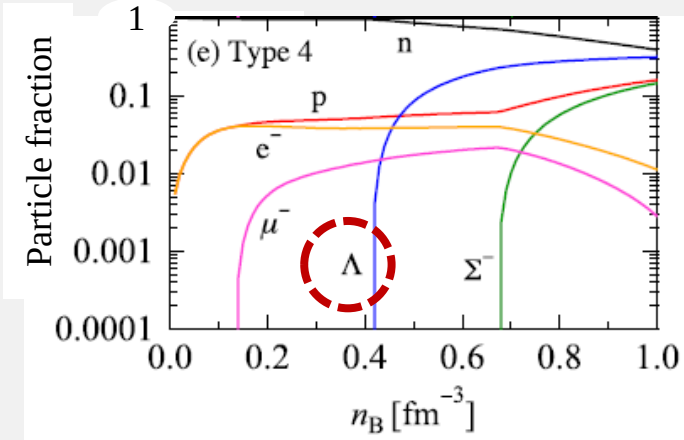
Neutron star (NS):
- ✓ Very dense nuclear matter
- ✓ $\leq 2M_{\odot}$

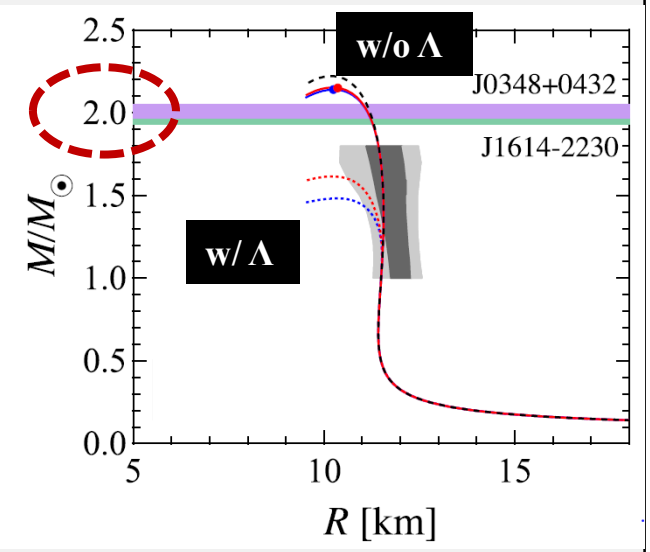


Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic theories of gravity, the binary system is subject to energy loss by gravitational waves.

J. Antoniadis *et al.*, *Science* 340, 1233232 (2013).

H. Togashi, E. Hiyama, Y. Yamamoto, M. Takano, *Phys. Rev. C* ***93***, 035808 (2016).

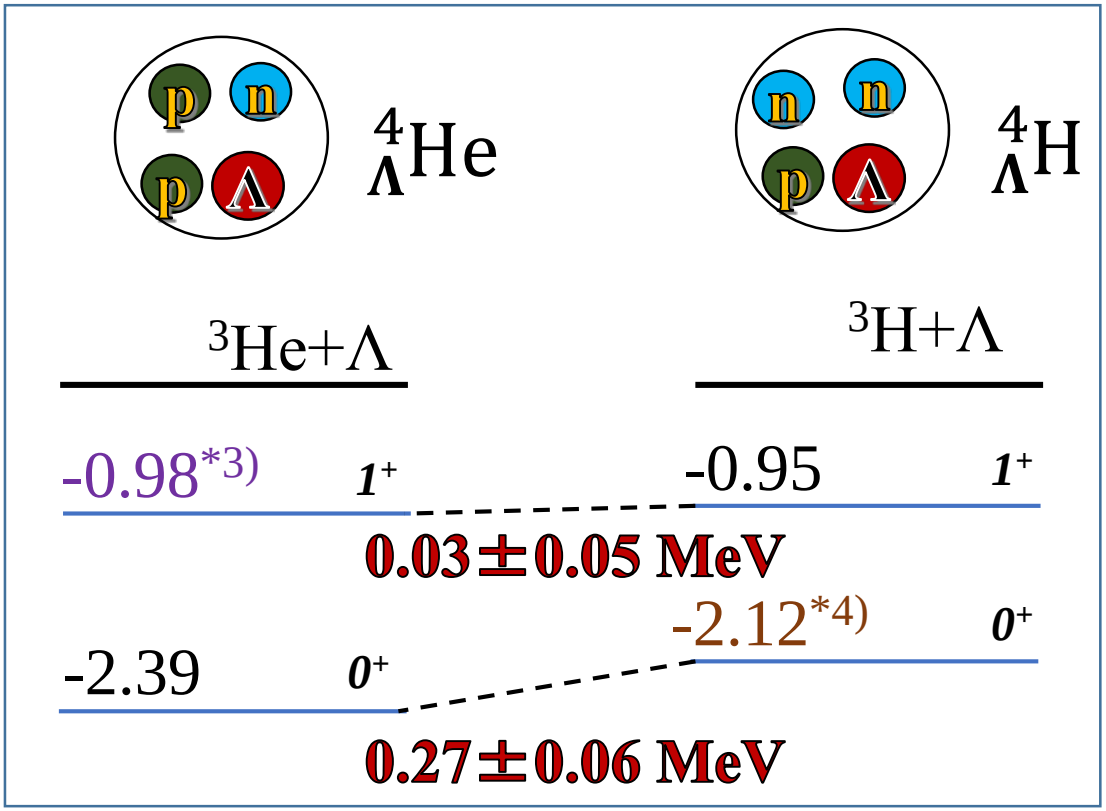


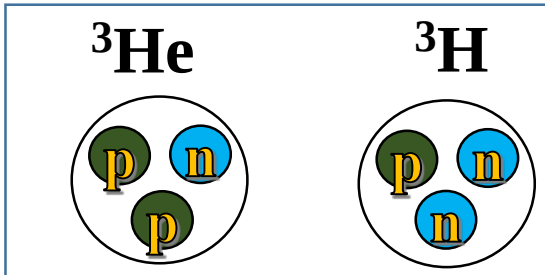


Λ generation in NS ⟷ **CONFLICT!!** ⟷ $2M_{\odot}$ NS

Need improvement our understanding of the ΛN and ΛNN interaction

Charge symmetry breaking (CSB)
in the A=4 hypernuclear system





$\Delta B = 0.76384\ (26)^{*1)}$ MeV

$\Delta B_{\mathrm{Coulomb}} = 0.683^{*2)}$ MeV

0.081 MeV

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

*2) R.A.Brandenburg, S.A.Coon *et al.*, *NPA***294,** 305 (1978).

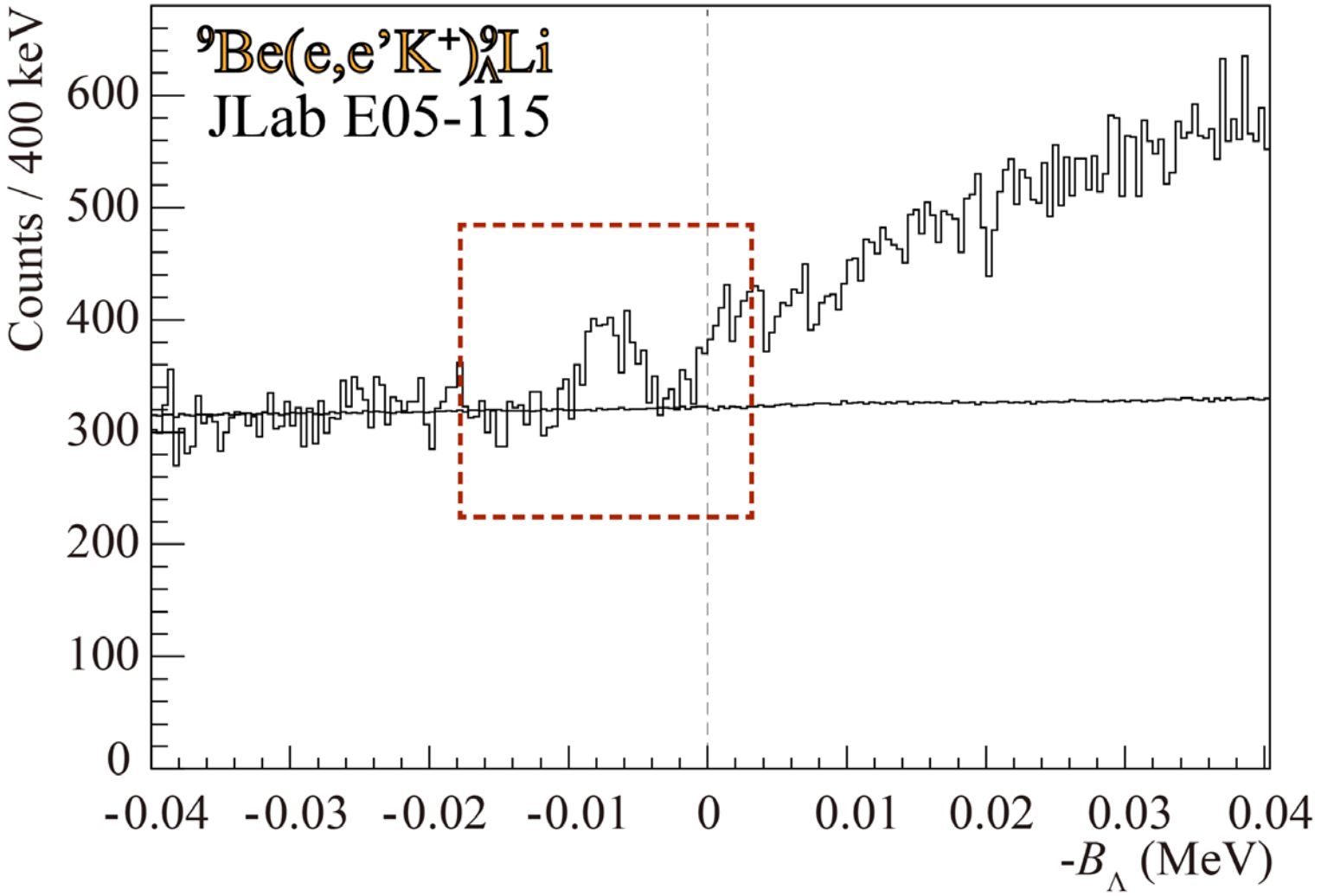
*3) **T. O. Yamamoto *et al.* (J-PARC E13 Collaboration), Phys. Rev. Lett. 115, 222501 (2015)**

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

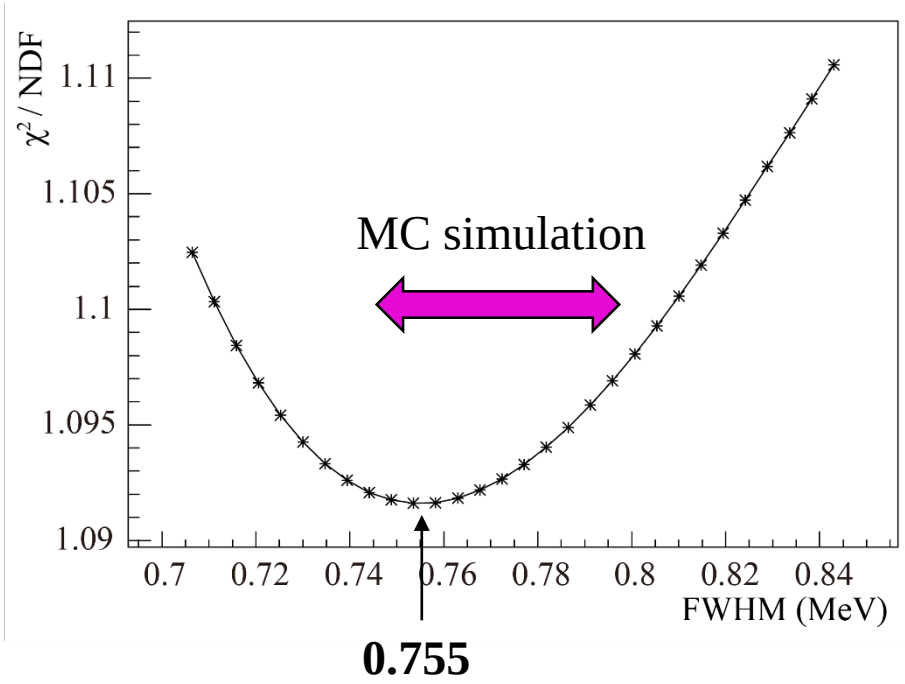
2017年秋

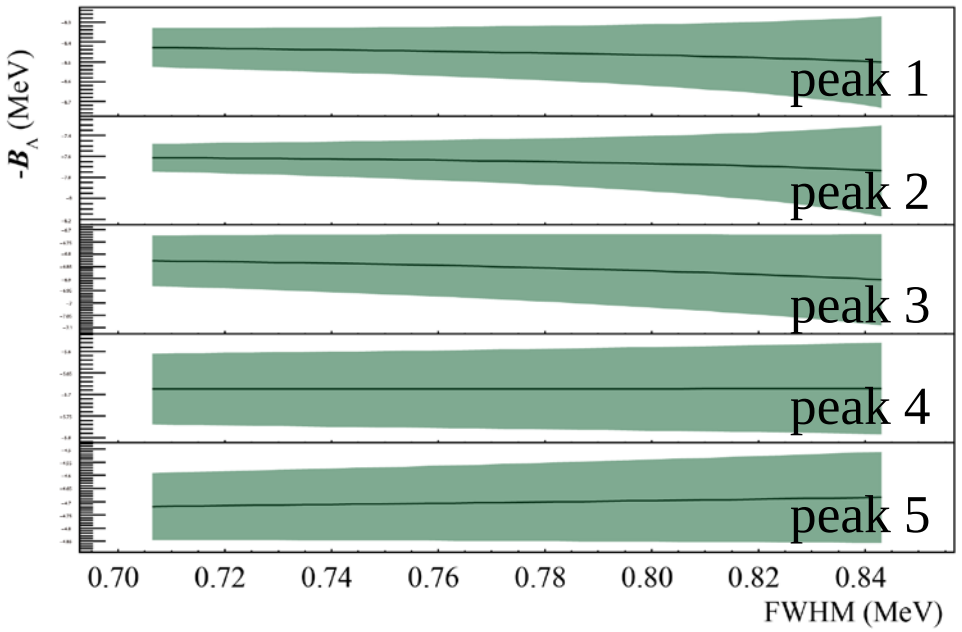
山本、永尾: 第23回原子核談話会新人賞

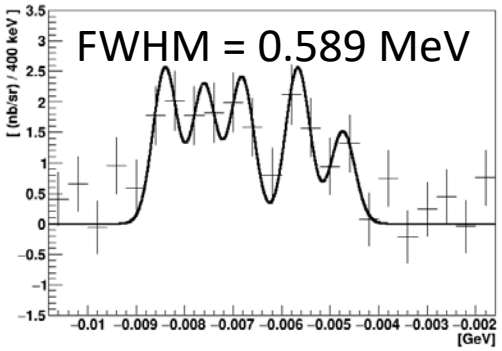
$^{9}\mathrm{Be}(e,e'K^{+})\,^{9}_{\Lambda}\mathrm{Li}$ from E05-115

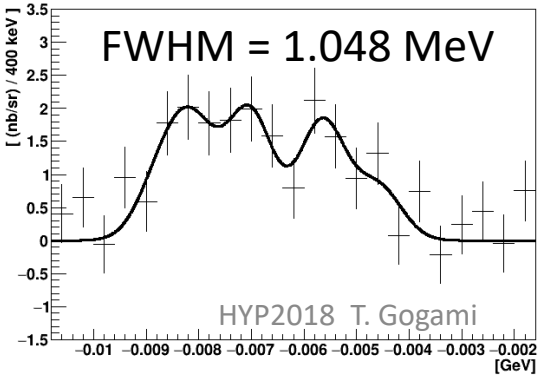


Search for an initial peak width which is initial parameter for final fitting



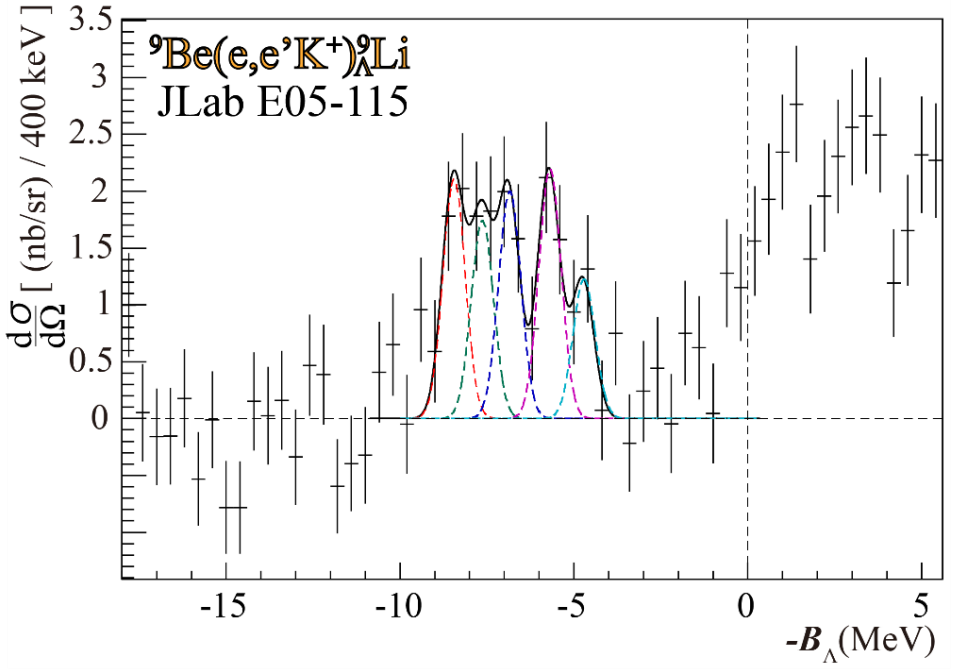


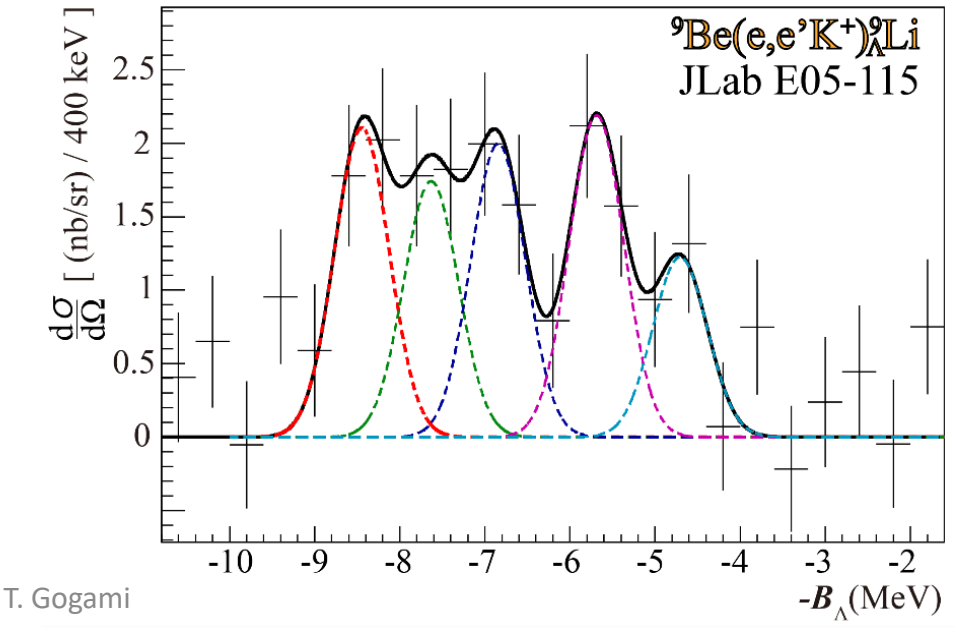




Five Gaussians for fitting

Fitting result





Theoretical calculation for energy levels

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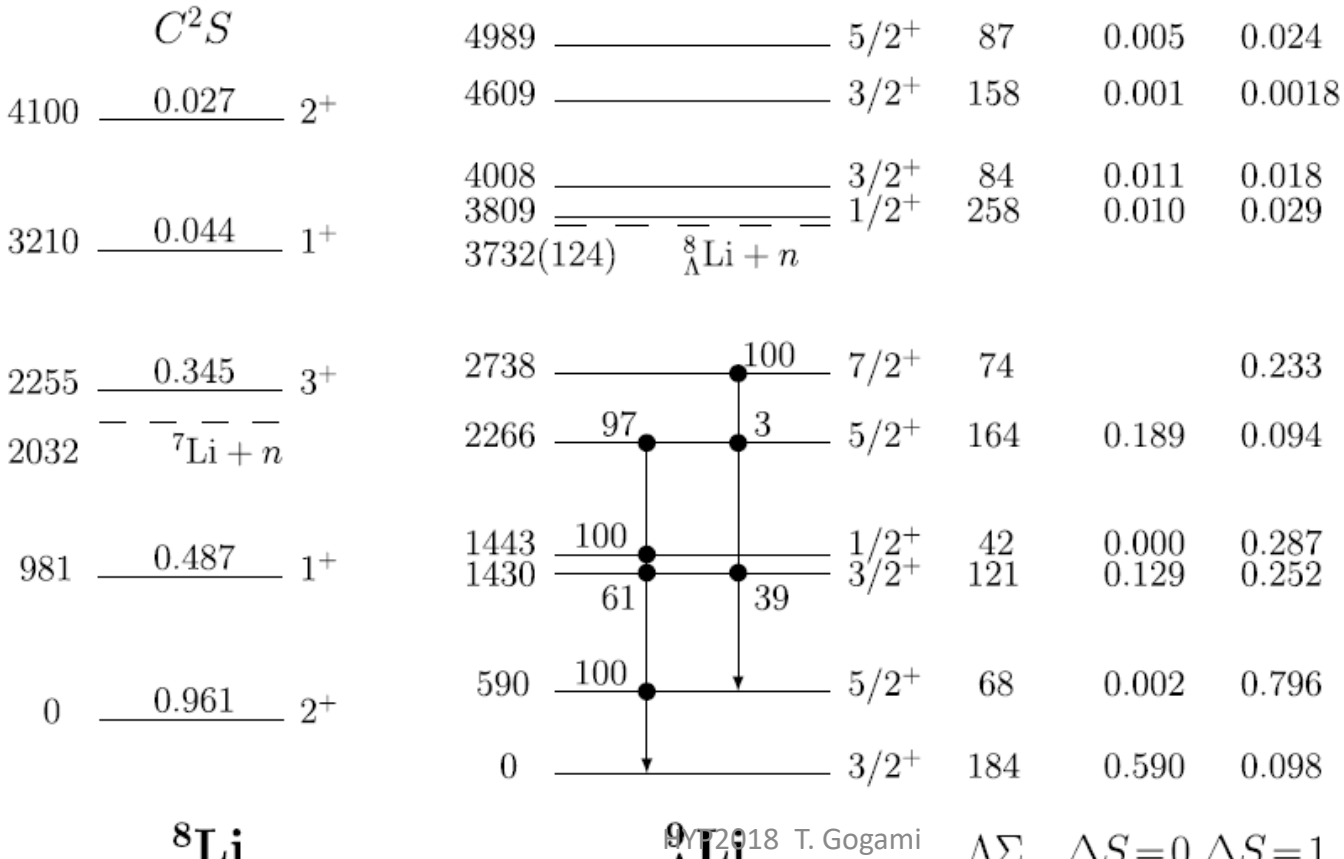
SciVerse ScienceDirect
Nuclear Physics A 881 (2012) 298–309
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Shell-model calculations for p-shell hypernuclei

D.J. Millener

Brookhaven National Laboratory, Upton, NY 11973, USA

Received 24 January 2012; accepted 25 January 2012
Available online 28 January 2012



^{8}Li

Table 8.2
Energy levels of ^{8}Li[a]

E_x (MeV ± keV)	J^π; T	τ or Γ_{cm} (keV)	Decay	Reactions
g.s.	2^+; 1	$\tau_{1/2} = 839.9 \pm 0.9$ ms[c]	β^-	1, 3, 4, 8, 9, 10, 14, 15, 16, 17, 18, 21, 22
0.9808 ± 0.1	1^+; 1	$\tau_m = 12 \pm 4$ fs[c]	γ	3, 8, 9, 11, 14, 15, 16, 21, 22, 28
2.255 ± 3	3^+; 1	$\Gamma = 33 \pm 6$ keV[c]	γ, n	3, 4, 5, 8, 14, 15, 16, 31
3.21	1^+; 1	≈ 1000	n	6, 11
5.4[d]	1^+; 1	≈ 650	n	6, 11
6.1 ± 100	(3); 1	≈ 1000	n	5
6.53 ± 20	4^+; 1	35 ± 15	n	3, 5, 8, 15, 16
7.1 ± 100		≈ 400	n	5
(9)		≈ 6000		14
≈ 9.67[b,c]	1^+	≈ 1000[c]	t	11
10.8222 ± 5.5	0^+; 2	< 12		19

[a] For additional states see reactions 5 and 16.
[a] From multi-level multi-channel R-matrix fit to ^{8}He decay spectra.
[a] From information given in this evaluation.
[d] A level at $E_x = 5.4$ MeV with uncertain $J^\pi = (2^+)$ was observed in ^{7}Li(n, n′) [1972PR03].

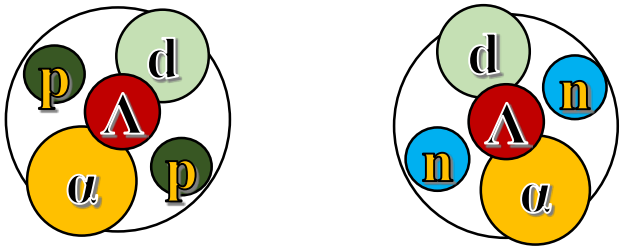
^{8}Li

Table 8.8
Spectroscopic factors of the ^{9}Be(t, α) reaction[a]

E_x (MeV)	J^π	l	$C^2S_{rel.}$	$C^2S_{abs.}$
0	2^+	1	0.843	1.059
0.981	1^+	1	0.506	0.636
2.255	3^+	1	0.552	0.693
2.4–2.8		1	0.099	

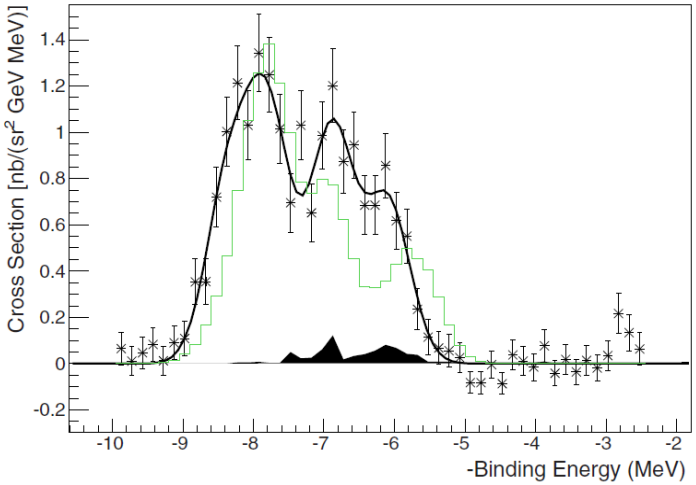
[a] See [1988LI27].

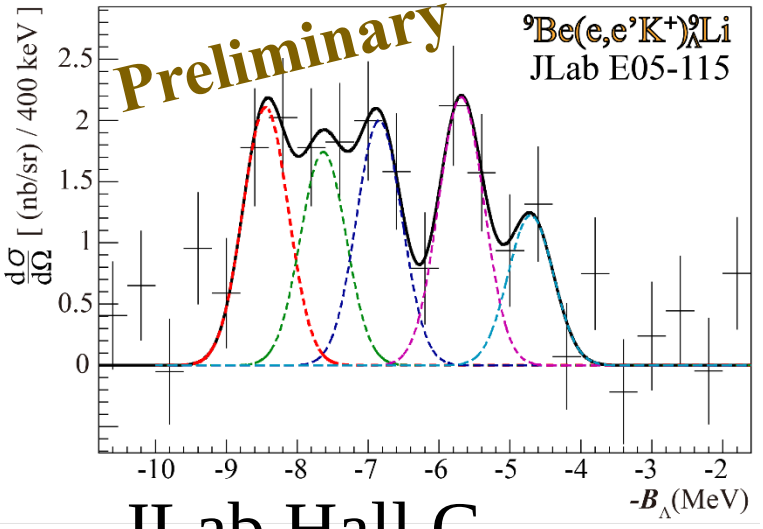
$^{9}\mathrm{Be}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Li}$



	$^{9}_{\Lambda}$B (α+d+p+p+Λ)	$^{9}_{\Lambda}$Li (α+d+n+n+Λ)
Emulsion[1]	8.29 ± 0.18 MeV (3 events; 1 event removal)	8.50 ± 0.12 MeV (13 events)
(e,e'K^{+}) @Hall A[2]	-	8.36 ± 0.08 MeV
(e,e'K^{+}) @Hall C	-	New

JLab Hall A





JLab Hall C

[1] J. Pniewski *et al.*, *Nucl. Phys. A* ***443*** (1985) 685.
[2] G.M. Urciuoli *et al.*, *Phys. Rev. C* ***91*** (2015) 034308.