Λ hypernuclear spectroscopy by S-2S at J-PARC and HKS at JLab

Kyoto University
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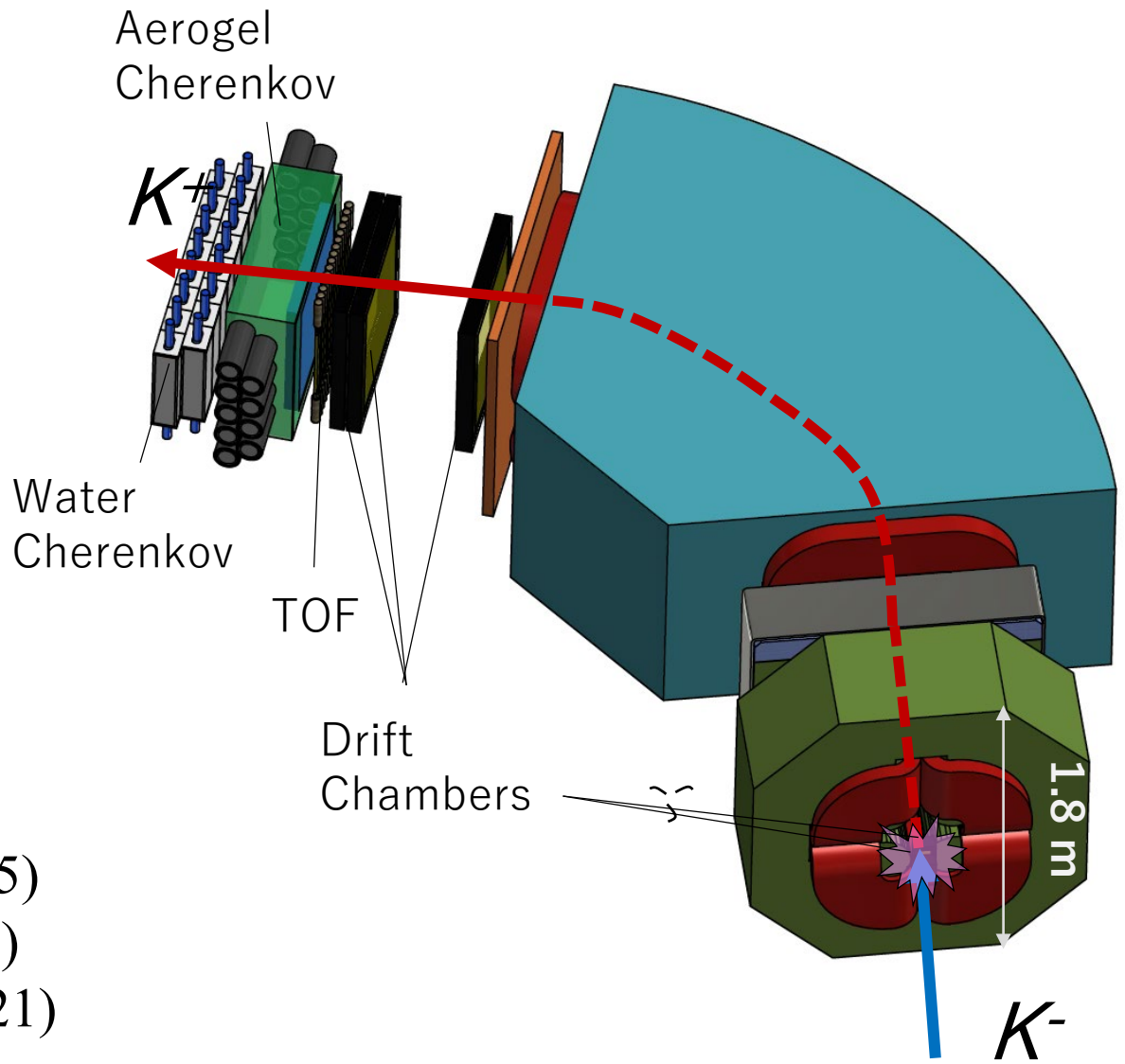
京都大学　理学研究科・理学部
GRADUATE SCHOOL OF FACULTY OF SCIENCE
KYOTO UNIVERSITY

SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

科研費
KAKENHI

J-PARC E70 ($^{12}_{\Xi}$Be)

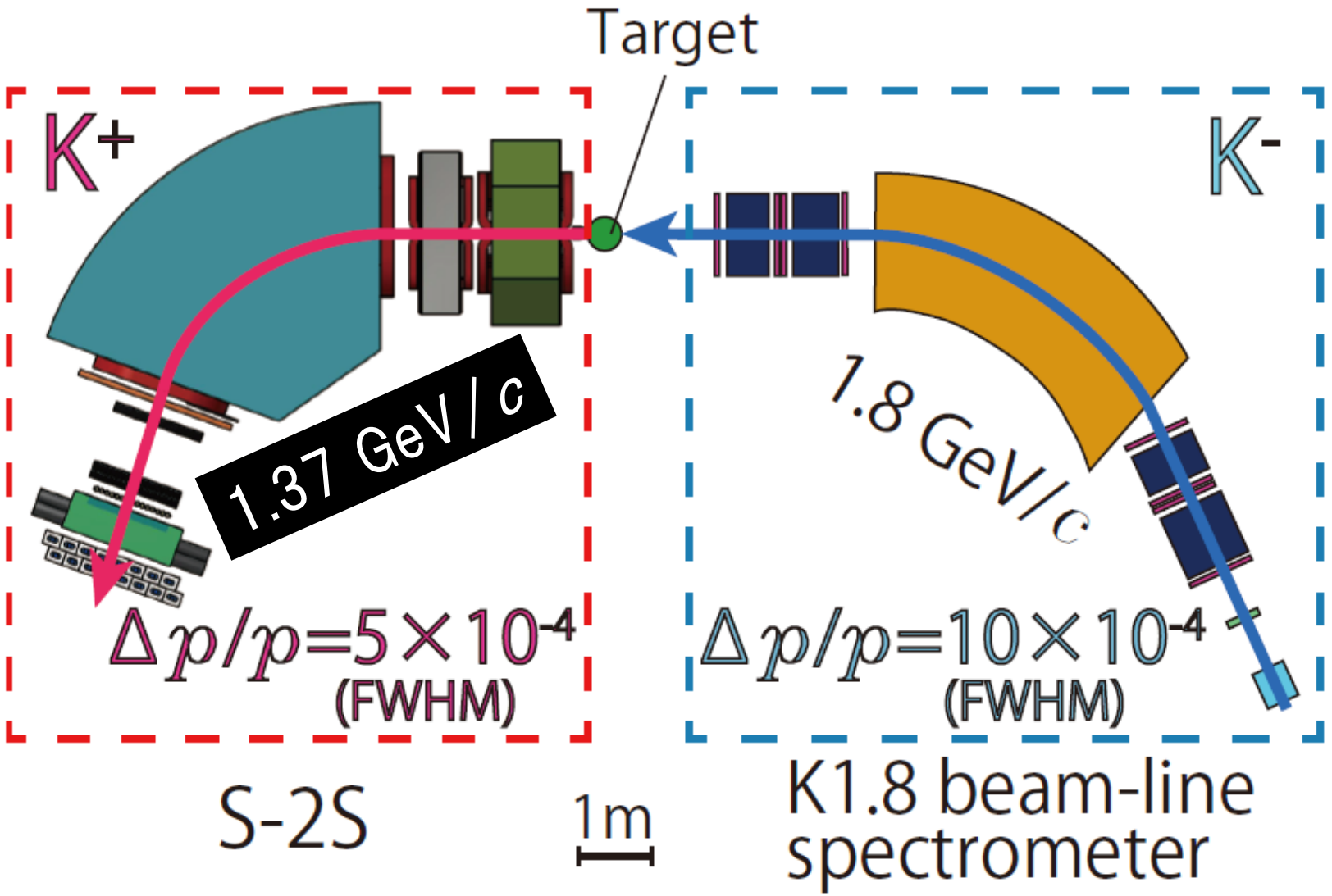
Missing mass experiment with $^{12}\mathrm{C}(K^-, K^+)$



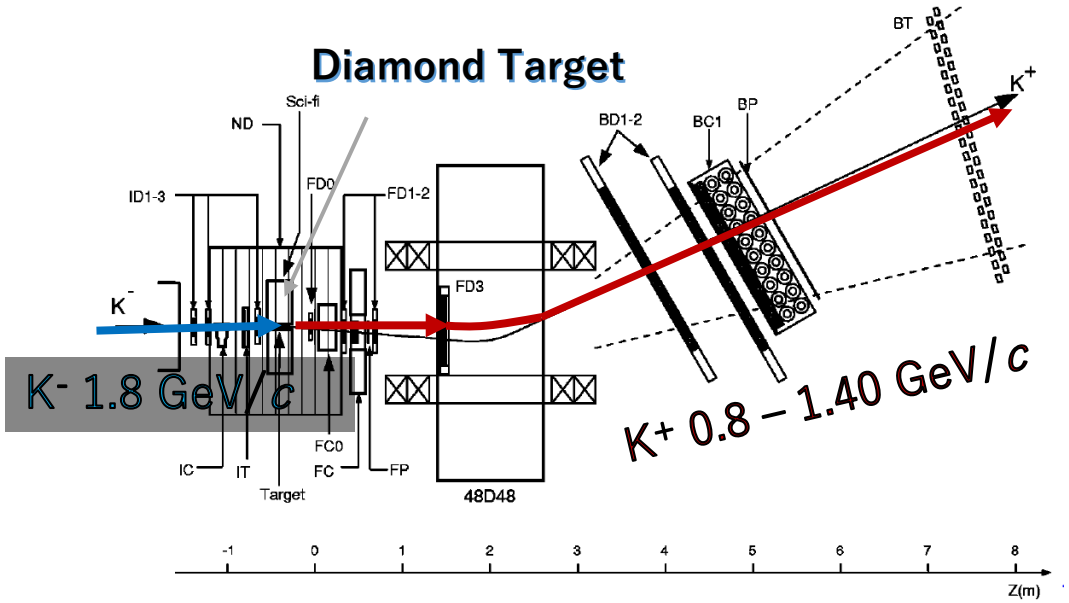
c.f.) Emulsion studies:

- K. Nakazawa et al., PTEP 2015, 033D02 (2015)
- S. H. Hayakawa et al., PRL 126 062501 (2021)
- M. Yoshimoto et al., PTEP 2021, 073D02 (2021)

J-PARC E70 w/ S-2S



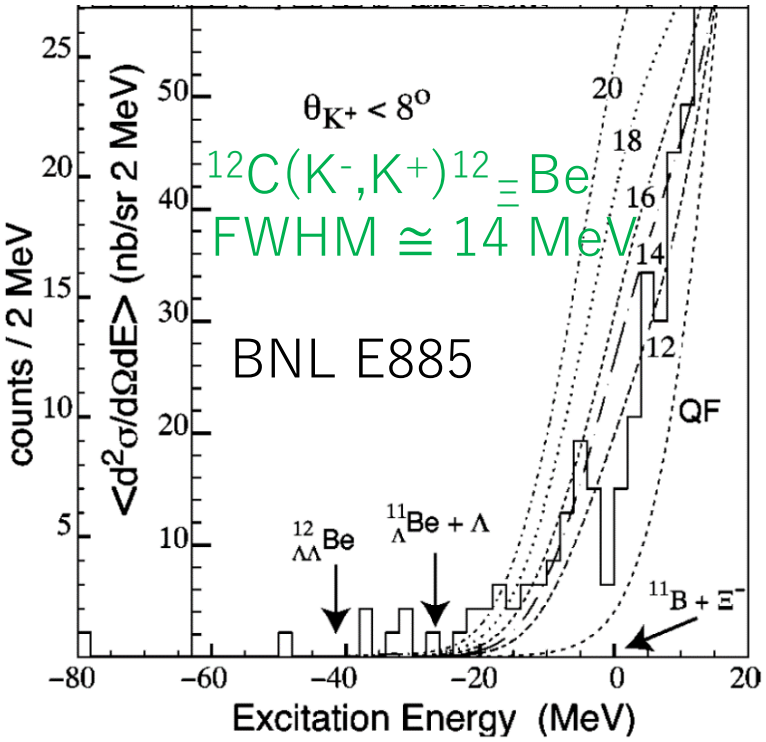
Xi hypernuclear spectroscopy - BNL E885



Experiment	KEK E224	BNL E885
FWHM (MeV)	22	14

➔ < 2 MeV in E70

P.Khaustov *et al.*, *PRC* **61** (2000) 054603



89 ± 14 nb/sr $(\theta < 8\ deg)$

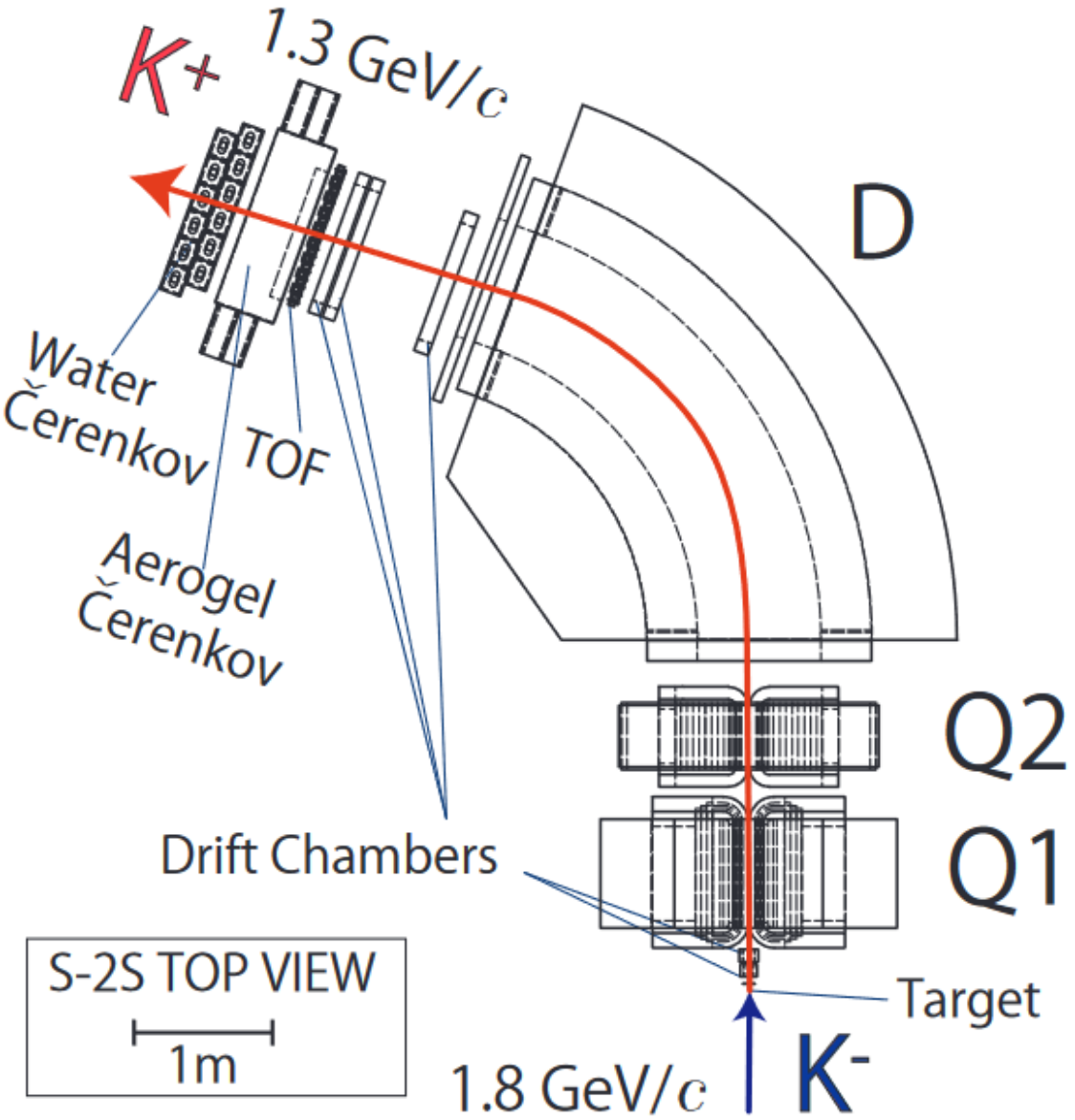
42 ± 5 nb/sr $(\theta < 14\ deg)$

(-20 < E_{Ξ} < 0 MeV)

➔ $V_{0\Xi} \leq 14$ MeV


2022/1～4月にかけて磁石
がインストールされる

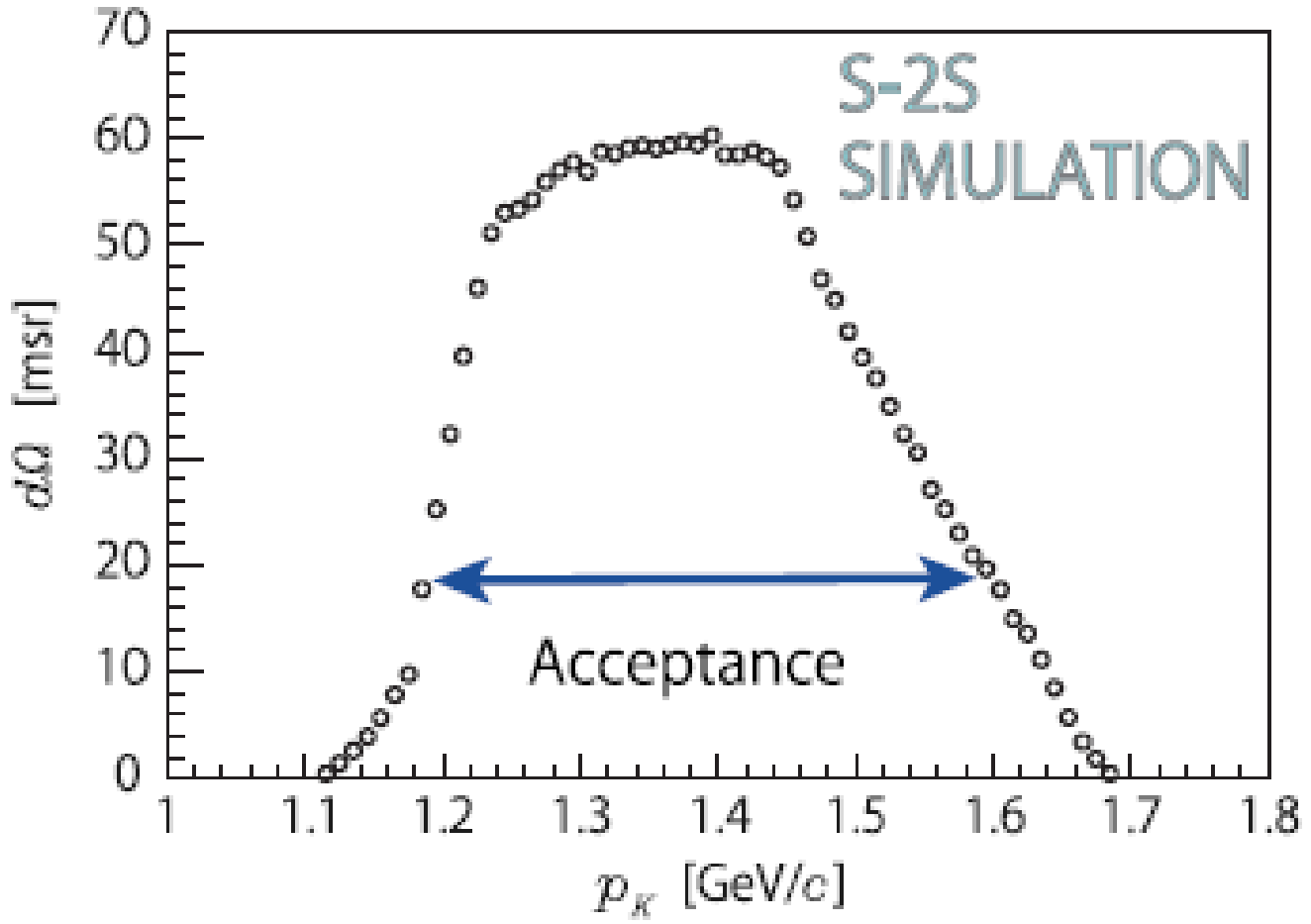
Detectors



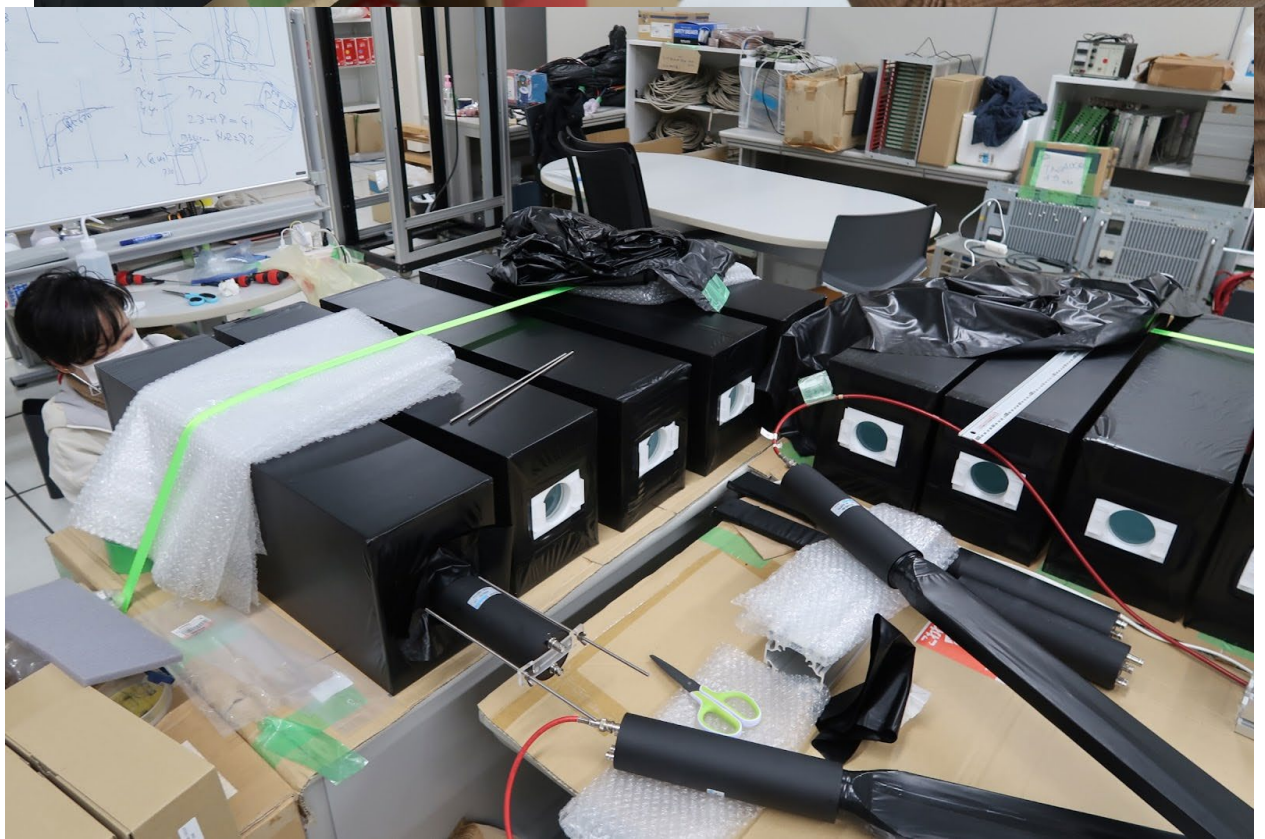
https://www-nh.scphys.kyoto-u.ac.jp/~gogami/s2s/s-2s/doc/buckingcoil/s2s_buckingcoil_20160408_2.pdf

S-2S Acceptance

TG et al., NIMA 817, 70—84 (2016)

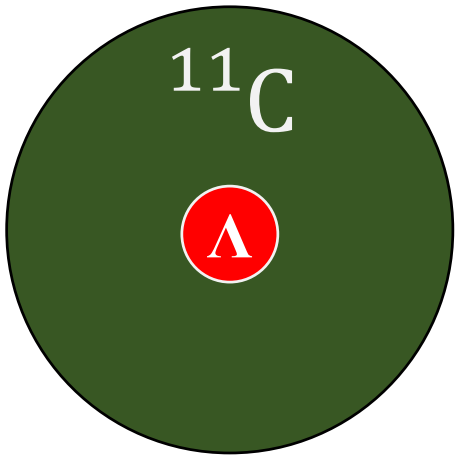


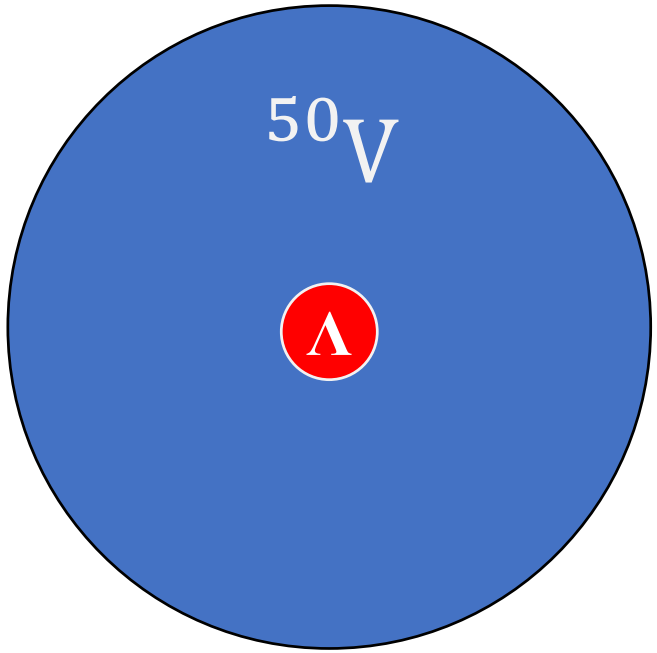
- $\delta p/p > 20\%$
- < 10 degrees



First targets for (π^+, K^+) experiment

FWHM $\simeq$ 1 MeV w/ S-2S





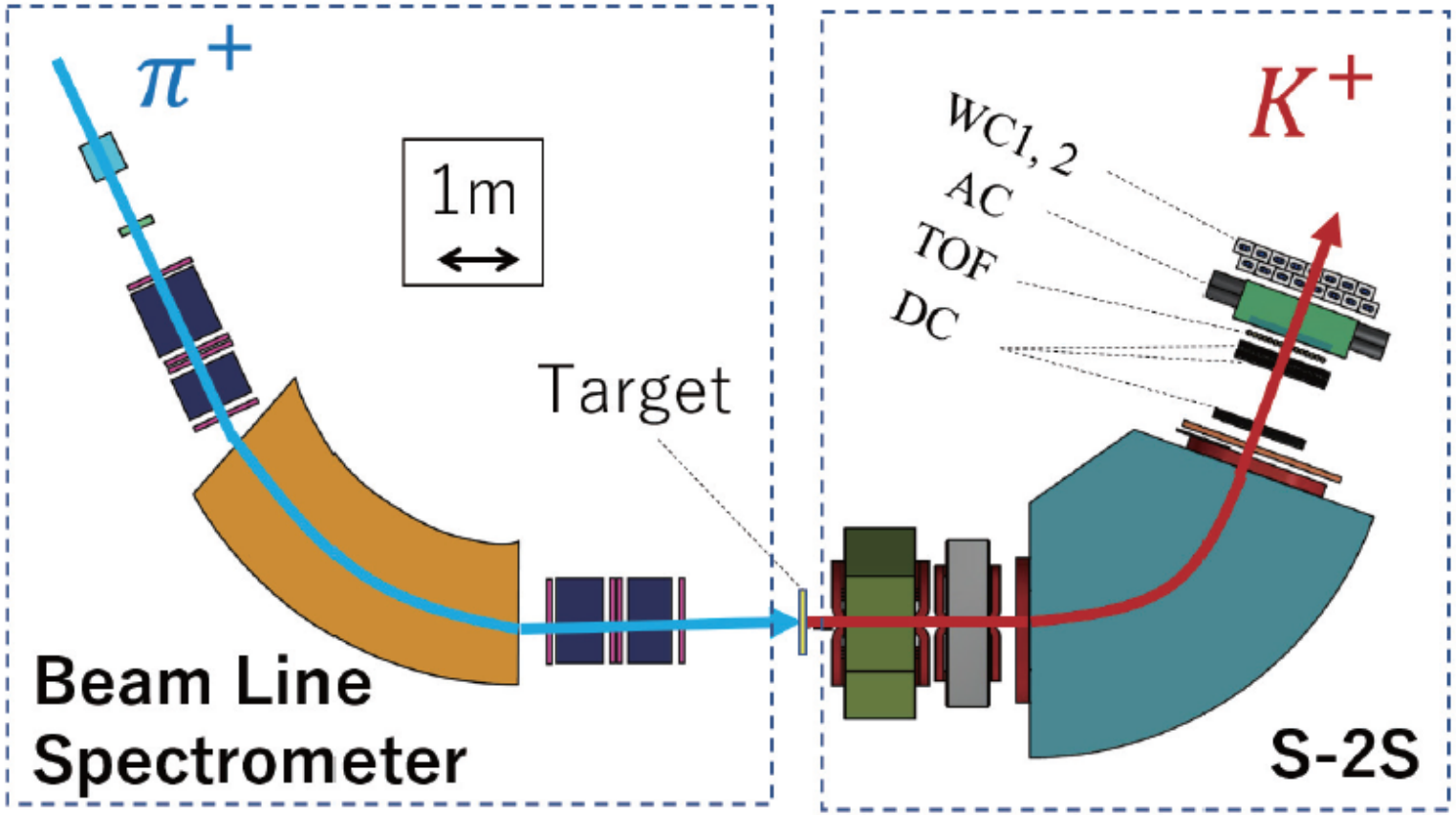
$^{12}_{\Lambda}$C

$^{51}_{\Lambda}$V

Experimental setup

$\Delta p/p$ (S-2S) = 6×10^{-4} FWHM

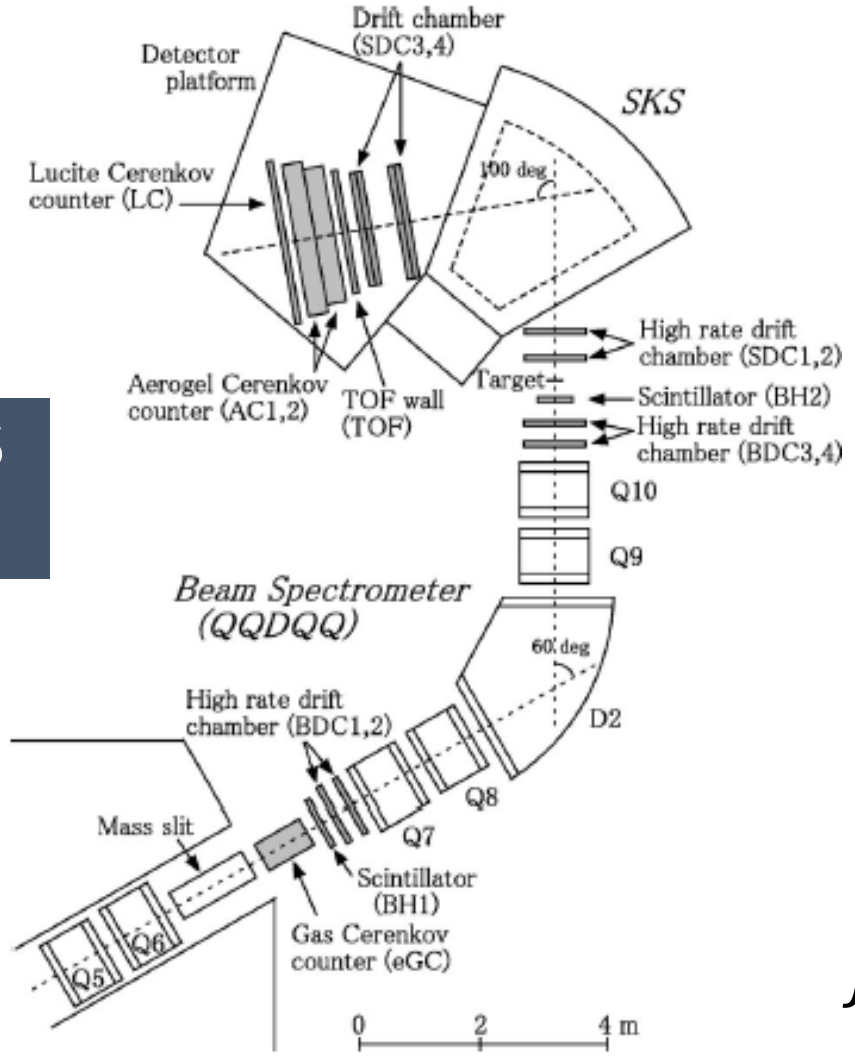
- Setup is the same as E70
- Beam polarity is opposite



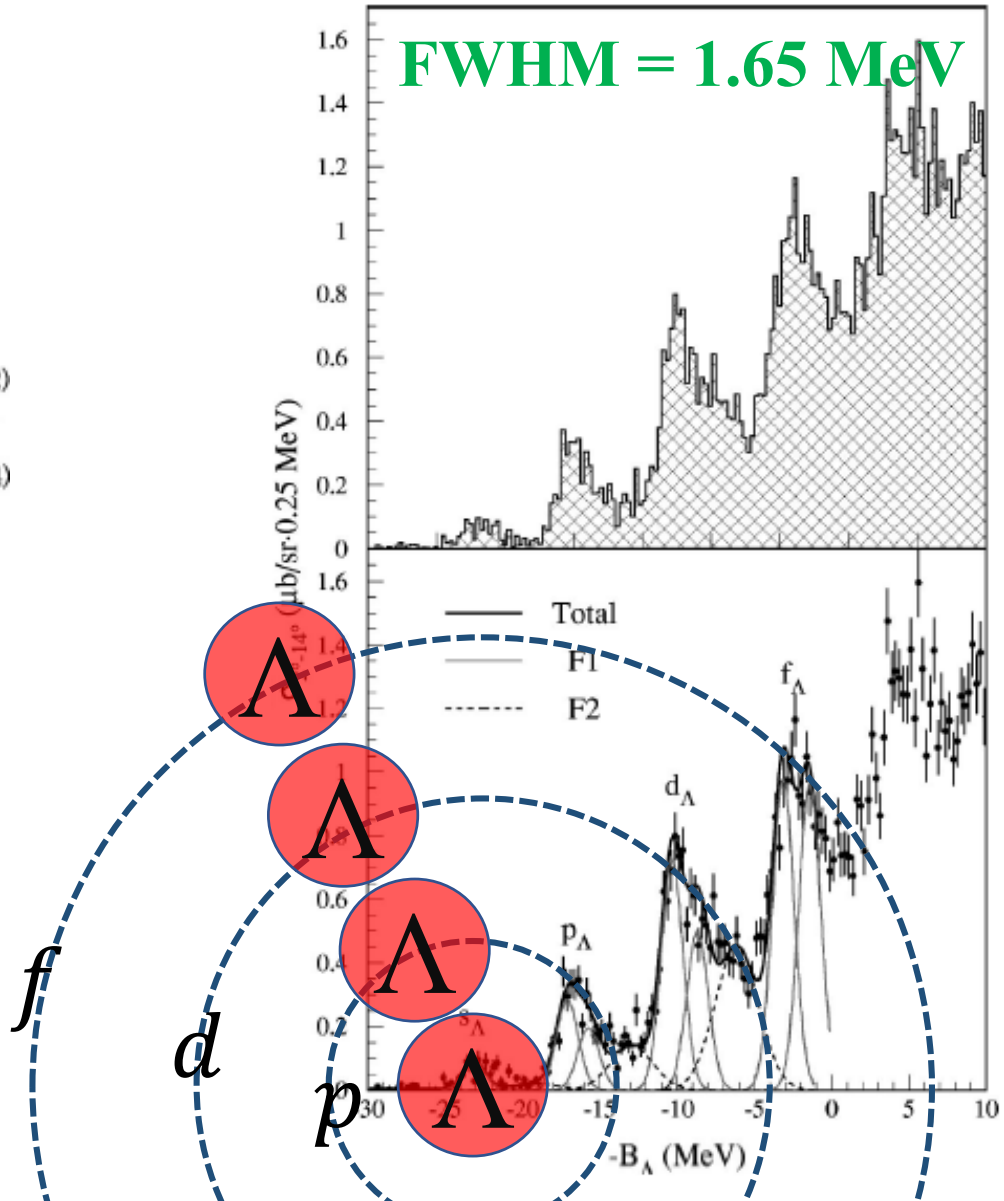
$\Delta p/p$ (BLS) = 5—10 $\times 10^{-4}$ FWHM

Understanding of ${}^{89}_{\Lambda}$Y, and further study

KEK-PS
E369

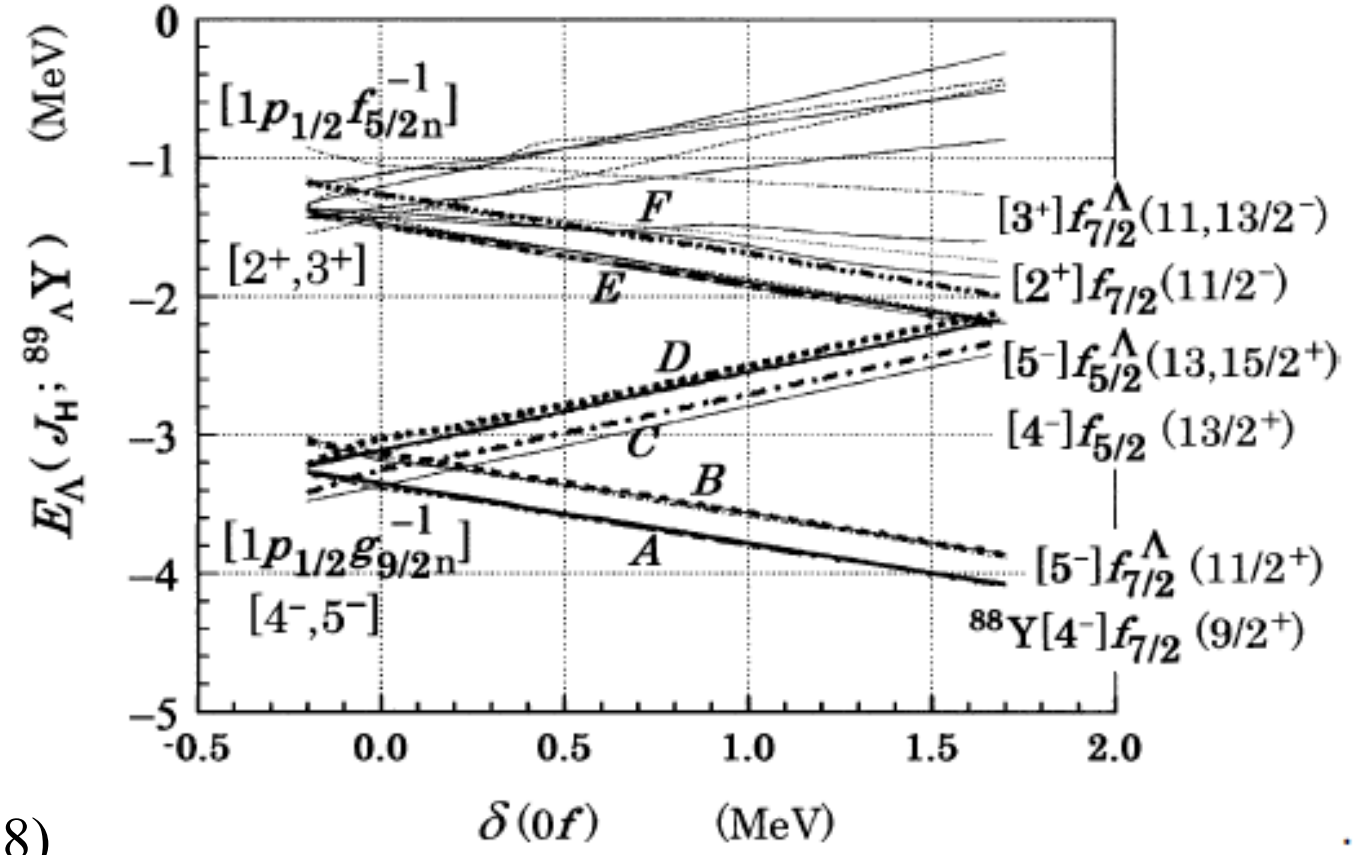


H. Hotchi et al., PRC 64, 044302 (2001)



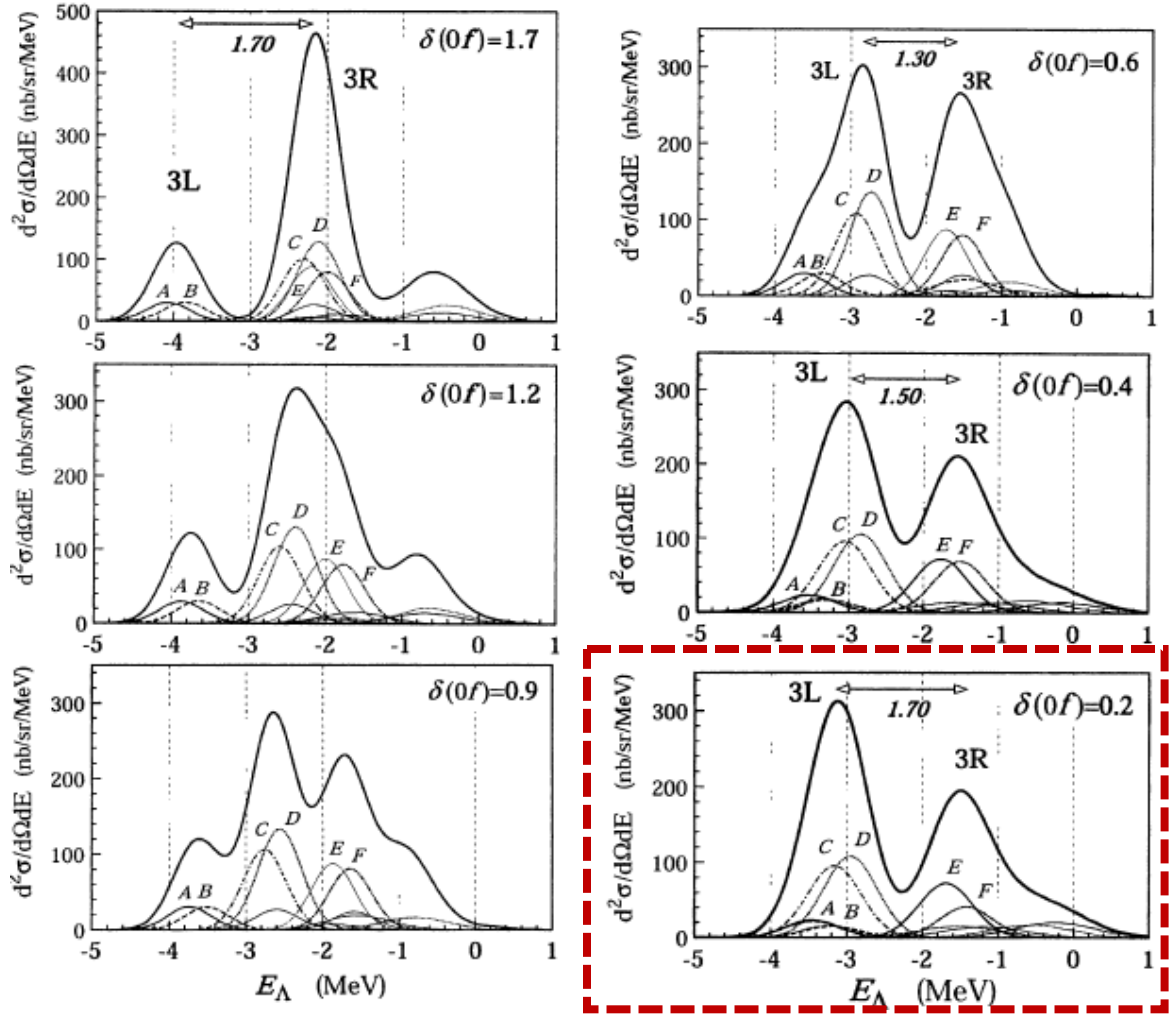
Test; splitting parameter

$$\delta = \epsilon(f^{\Lambda}_{5/2}) - \epsilon(f^{\Lambda}_{7/2})$$



T. Motoba et al., NPA 804, 99—115 (2008)
T. Motoba et al., PTPS 185, 197—223 (2010)

Expected spectra with different δ (Λ in f-orbit)



A : $[^{88}\mathrm{Y}(4^-)\ f^{\Lambda}_{7/2}](J_H = 9/2^+)$ or $[1p_{1/2p}\ (g^{-1}_{9/2n}\ f^{\Lambda}_{7/2})_{J_{ph}=5^-}]$,

B : $[^{88}\mathrm{Y}(5^-)\ f^{\Lambda}_{7/2}](J_H = 11/2^+)$ or $[1p_{1/2p}\ (g^{-1}_{9/2n}\ f^{\Lambda}_{7/2})_{J_{ph}=5^-}]$,

C : $[^{88}\mathrm{Y}(4^-)\ f^{\Lambda}_{5/2}](J_H = 13/2^+)$ or $[1p_{1/2p}\ (g^{-1}_{9/2n}\ f^{\Lambda}_{5/2})_{J_{ph}=7^-}]$,

D : $[^{88}\mathrm{Y}(5^-)\ f^{\Lambda}_{5/2}](J_H = 15/2^+, 13/2^+)$ or $[1p_{1/2p}\ (g^{-1}_{9/2n}\ f^{\Lambda}_{5/2})_{J_{ph}=7^-}]$,

E : $[^{88}\mathrm{Y}(2^+)\ f^{\Lambda}_{7/2}](J_H = 11/2^-)$ or $[1p_{1/2p}\ (f^{-1}_{5/2n}\ f^{\Lambda}_{7/2})_{J_{ph}=6^+}]$,

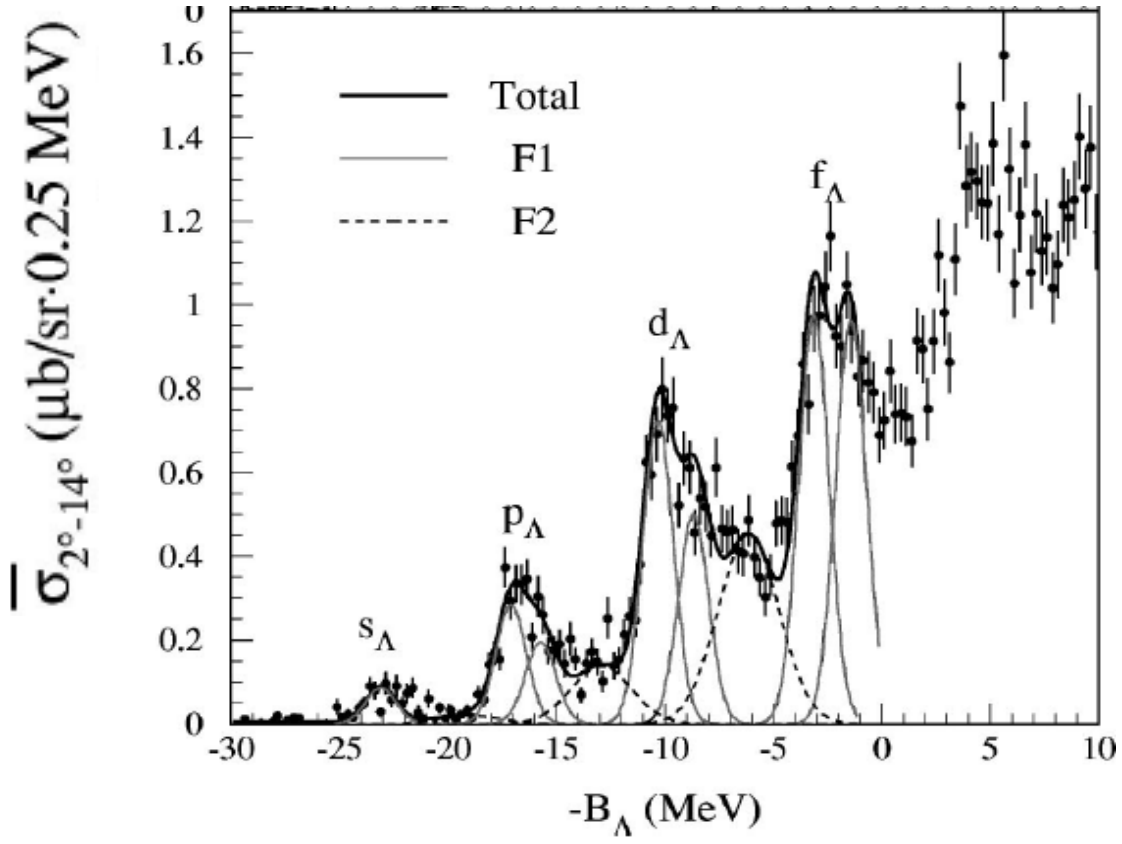
F : $[^{88}\mathrm{Y}(3^+)\ f^{\Lambda}_{7/2}](J_H = 11/2^-, 13/2^-)$ or $[1p_{1/2p}\ (f^{-1}_{5/2n}\ f^{\Lambda}_{7/2})_{J_{ph}=6^+}]$.

Small LS force seems to be better consistency with $^{89}_{\Lambda}$Y data

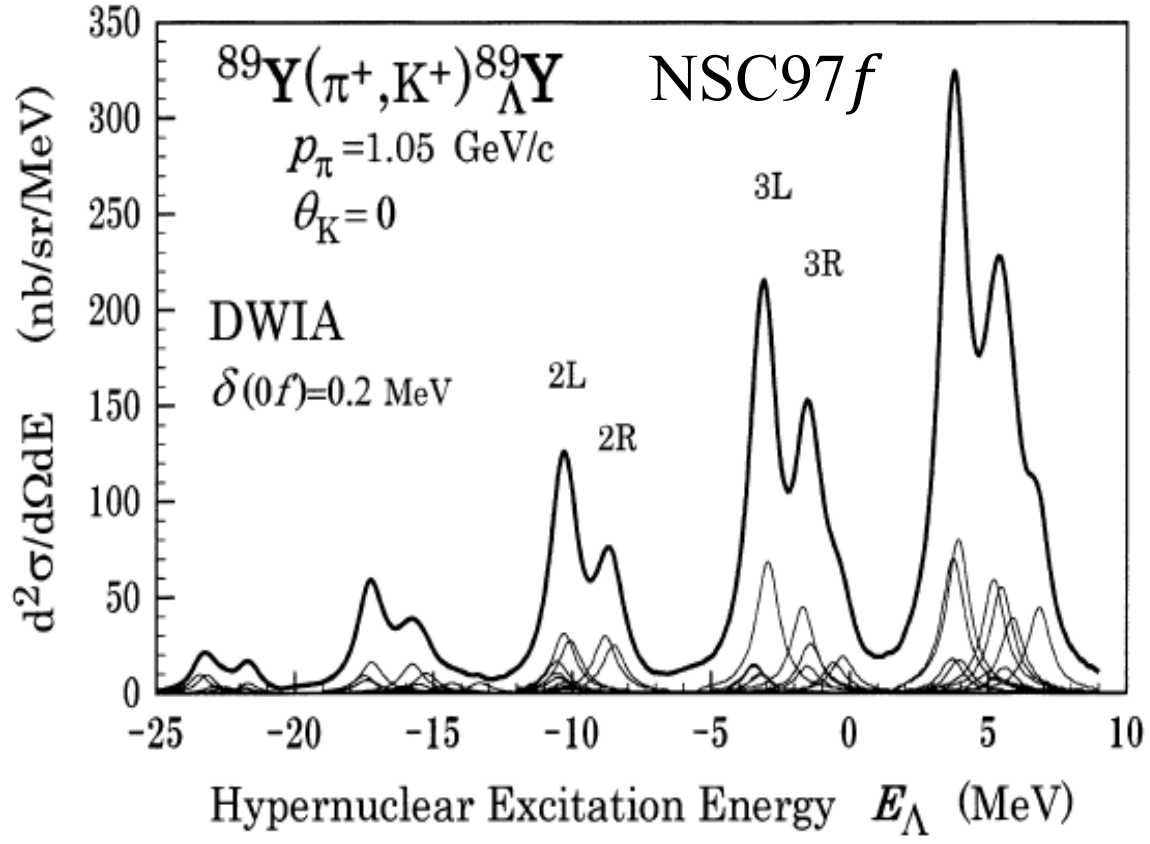
← Consistent with results of the γ ray measurements as well

Experiment vs. calculation (KEK PS E)

H. Hotchi et al., PRC 64, 044302 (2001)

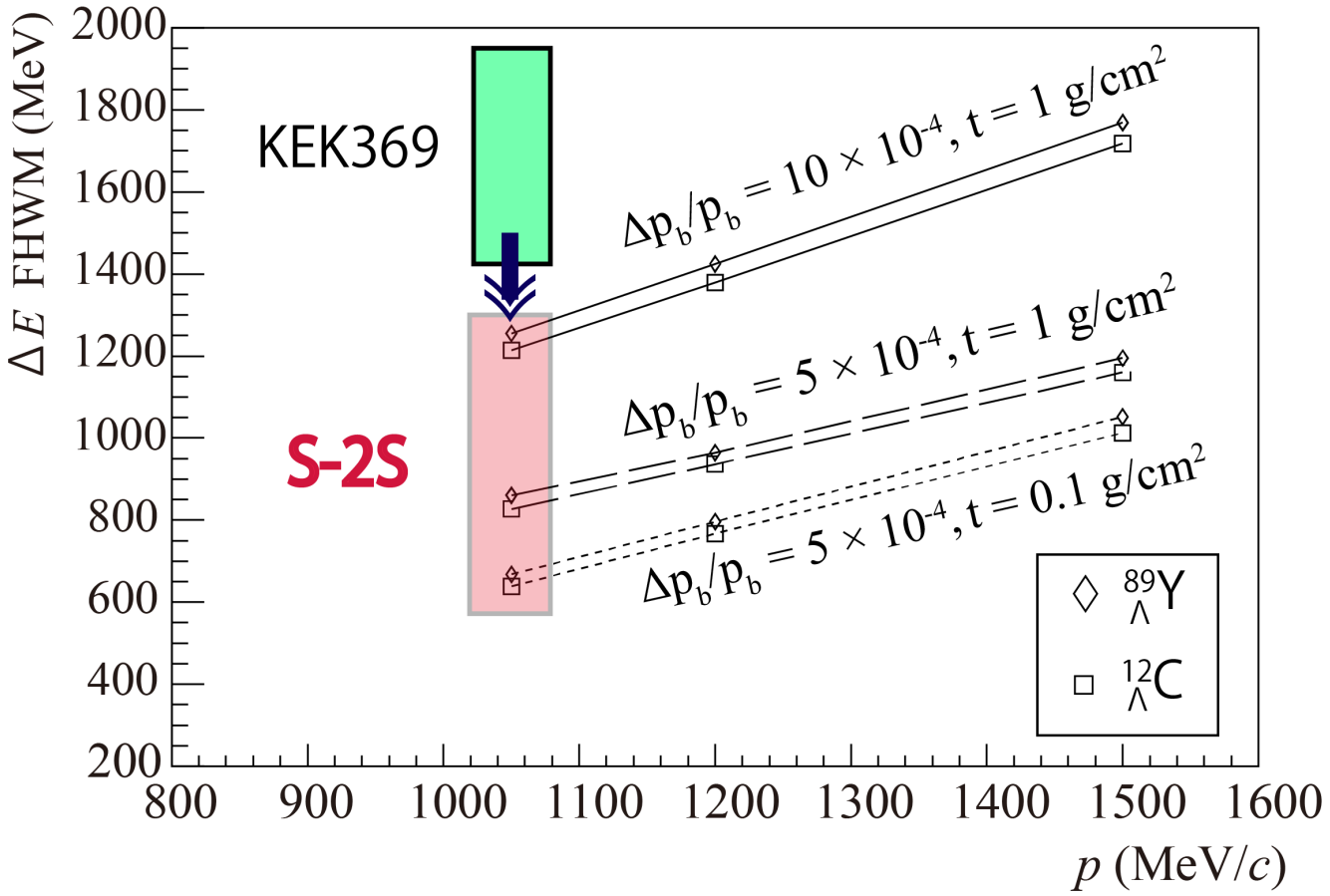


T. Motoba et al., NPA 804, 99—115 (2008)
T. Motoba et al., PTPS 185, 197—223 (2010)



Did we satisfied? → We need further investigation (e.g. F2)

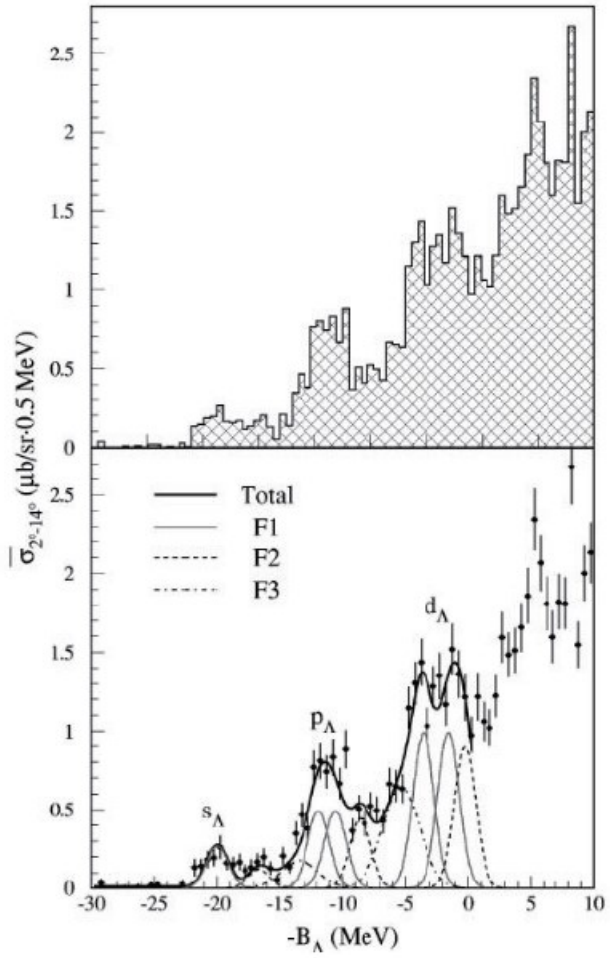
Expected energy resolution

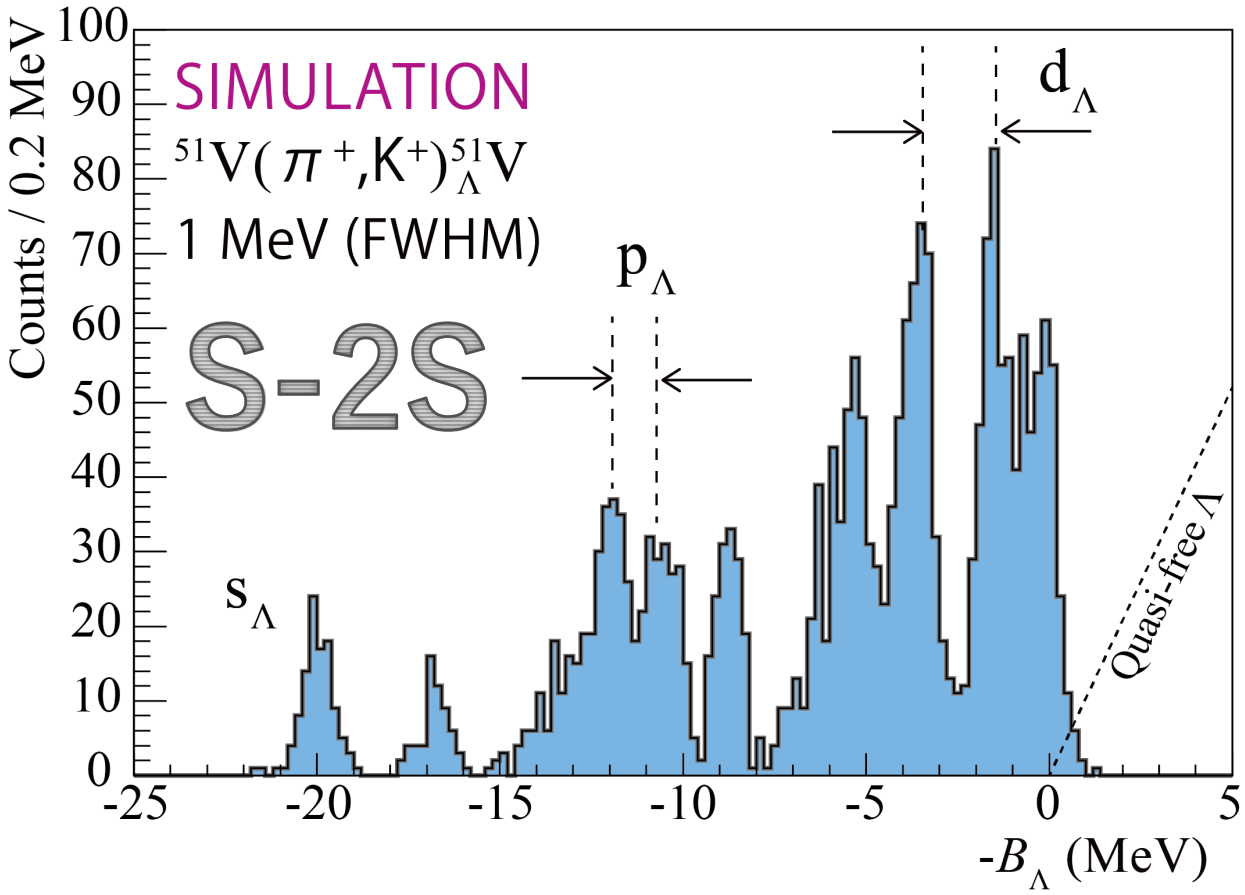


1 MeV FWHM

Expected spectrum

will be proposed in the next J-PARC PAC (Jan 2022)



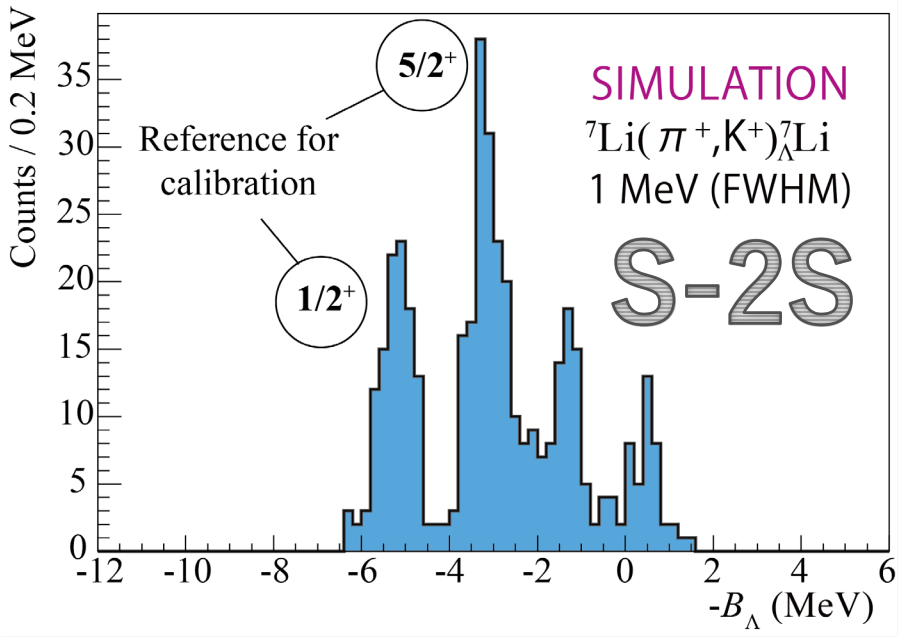


H. Hotchi et al., PRC 64, 044302 (2001)

5M pion/spill, 5.2 sec cycle, 1 g/cm^2, 20 days

Absolute energy calibration

5M pion/spill, 5.2 sec cycle, 1 g/cm^2, 1 day



5M pion/spill, 5.2 sec cycle, 1 g/cm^2, 2 days

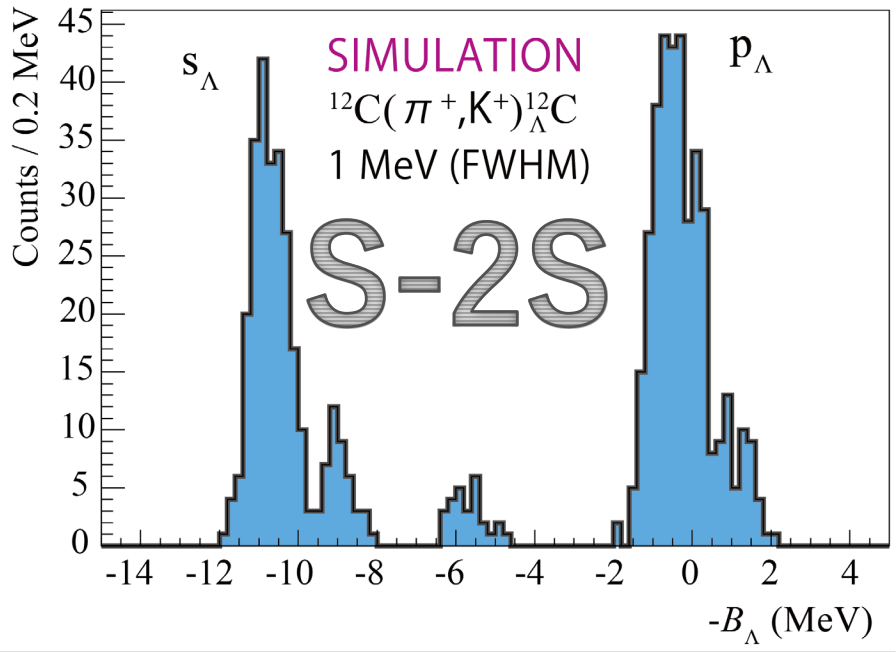


TABLE VIII. Reference energies ($B_\Lambda^{\mathrm{ref.}}$) for the present experiment. Expected statistical errors on the binding-energy measurement ($|\Delta B_\Lambda^{\mathrm{stat.}}|$) in the present experiment are shown in the last column.

Hypernucleus	J^π	$B_\Lambda^{\mathrm{ref.}}$ (/MeV)	Remarks	$\lvert\Delta B_\Lambda^{\mathrm{stat.}}\rvert$ (/MeV)
${}^{7}_{\Lambda}$Li	$1/2^+$ (g.s.)	5.58 ± 0.03	Ref. [8]	0.04
	$5/2^+$	3.53 ± 0.03	Refs. [6, 8]	0.03
${}^{12}_{\Lambda}$C	1^- (g.s.)	11.45 ± 0.13	weighted average of Refs. [4, 9]	0.03

Plan up to physics runs (J-PARC E70)

2022

Jan—Mar
- S-2S will be moved to J-PARC
- S-2S installation
- Excitation test

Apr—Oct
- Detectors' installation / check

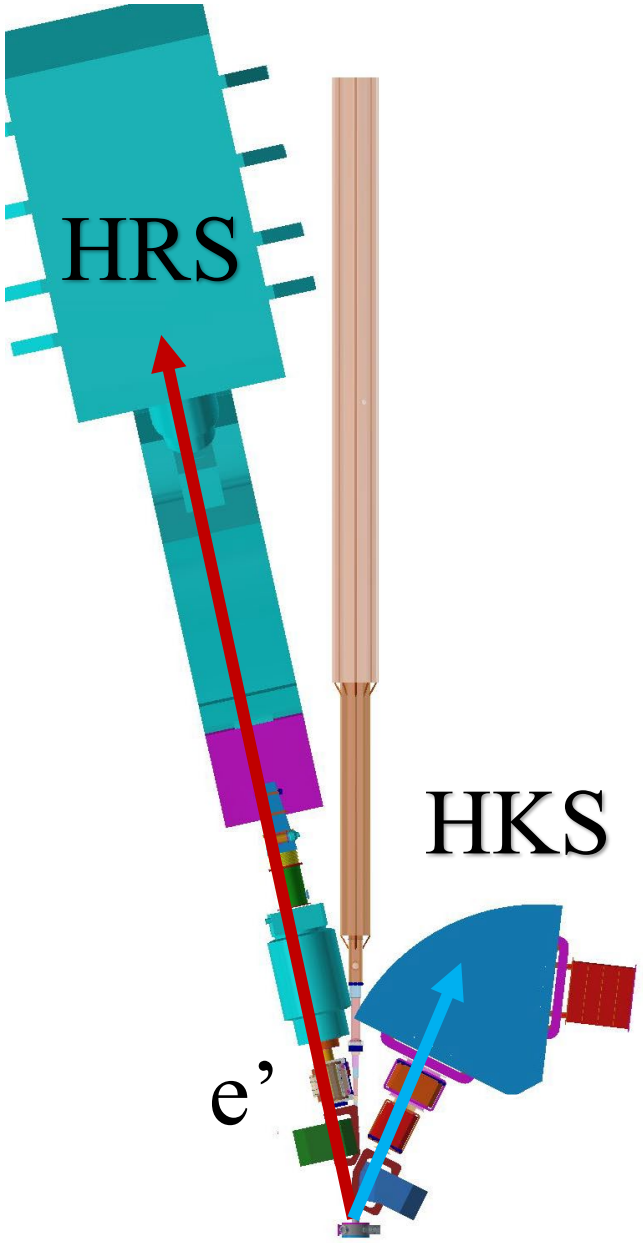
Nov—Dec
- Commissioning with beam
  (～ two weeks of beamtime)

2023

(about 1—2 months for analysis)

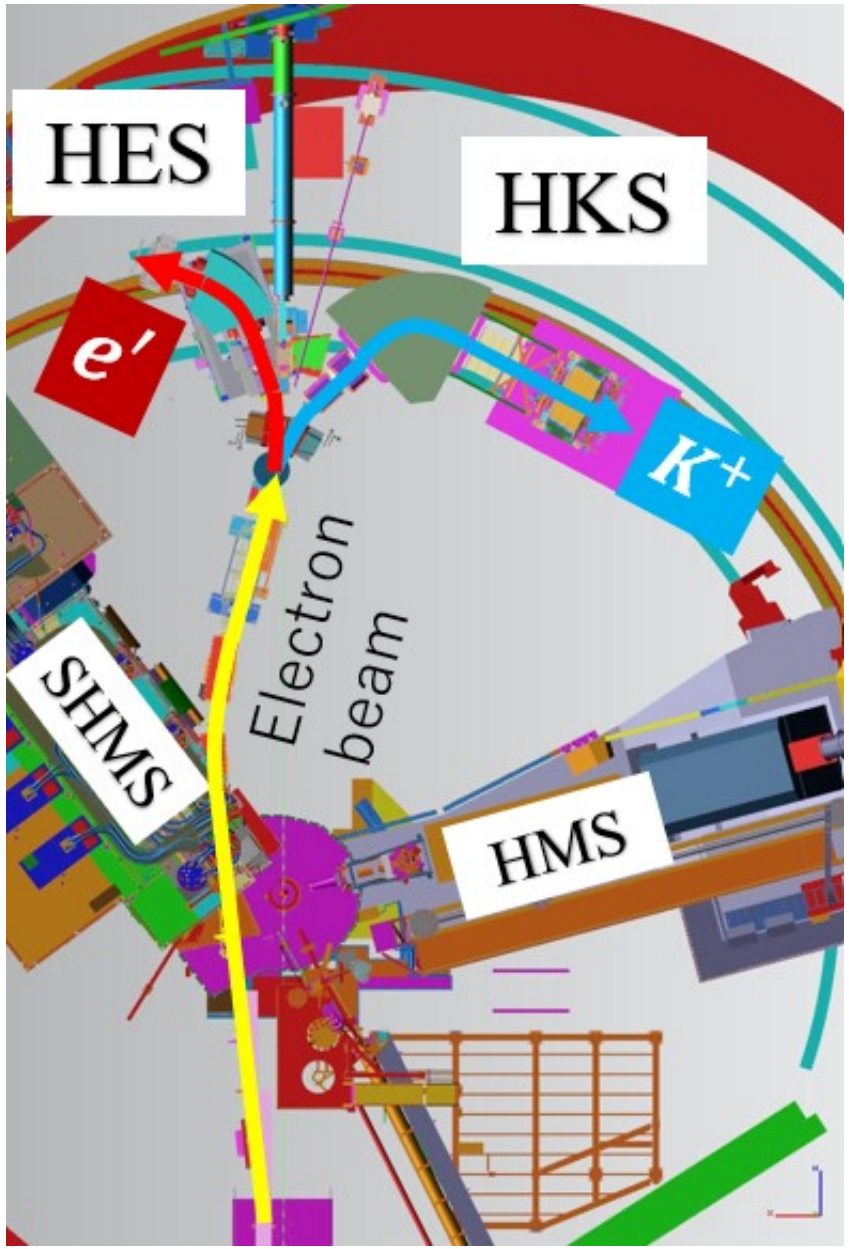
Jan～Mar—
- Commissioning runs
  (a few days of beamtime)
- **Physics runs**

Experiment	Target (thickness [/(g/cm^2)])	Contents	($p^{\text{cent.}}_{\text{Beam}}$, $p^{\text{cent.}}_{\text{S-2S}}$) [/(MeV/$c$)]	beam time (/hours)
New	^{12}C (0, 3)	Beam through (BT)	$\sim$ A: (1050, 740)	12
New	^{12}C (3)	$^{12}\text{C}(\pi^+, K^+)^{12}_{\Lambda}\text{C}$	A	24
New	^{12}C (1)	$^{12}\text{C}(\pi^+, K^+)^{12}_{\Lambda}\text{C}$	A	48
New	^{7}Li (1)	$^{7}\text{Li}(\pi^+, K^+)^{7}_{\Lambda}\text{Li}$	A	24
New	^{51}V (1)	$^{51}\text{V}(\pi^+, K^+)^{51}_{\Lambda}\text{V}$	A	160
New	^{12}C (3)	$^{12}\text{C}(\pi^+, K^+)^{12}_{\Lambda}\text{C}$	B: (1300, 1000)	24
E70	^{12}C (3)	$^{12}\text{C}(\pi^+, K^+)^{12}_{\Lambda}\text{C}$	C: (1640, 1370)	80
E70	^{12}C (0, 3)	BT	$\sim$ D: (1800, 1370)	12
E70	CH_2 (3)	$p(K^-, K^+)\Xi^-$	D	24
E70	CH_2 (1)	$p(K^-, K^+)\Xi^-$	D	24
E70	AFT (9)	AFT commissioning	D	48
E70	AFT (9)	$^{12}\text{C}(K^-, K^+)^{12}_{\Xi}\text{Be}$	D	48
Analysis				($>\approx$ 1 month)
E70	^{12}C (0, 3)	BT + detector commis.	$\sim$ D	48
E70	AFT (9)	$^{12}\text{C}(K^-, K^+)^{12}_{\Xi}\text{Be}$	D	$\approx$ 576
New	^{12}C (0, 3)	BT + detector commis.	$\sim$ A	12
New	^{51}V (1)	$^{51}\text{V}(\pi^+, K^+)^{51}_{\Lambda}\text{V}$	A	320



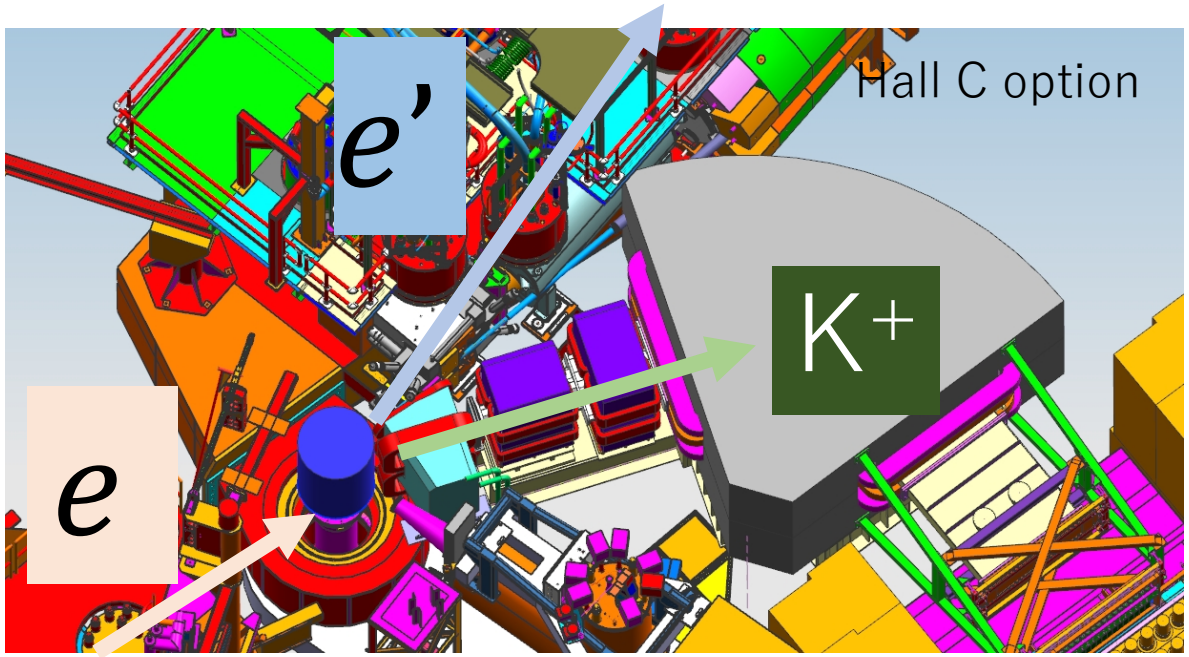
Hall A

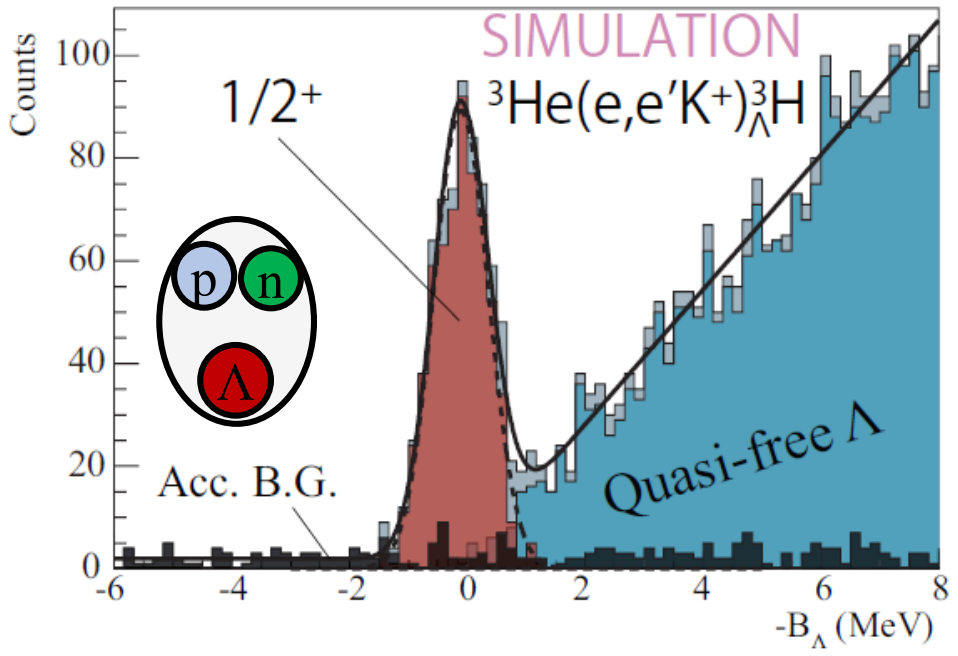
Future experiment at JLab



Hall C

Future programs being prepared





- ${}^{3,4}_{\Lambda}\mathrm{H}$ (E12-19-002) → lifetime puzzle, CSB, $3/2^+$
- ${}^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008) → Isospin dependence
- ${}^{208}_{\Lambda}\mathrm{Tl}$ (E12-20-013) → NN Λ interaction

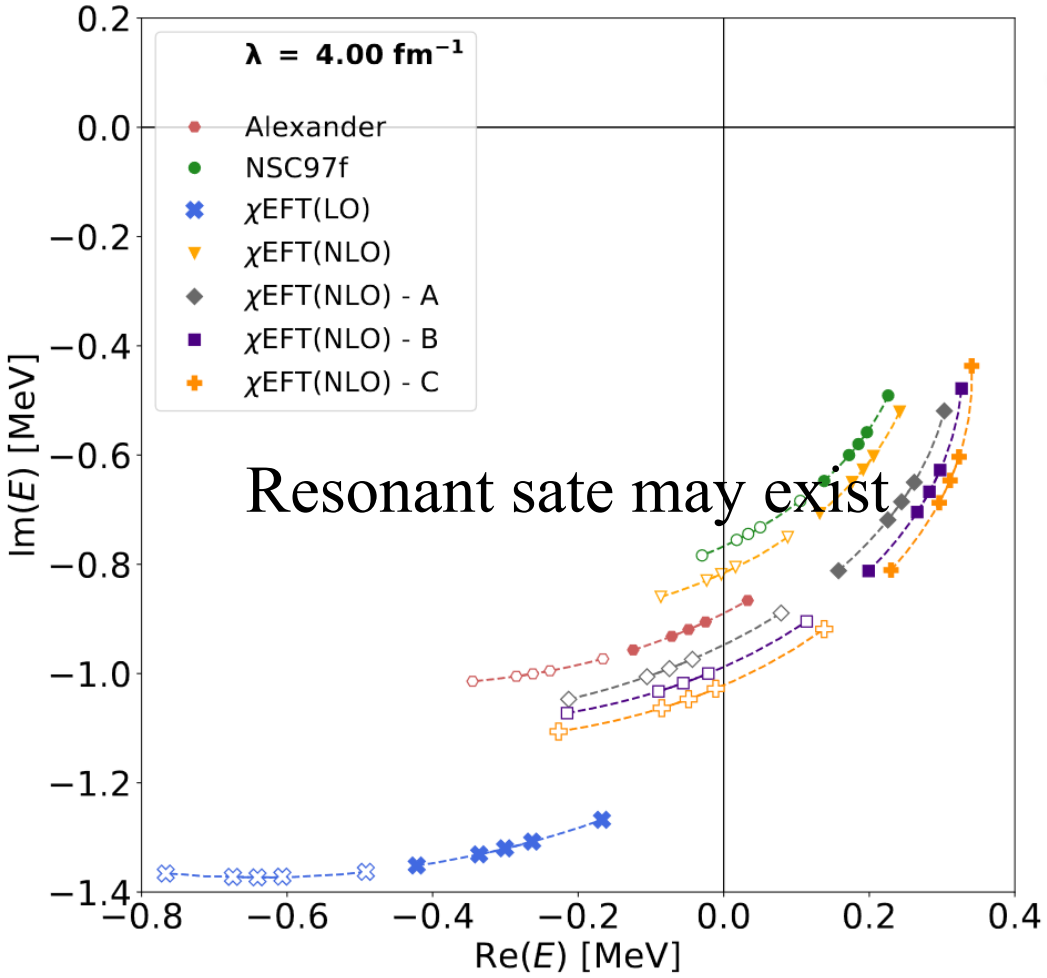
Very high accuracy

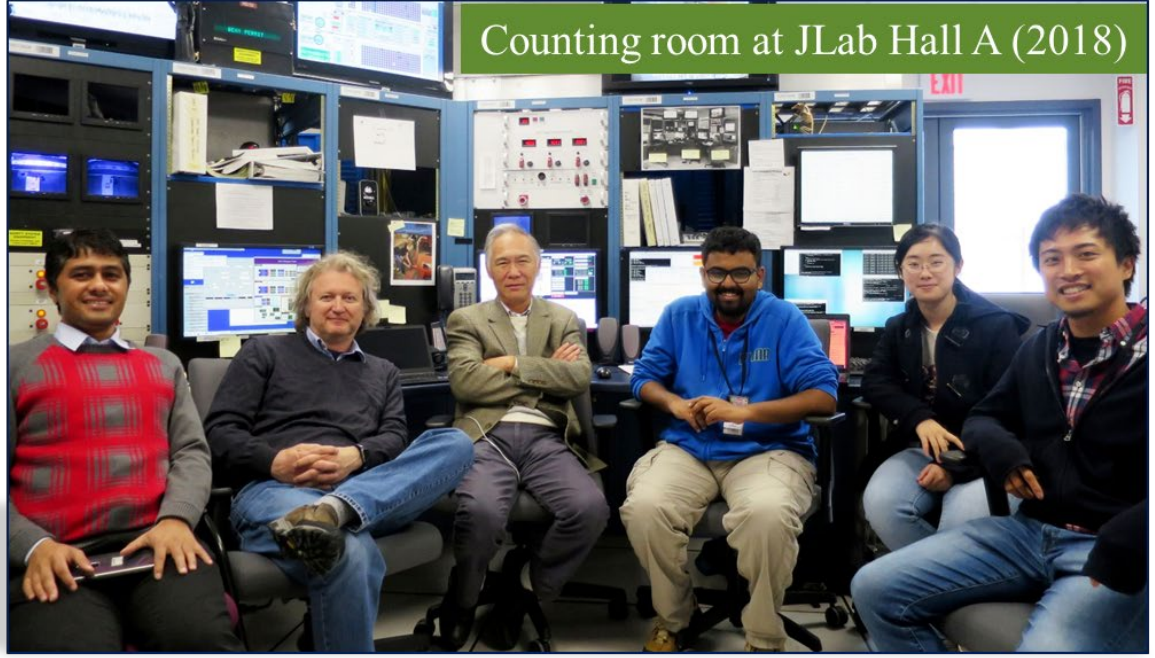
$$\Delta B^{\mathrm{total}}{}_{\Lambda} = \pm 60\ \mathrm{keV}$$

Aim to carry out in 2024～

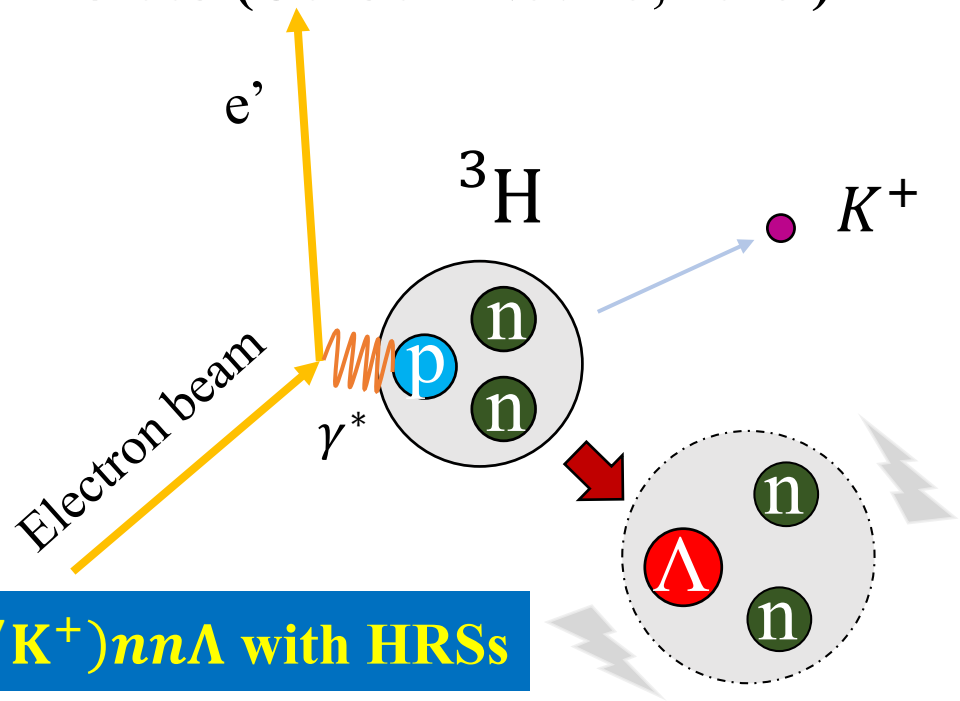
nn Λ search

M. Schafer et al., arXiv:2108.13900v1 [nucl-th]
31 Aug 2021





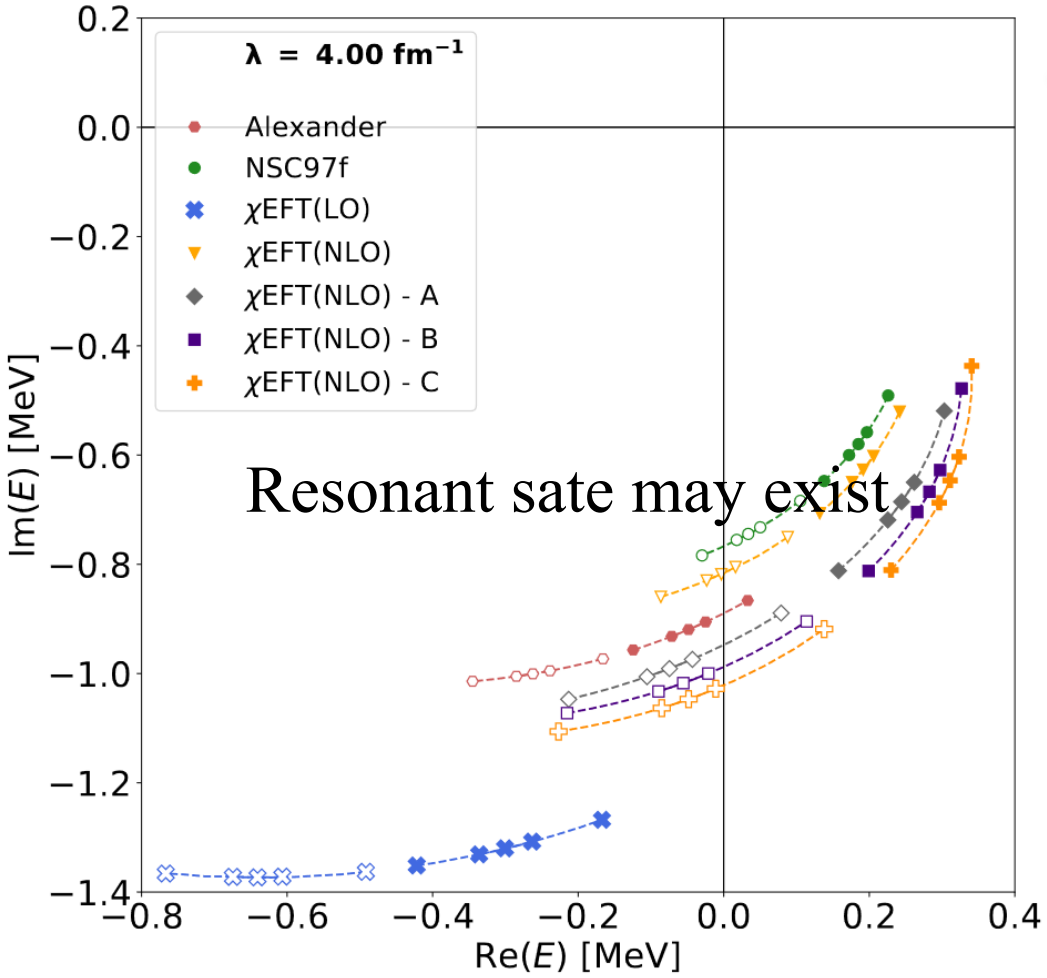
E12-17-003 (Oct 30—Nov 25, 2018)

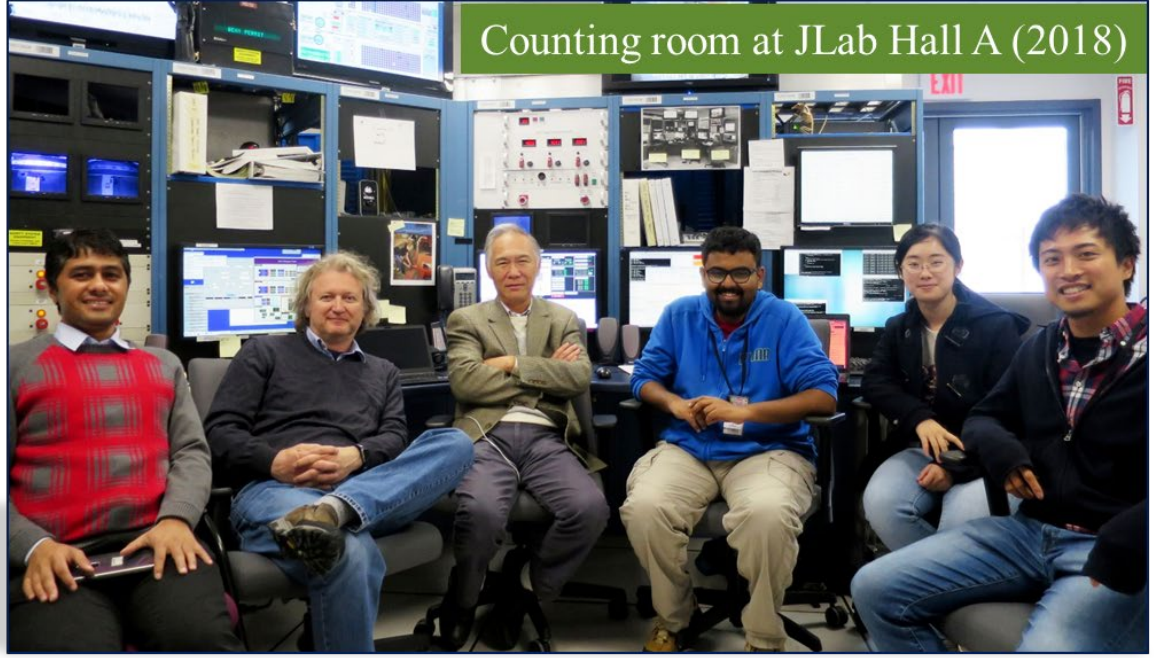


^{3}H(e, e′K$^+$)*nn*Λ with HRSs

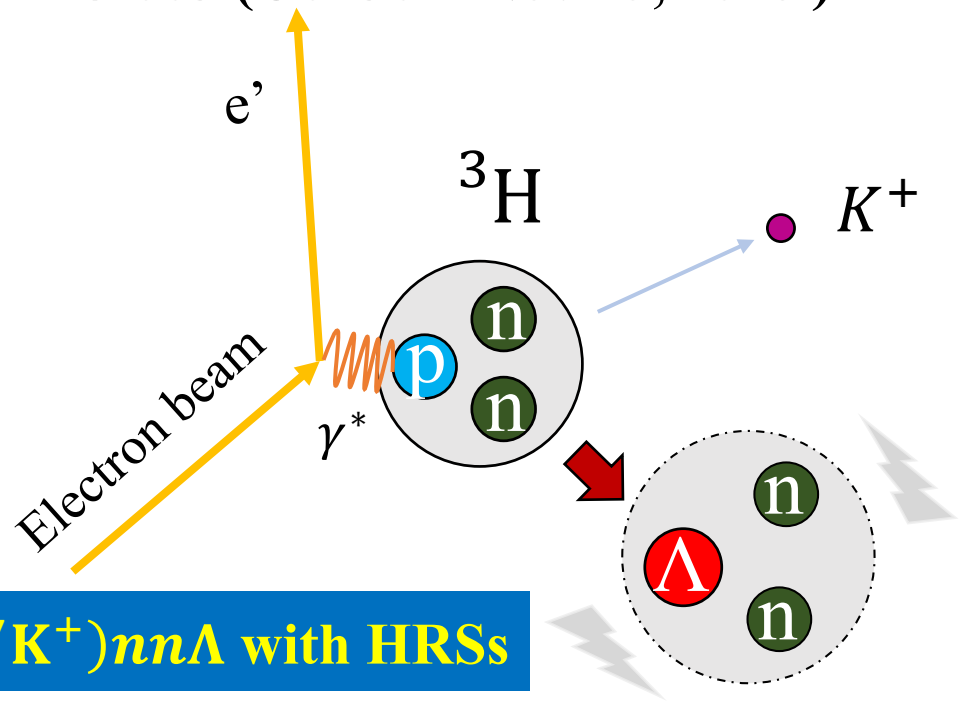
nn Λ search

M. Schafer et al., arXiv:2108.13900v1 [nucl-th]
31 Aug 2021





E12-17-003 (Oct 30—Nov 25, 2018)



^{3}H(e, e′K$^+$)*nn*Λ with HRSs

PTEP Progress of Theoretical and Experimental Physics

ACCEPTED MANUSCRIPT

The cross-section measurement for the $^{3}\mathrm{H}(e, e'K^{+})nn\Lambda$ reaction

K N Suzuki ✉, T Gogami ✉, B Pandey, K Itabashi, S Nagao, K Okuyama, S N Nakamura, L Tang, D Abrams, T Akiyama ... Show more

Progress of Theoretical and Experimental Physics, ptab158, https://doi.org/10.1093/ptep/ptab158

Published: 06 December 2021

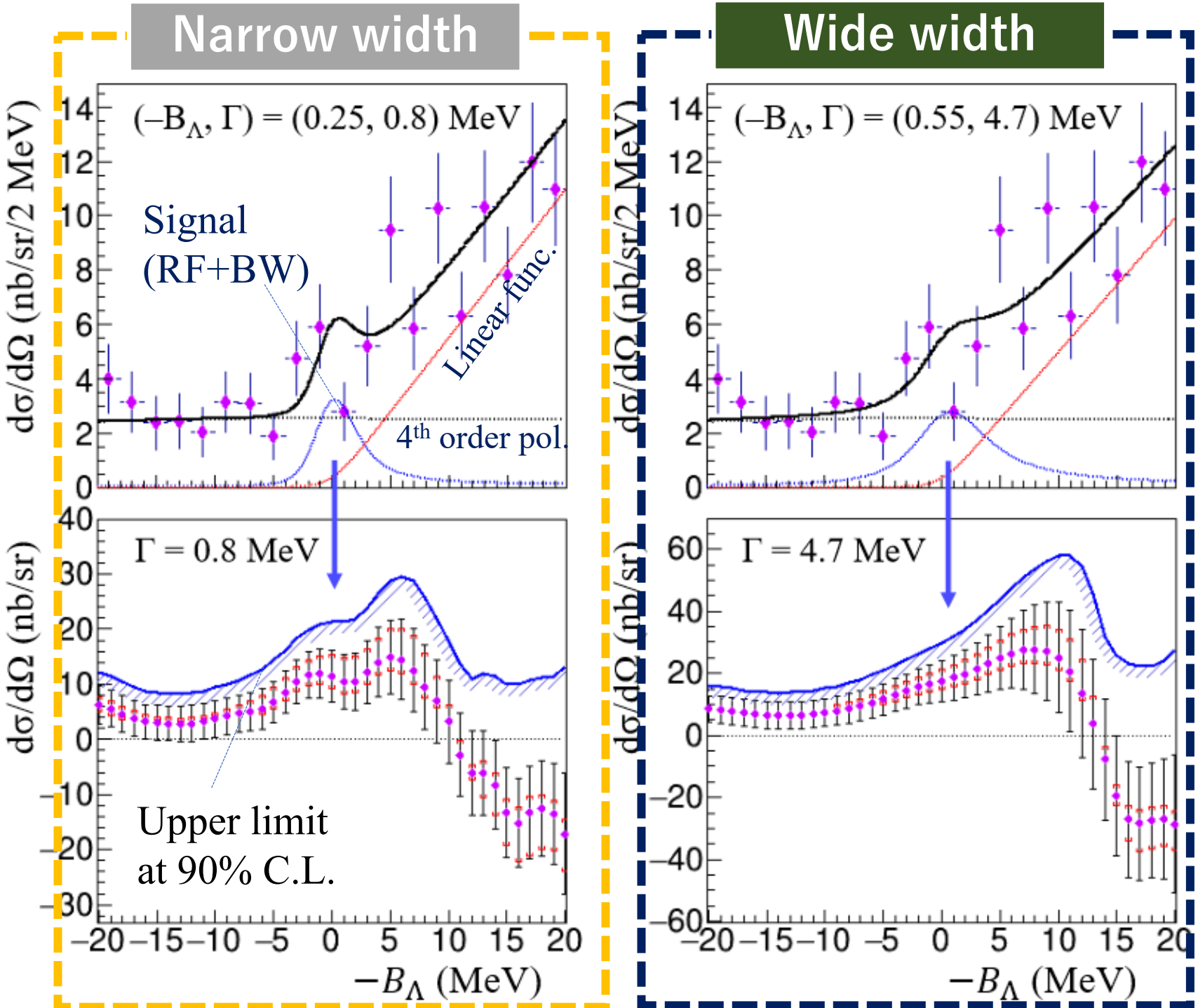
Result (nnΛ)

PTEP (2021)
arXiv:2110.09104 [nucl-ex]

Test case1: narrow width Γ = 0.8 MeV
K.M.Kamada et al.,
EPJ Conf. 113, 07004 (2016)

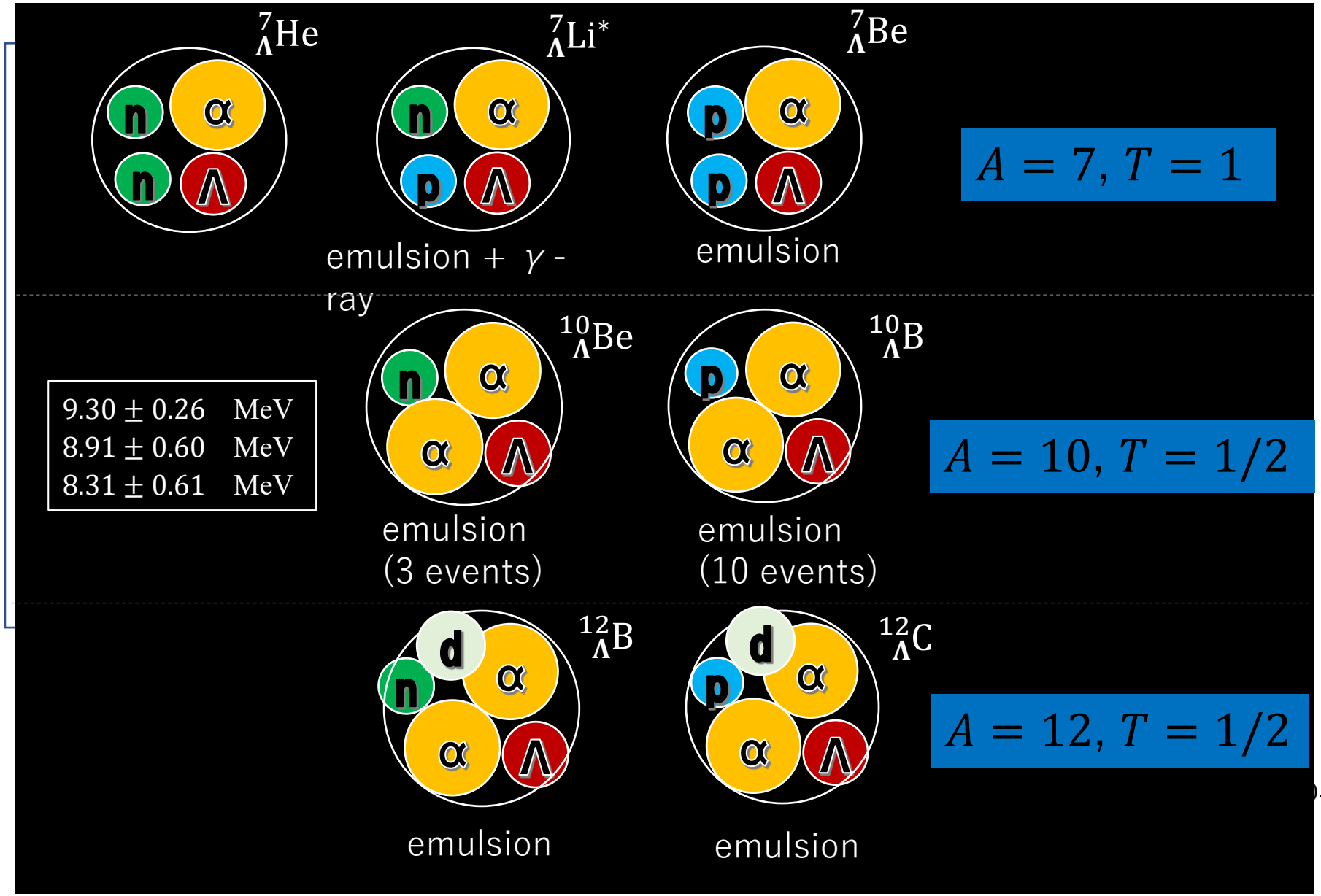
Test case2: wide width Γ = 4.7 MeV
V.B. Belyaev et al., NPA 803, 210 (2008)

Unbinned maximum likelihood fitting
→ Cross section



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

A. Gal et al., J. Phys.: Conf. Ser. 966 012006 (2018)

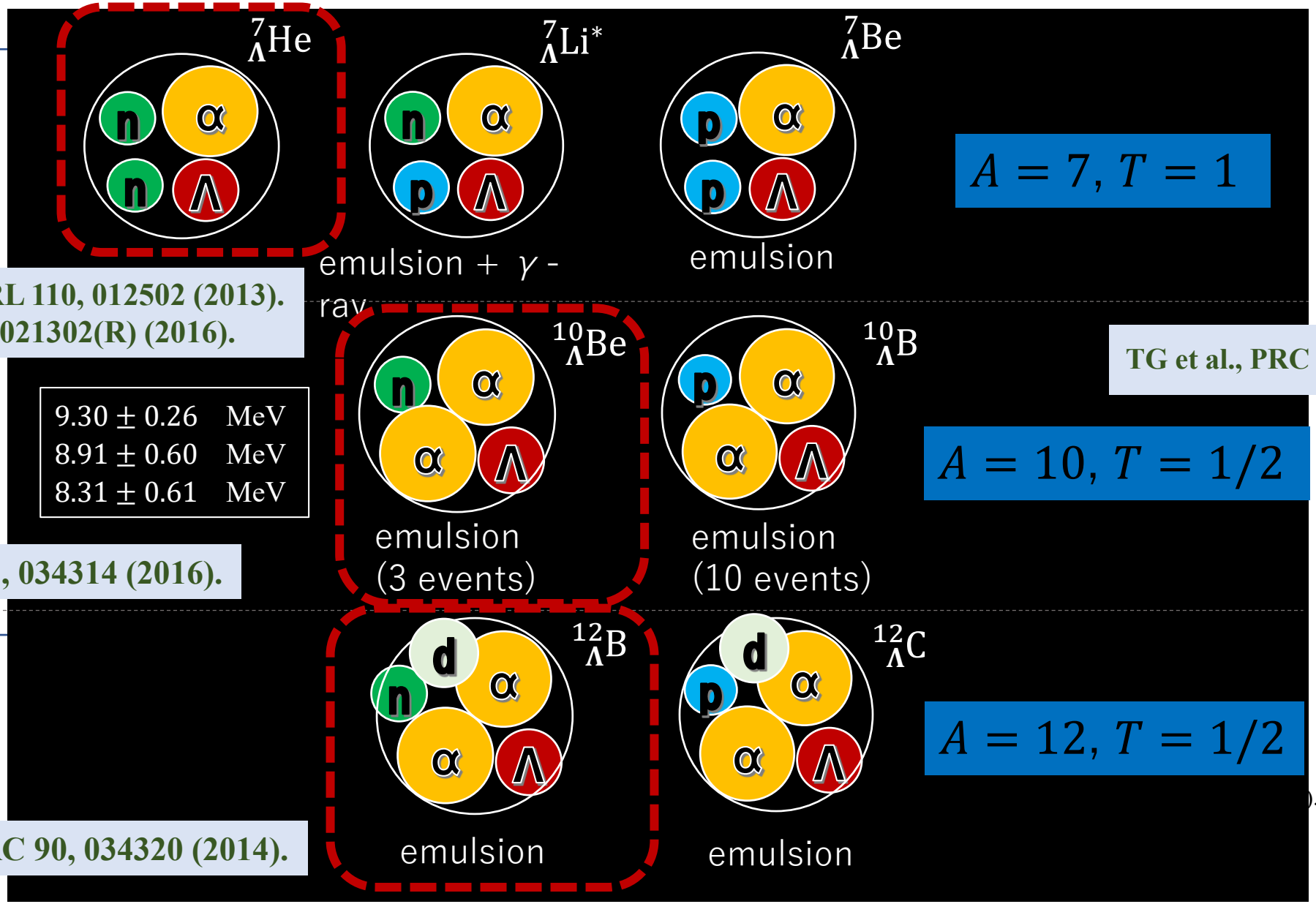


Expected difference

15—30 keV

136 keV

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



S.N.Nakamura, PRL 110, 012502 (2013).
TG et al., PRC 94, 021302(R) (2016).

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

TG et al., PRC 93, 034314 (2016).

L. Tang et al., PRC 90, 034320 (2014).

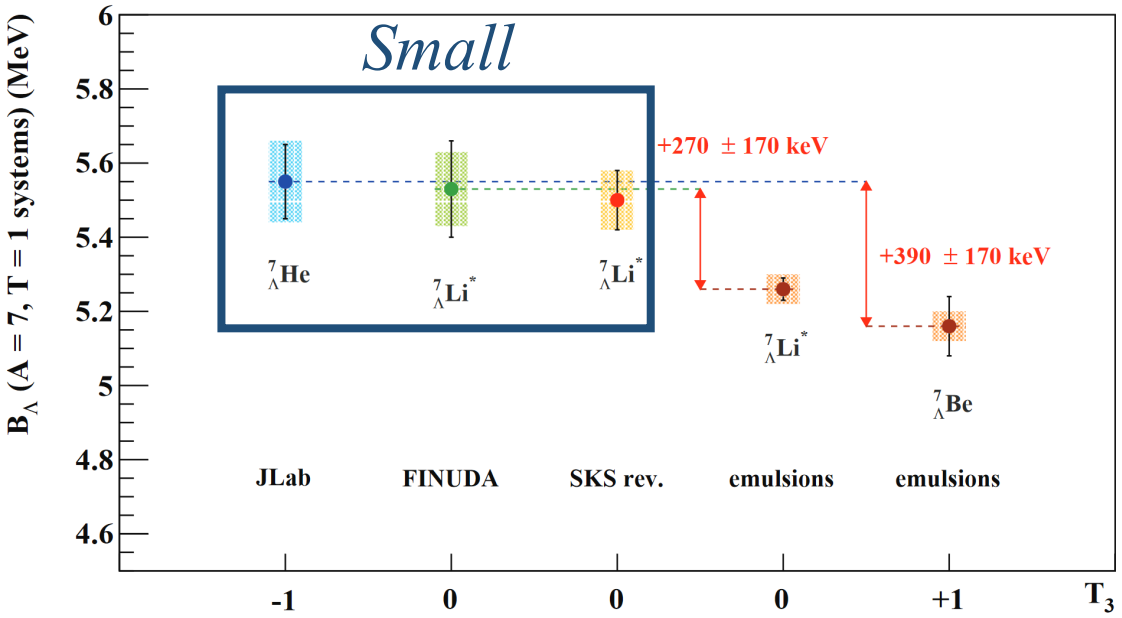
$^{9}_{\Lambda}$Li vs. $^{9}_{\Lambda}$B

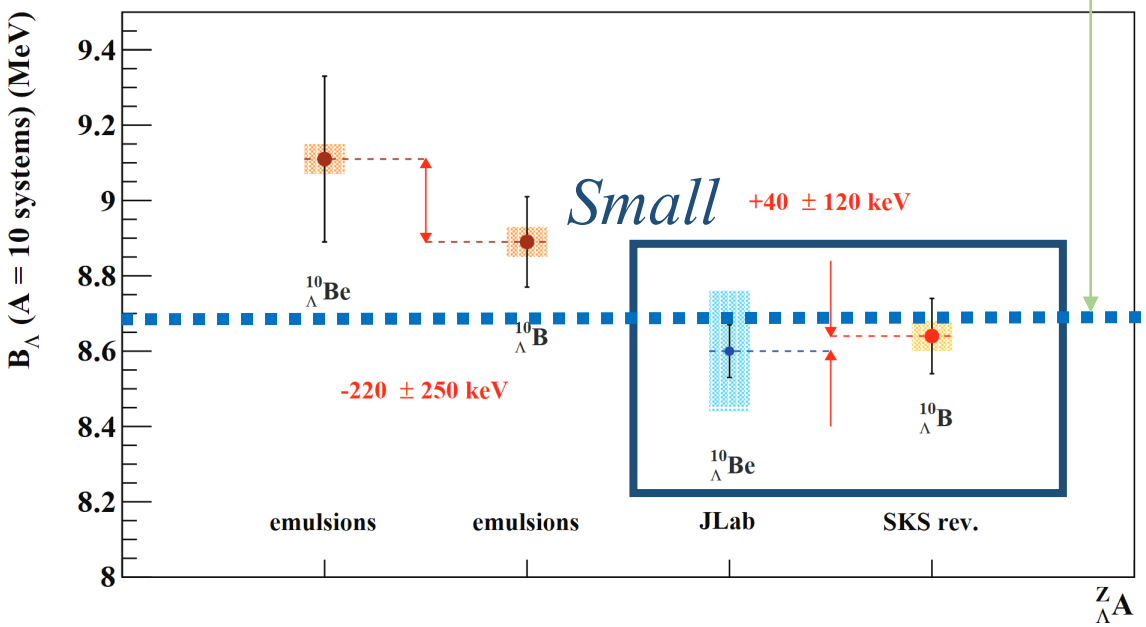
TG et al., PRC 103, L041301 (2021)

Results

Y. Kanada, PRC97, 034324 (2018);
ESC08a (DI)

E. Botta, AIP Conference Proceedings 2130, 030003 (2019)



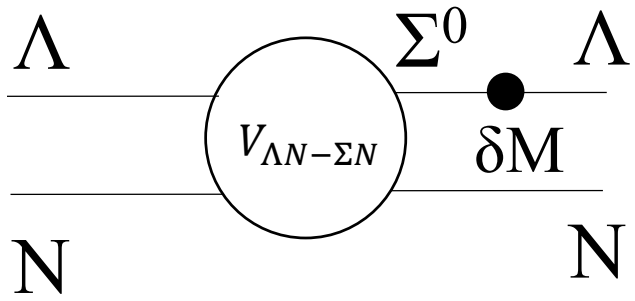


- CSB seems to be small in p-shell when counting experiments' data are used
- Double check is awaited for emulsion data → J-PARC E07 (data were taken)

Basic Information for the Λ n CSB study: $^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$

Explicit inclusion of Σ

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



$$\langle N\Lambda|V_{CSB}|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

Phenomenological potential

E. Hiyama et al., Phys. Rev. C **80**, 054321 (2009).
M. Isaka et al., Phys. Rev. C 101, 024301 (2020).

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

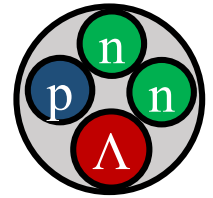
Basic Input

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

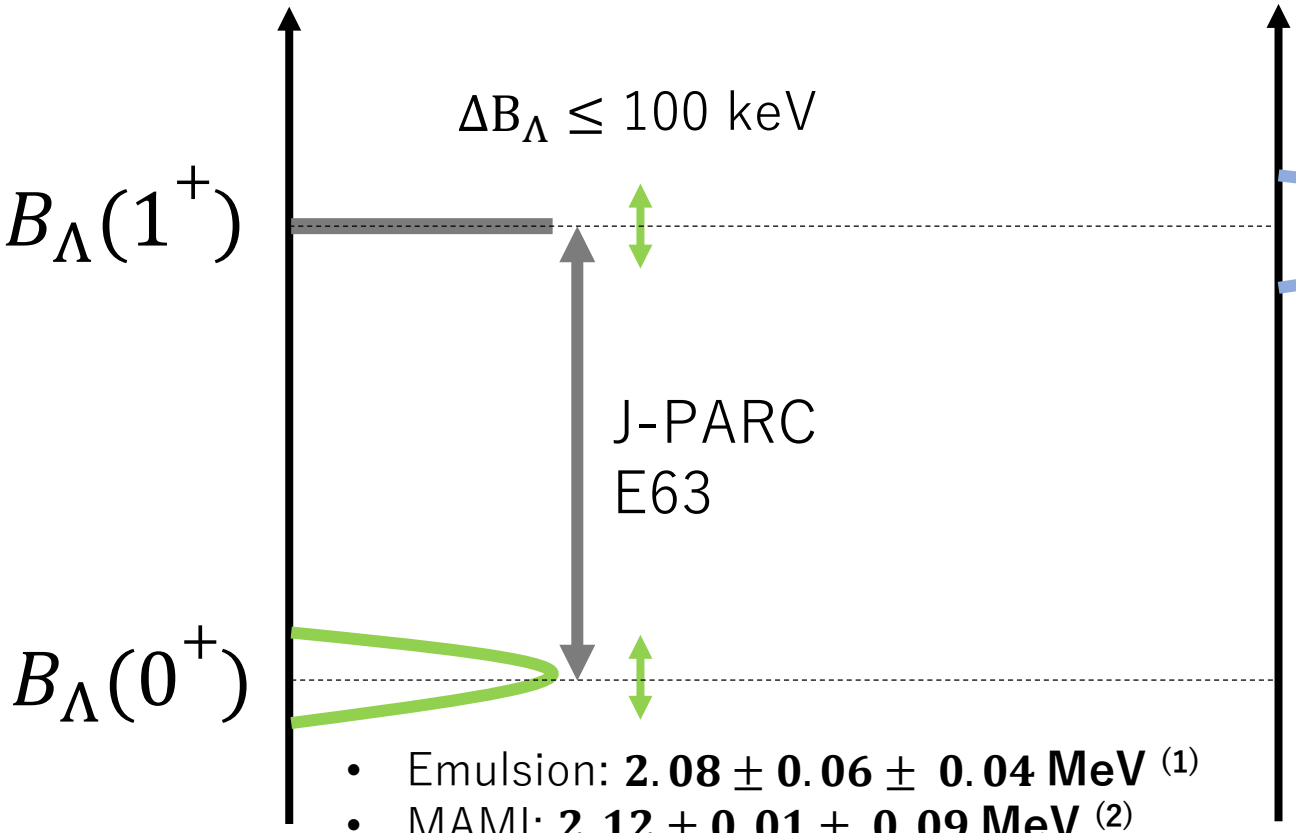
A=4 → **CSB interaction** → A=5, A=7, A=9, A=10 …

HKS, PRL 110, 012502 (2013)
HKS, PRC 94, 021302(R) (2016)
Hall A, PRC 91,034308 (2015)
HKS, PRC103, L041301 (2021)
HKS, PRC 93, 034314 (2016)
HKS, PRC 90, 034320 (2014) …

How we confirm the $B_\Lambda({}^{4}_{\Lambda}\mathrm{H};\ 1^+)$



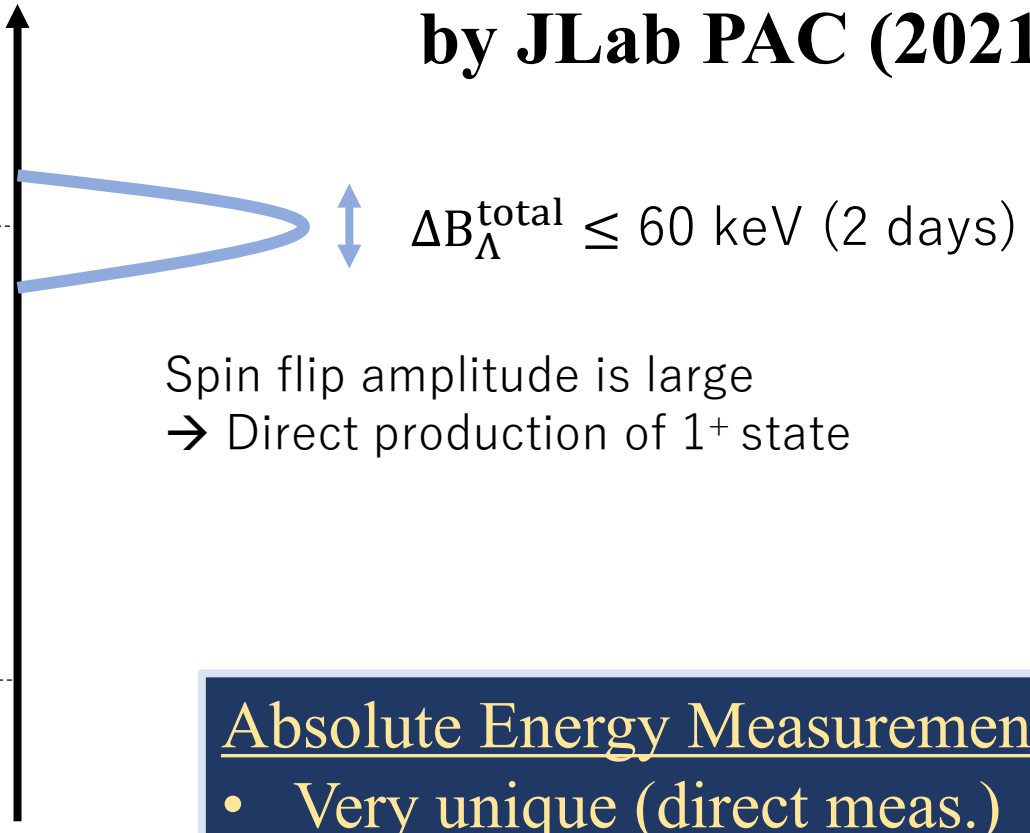
Conventional way



- Emulsion: $\mathbf{2.08 \pm 0.06 \pm 0.04}$ **MeV** (1)
- MAMI: $\mathbf{2.12 \pm 0.01 \pm 0.09}$ **MeV** (2)

JLab E12-19-002

Fully approved by JLab PAC (2021)



Spin flip amplitude is large
→ Direct production of 1^+ state

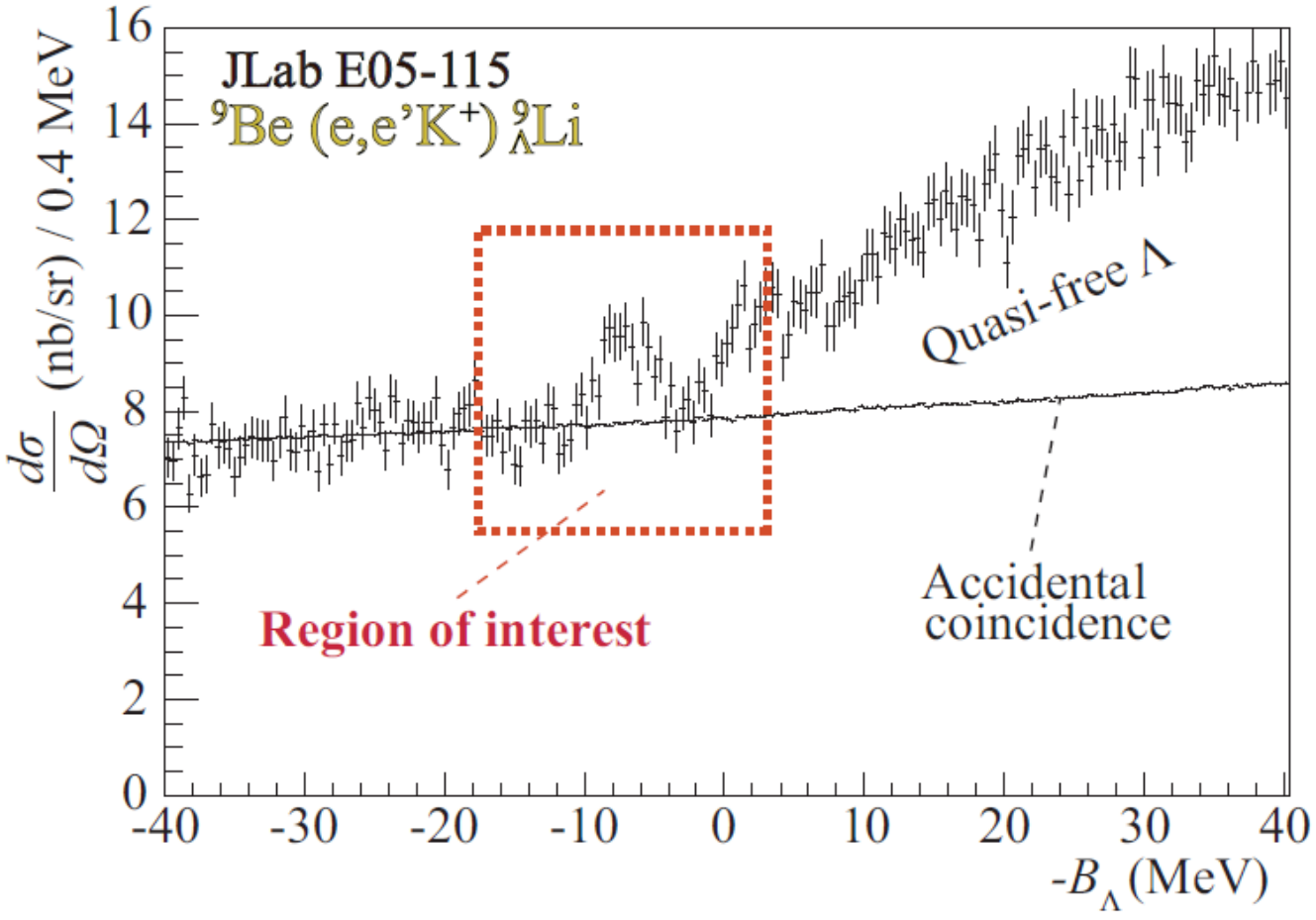
Absolute Energy Measurement:
- Very unique (direct meas.)
- Complementary with other data

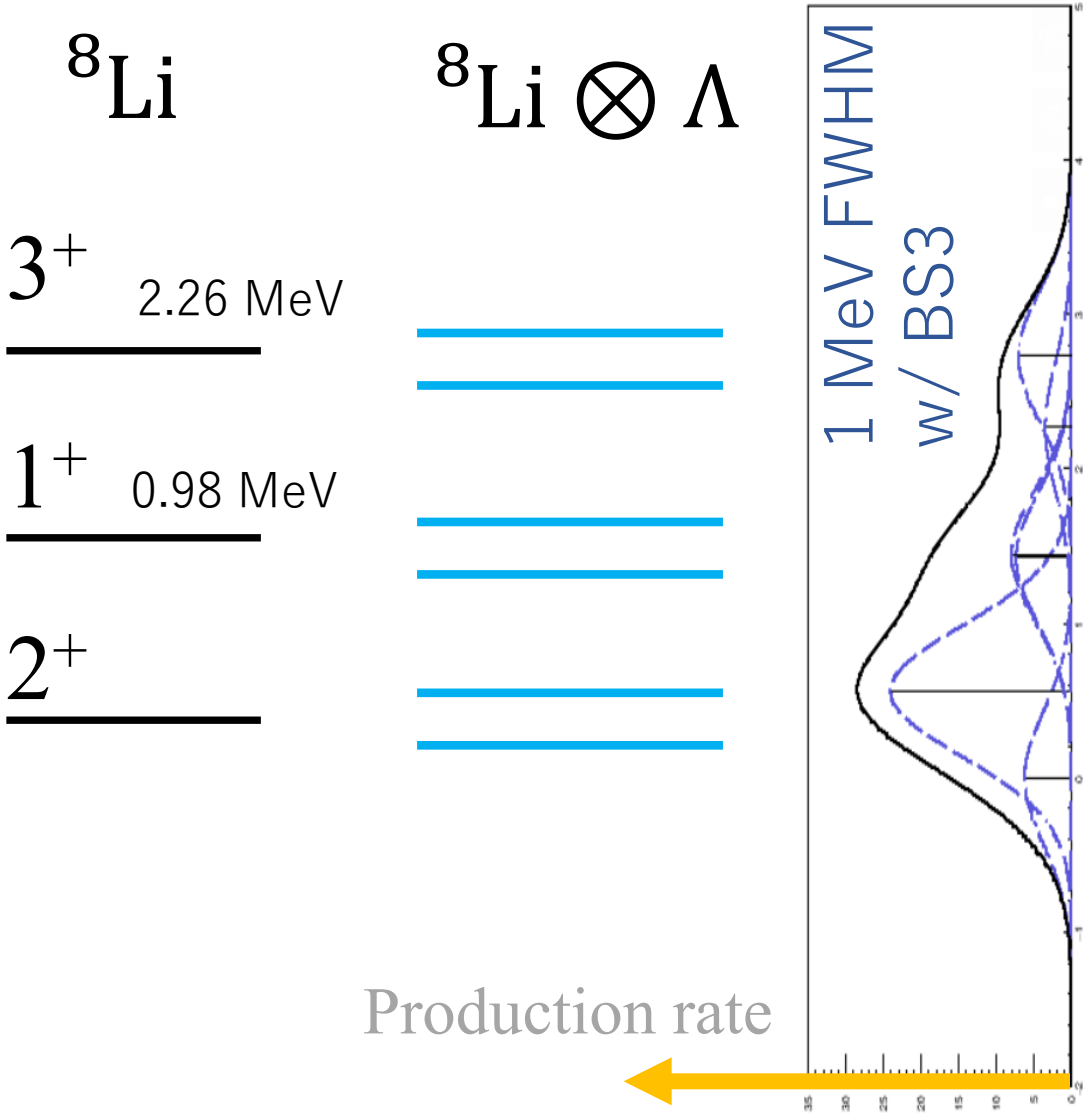
(1) NPB 52, 1-30 (1973)
(2) PRL 114, 232501 (2015)

$^{8}\mathrm{Li} \otimes \Lambda = {}^{9}_{\Lambda}\mathrm{Li}$ (Hyperlithium)

$^{8}\mathrm{Li}(e, e'K^{+})^{9}_{\Lambda}\mathrm{Li}$
P. Bydžovský
(private communication)

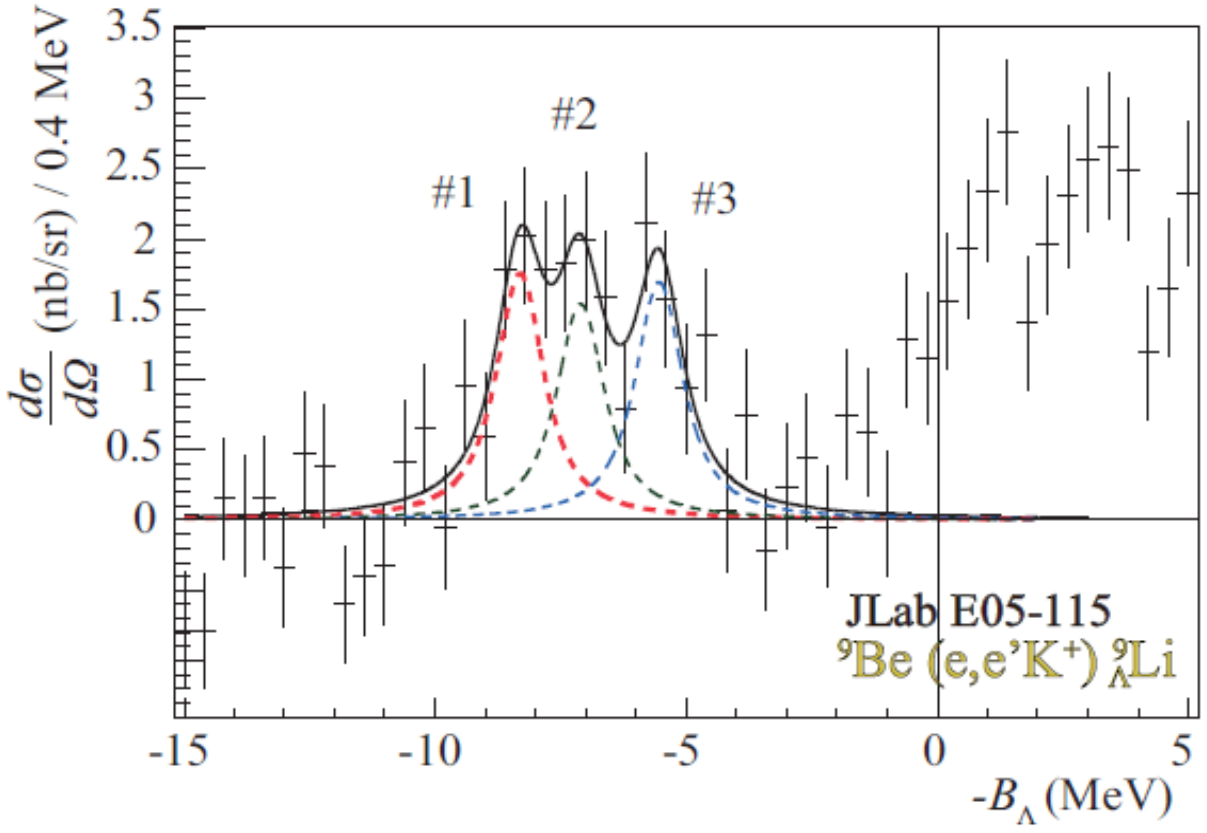
TG et al., PRC 103, L041301 (2021)

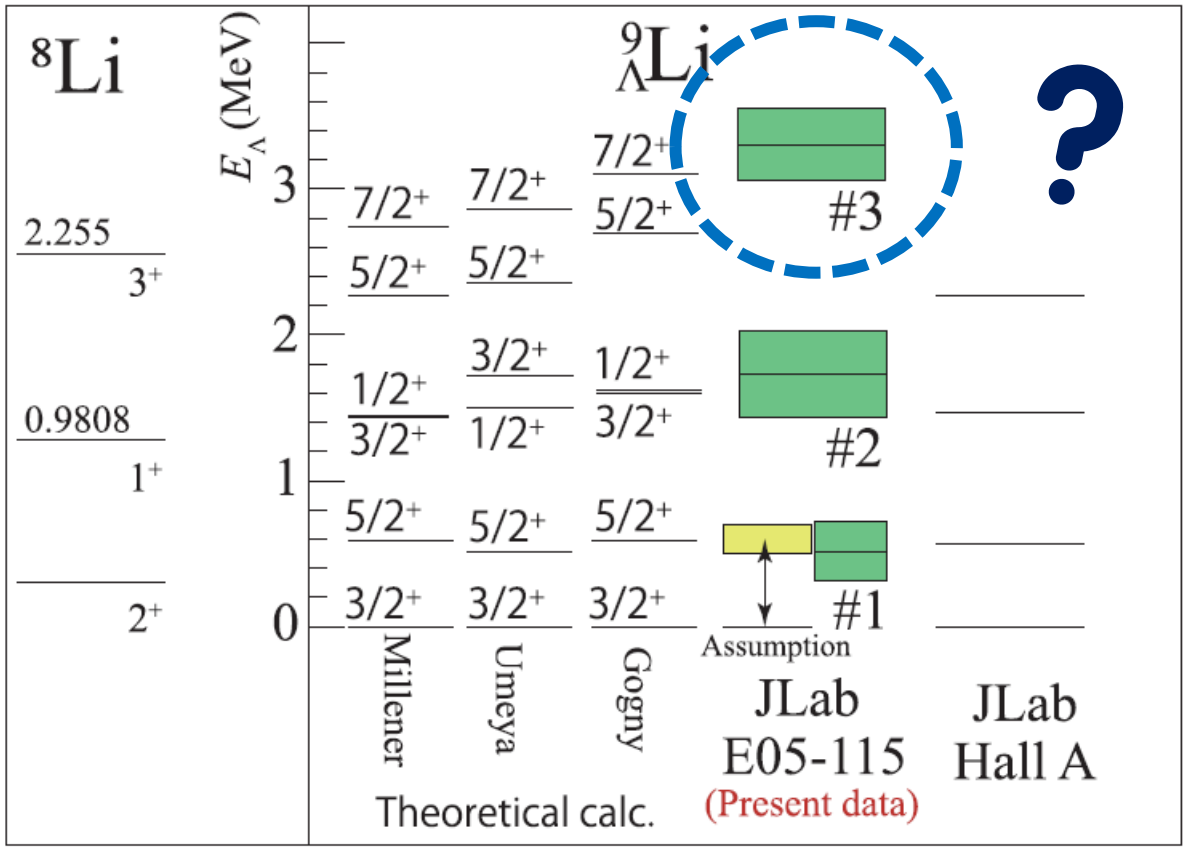




Small binding in $^{8}\mathrm{Li}\,(3^{+}) \otimes \Lambda$

HKS Collaboration, PRC 103, L041301 (2021)





Cluster structure?

H. Stowe and W. Zahn, NPA289, 317—328 (1977)

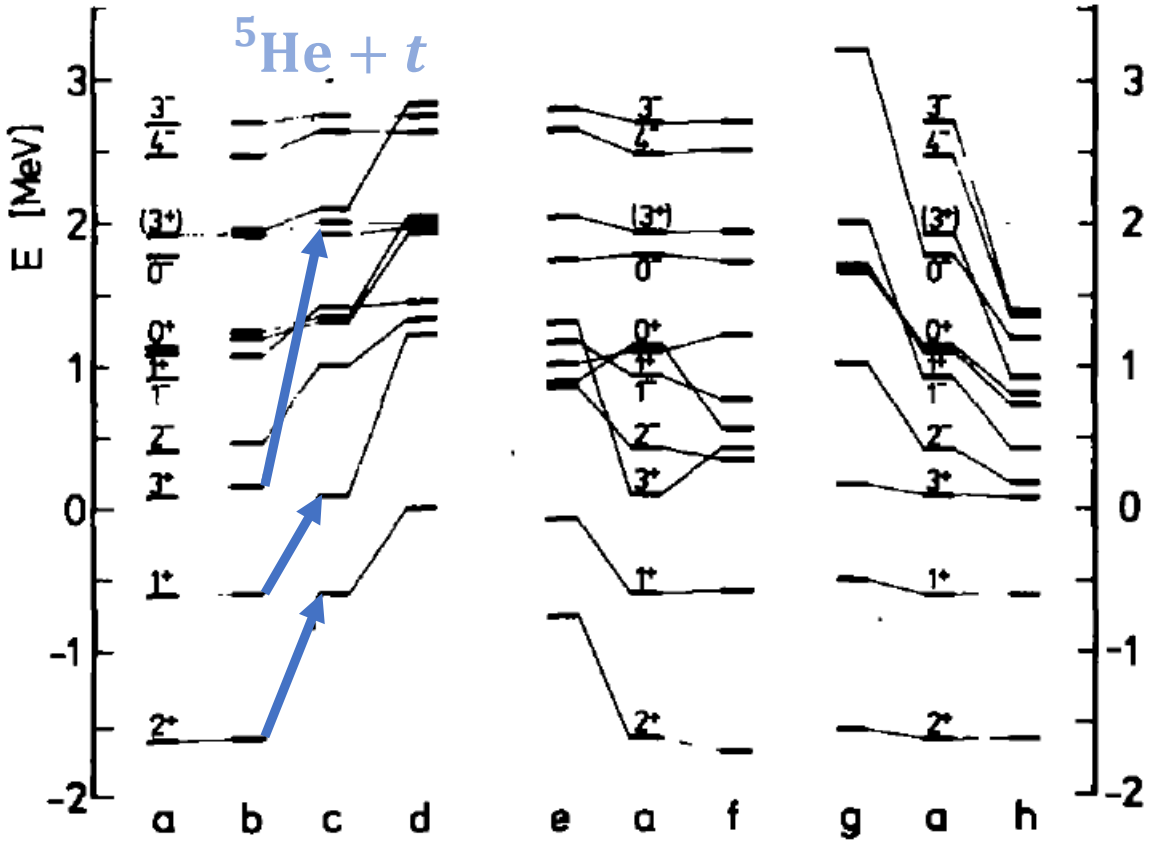
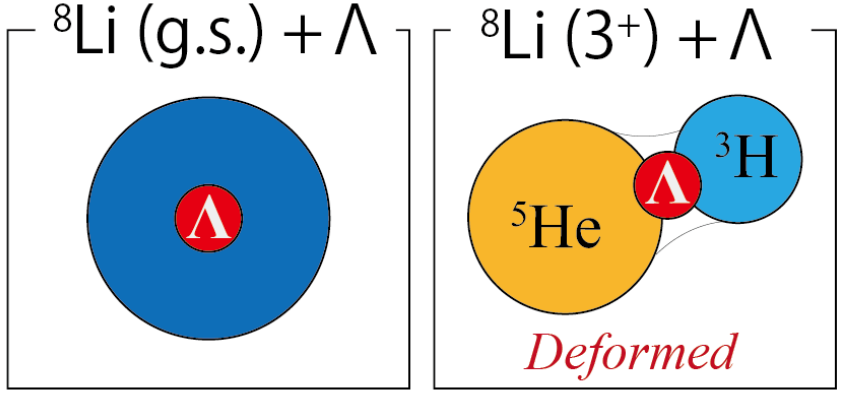
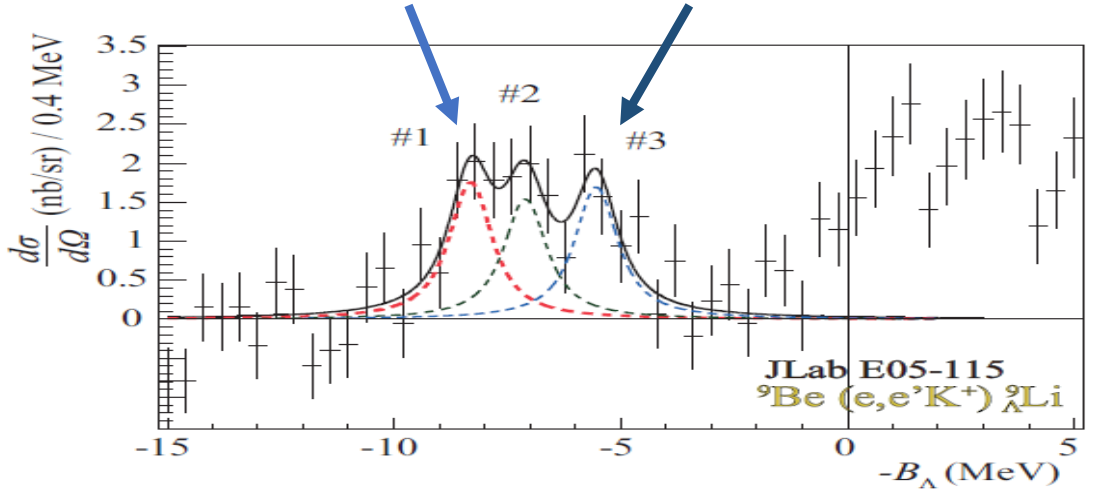


Fig. 4. Results of bound and quasibound state calculations. (a) Full calculation with relative parameters 7–11, (b) same as (a) but without ^{5}He*-t structure, (c) same as (b) but without ^{5}He-t structure, (d) same as (c) but without ^{7}Li*-n structure, (e) same as (a) but with spin-orbit strength 2, (f) same as (a) but with tensor strength 3, (g) same as (a) but with relative parameters 7–10, and (h) same as (a) but with relative parameters 7–12.

Λ probes the core structure



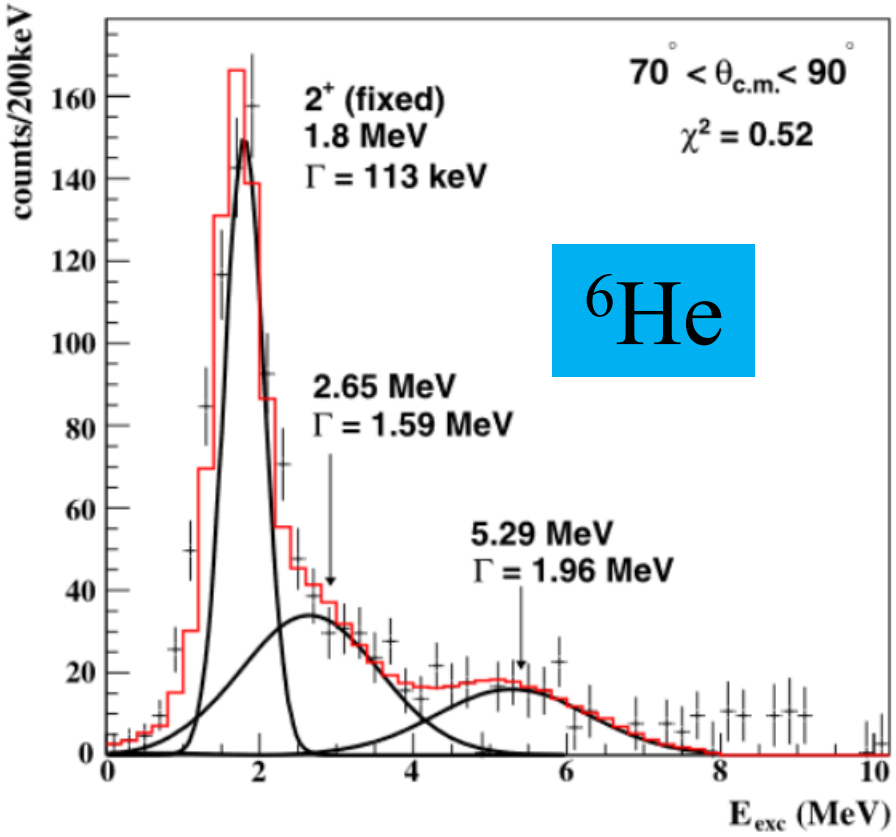
Lithium-9 Λ hypernucleus



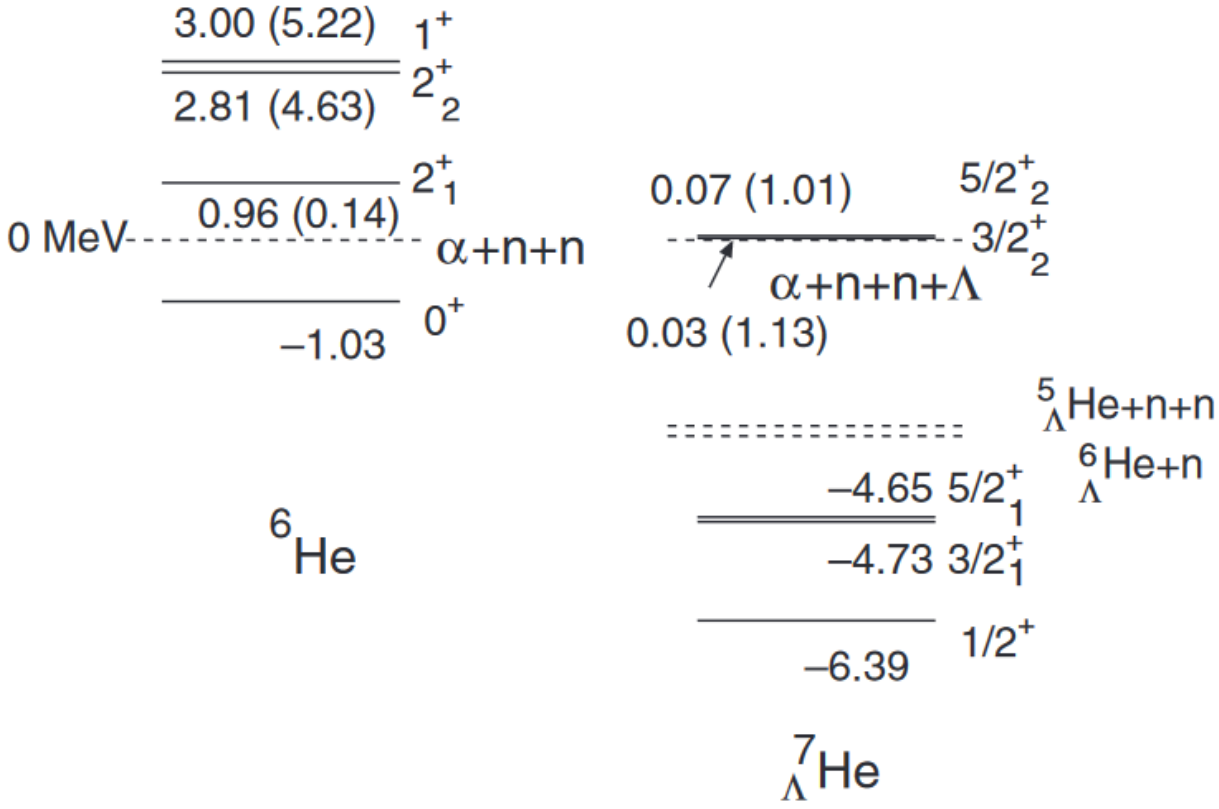
Theoretical calculation is awaited to be compared with the result!!

$^{6}\mathrm{He} \otimes \Lambda = {}^{7}_{\Lambda}\mathrm{He}$ (Hyperhelium)

$^{8}\mathrm{He}(p,t)$ @SPIRAL, GANIL



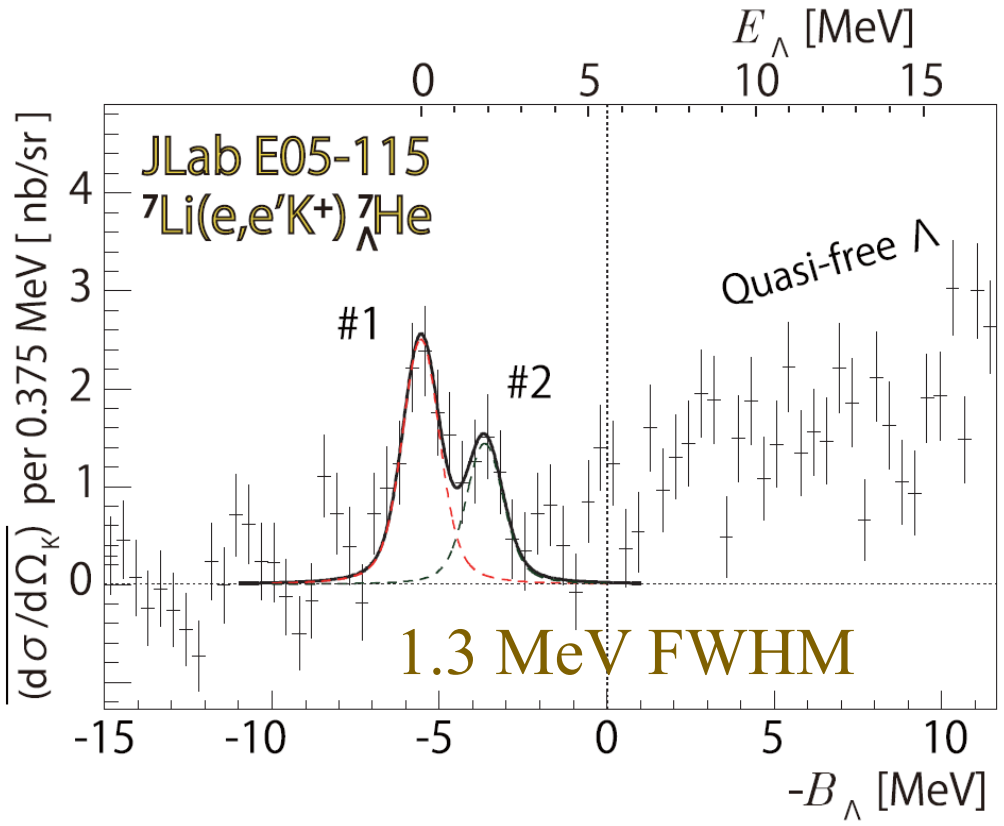
X. Mougeot et al., PLB718, 441—446 (2012)

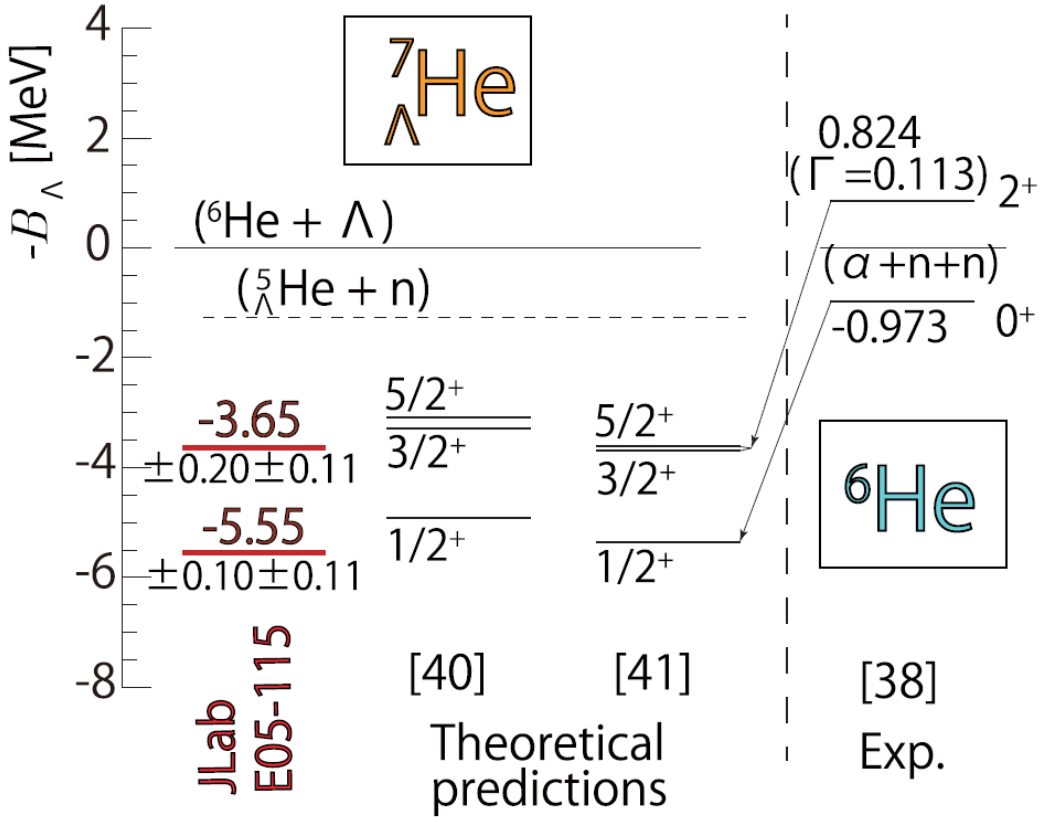


E. Hiyama et al., PRC91, 054316 (2015)

$^{6}\mathrm{He} \otimes \Lambda = {}^{7}_{\Lambda}\mathrm{He}$ (Hyperhelium)

HKS Collaboration, PRC 94, 021302(R) (2016)





Glue-like behavior can be a tool to investigate nuclear structures for neutron rich systems

Summary

1. S-2S @J-PARC

- ${}^{51}_{\Lambda}\mathrm{V}$ (+ ${}^{7}_{\Lambda}\mathrm{Li}$, ${}^{12}_{\Lambda}\mathrm{C}$)
  - **Feasibility of 1 MeV FWHM spectroscopy of Λ hypernuclei**
  - **Absolute → $|\Delta B_{\Lambda}| \sim 100$ keV**
  - **S-2S commissioning**

2. HKS @JLab

- ***nnΛ* search** (2018) → Cross section (PTEP 2021), peak search, FSI
- Future projects (2024～)
  - ${}^{3,4}_{\Lambda}\mathrm{H}$ (E12-19-002) → lifetime puzzle and $3/2^{+}$ existence for hypertriton, CSB
  - ${}^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008) → Isospin dependence
  - ${}^{208}_{\Lambda}\mathrm{Tl}$ (E12-20-013) → NNΛ interaction