New proposal

JLab P12-19-002

HIGH PRECISION MEASUREMENT OF Λ HYPERHYDROGENS

T. Gogami (Kyoto University),

S.N. Nakamura, F. Garibaldi, P. Markowitz, J. Reinhold, L. Tang, G.M. Urciuoli

for the JLab Hypernuclear Collaboration

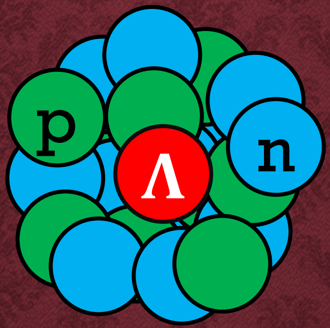
and for the JLab Hall A Collaboration

July 29, 2019

京都大学

KYOTO UNIVERSITY

WHAT WE LEARN FROM HYPERNUCLEI

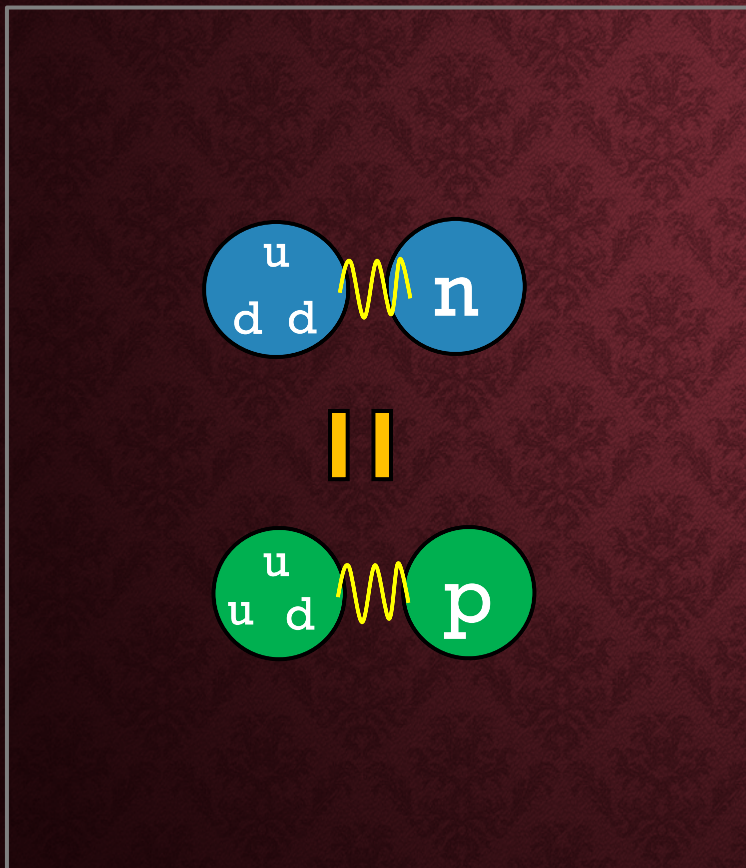


① Investigating the YN interaction

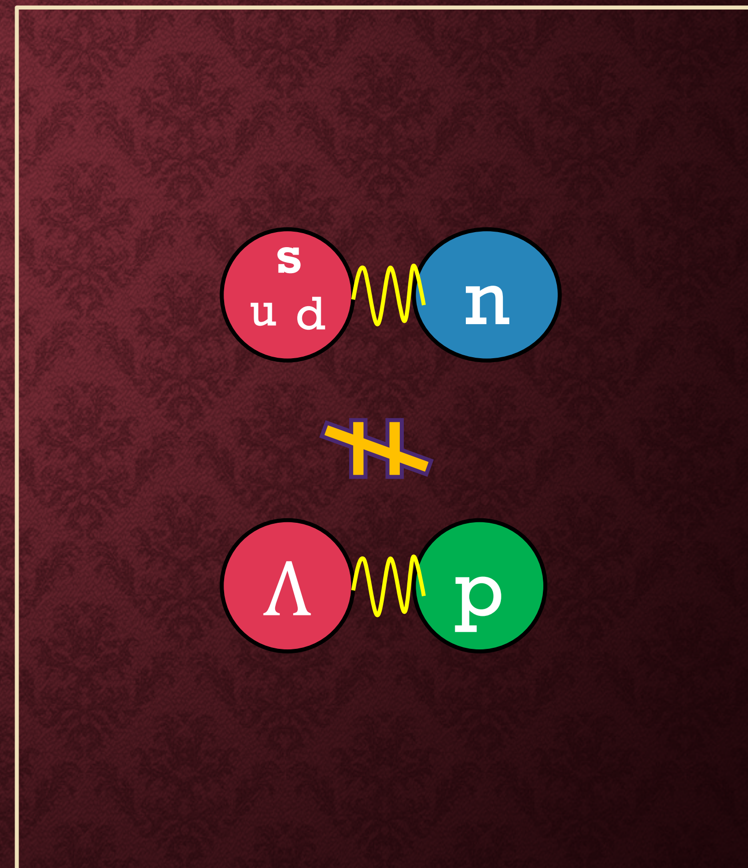
② Probing deep inside of nuclei

③ Unique features with hyperons (impurity effect)

ΛN CHARGE SYMMETRY BREAKING



$S = 0$



$S = -1$

JLab measurements for the CSB study

PHYSICAL REVIEW C
covering nuclear physics
HES-HKS

Rapid Communication

Spectroscopy of the neutron-rich hypernucleus ${}^{7}_{\Lambda}\mathrm{He}$ from electron scattering

T. Gogami *et al.* (HKS (JLab E05-115) Collaboration)
Phys. Rev. C **94**, 021302(R) – Published 12 August 2016

PHYSICAL REVIEW C
covering nuclear physics
HES-HKS
ENGE-HKS

Editors' Suggestion

Experiments with the High Resolution Kaon Spectrometer at JLab Hall C and the new spectroscopy of ${}^{12}_{\Lambda}\mathrm{B}$ hypernuclei

L. Tang *et al.* (HKS (JLab E05-115 and E01-011) Collaborations)
Phys. Rev. C **90**, 034320 – Published 25 September 2014

PHYSICAL REVIEW C
covering nuclear physics
HES-HKS

Editors' Suggestion

High resolution spectroscopic study of ${}^{10}_{\Lambda}\mathrm{Be}$

T. Gogami *et al.* (HKS(JLab E05-115) Collaboration)
Phys. Rev. C **93**, 034314 – Published 10 March 2016

PHYSICAL REVIEW C
covering nuclear physics
HRS-HRS

Spectroscopy of ${}^{9}_{\Lambda}\mathrm{Li}$ by electroproduction

G. M. Urciuoli *et al.* (Jefferson Lab Hall A Collaboration)
Phys. Rev. C **91**, 034308 – Published 4 March 2015

PHYSICAL REVIEW LETTERS
ENGE-HKS

Observation of the ${}^{7}_{\Lambda}\mathrm{He}$ Hypernucleus by the $(e, e'K^{+})$ Reaction

S. N. Nakamura *et al.* (HKS (JLab E01-011) Collaboration)
Phys. Rev. Lett. **110**, 012502 – Published 2 January 2013

JLab measurements for the CSB study

- The ΛN CSB in p-shell is small
- Phenomenological CSB is too naïve
- $B_\Lambda({}^{12}_{\Lambda}C)$ measured by emulsion has a shift
  - → Needs a half MeV correction for many hypernuclei
  - → $A = 12$ puzzle solved

PHYSICAL REVIEW C
covering nuclear physics
HES-HKS

Rapid Communication

Spectroscopy of the neutron-rich hypernucleus ^{7}H…

PHYSICAL REVIEW C
covering nuclear physics
HES-HKS

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T. Gogami *et al.* (HKS(JLab E…

Phys. R…

…Jefferson Lab Hall A Collaboration)
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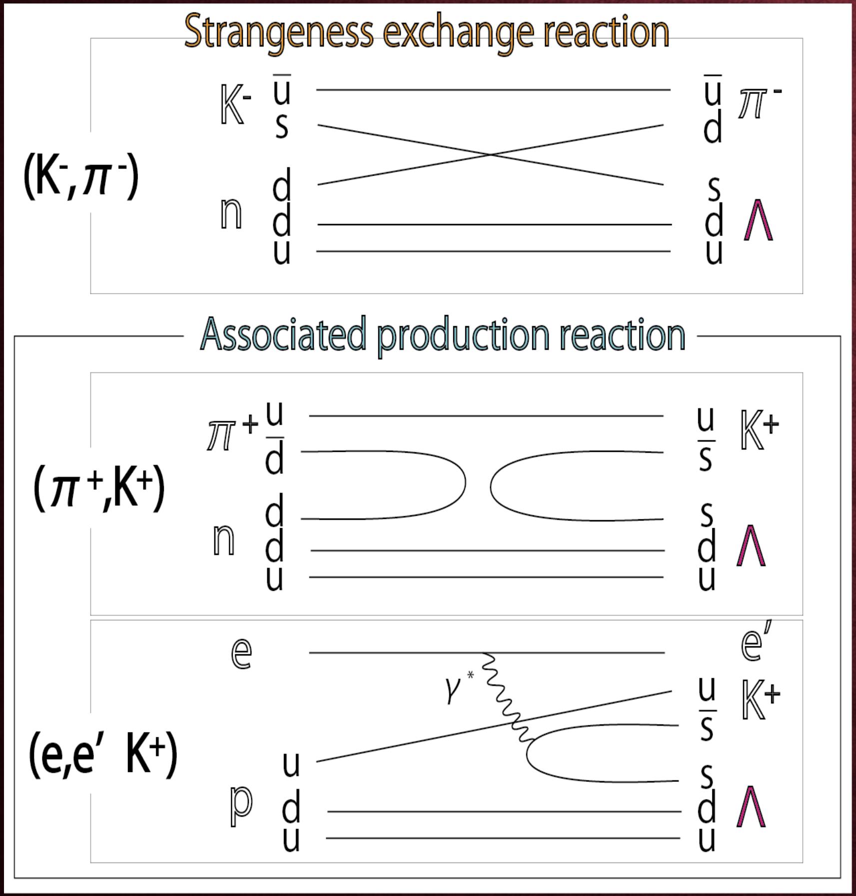
ADVANTAGE OF ELECTRON BEAM SPECTROSCOPY

Experimental technique with (e,e'K$^+$):
T. Gogami et al., NIMA 900, 69—83 (2018)



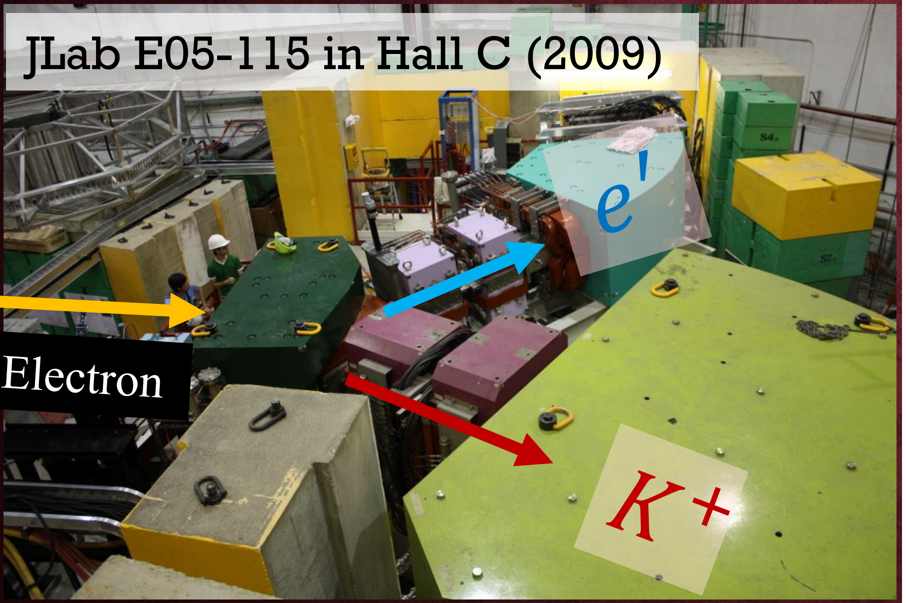
e beam vs. hadron beam

1. Better control of e beams
   ➔ **Better resolution**

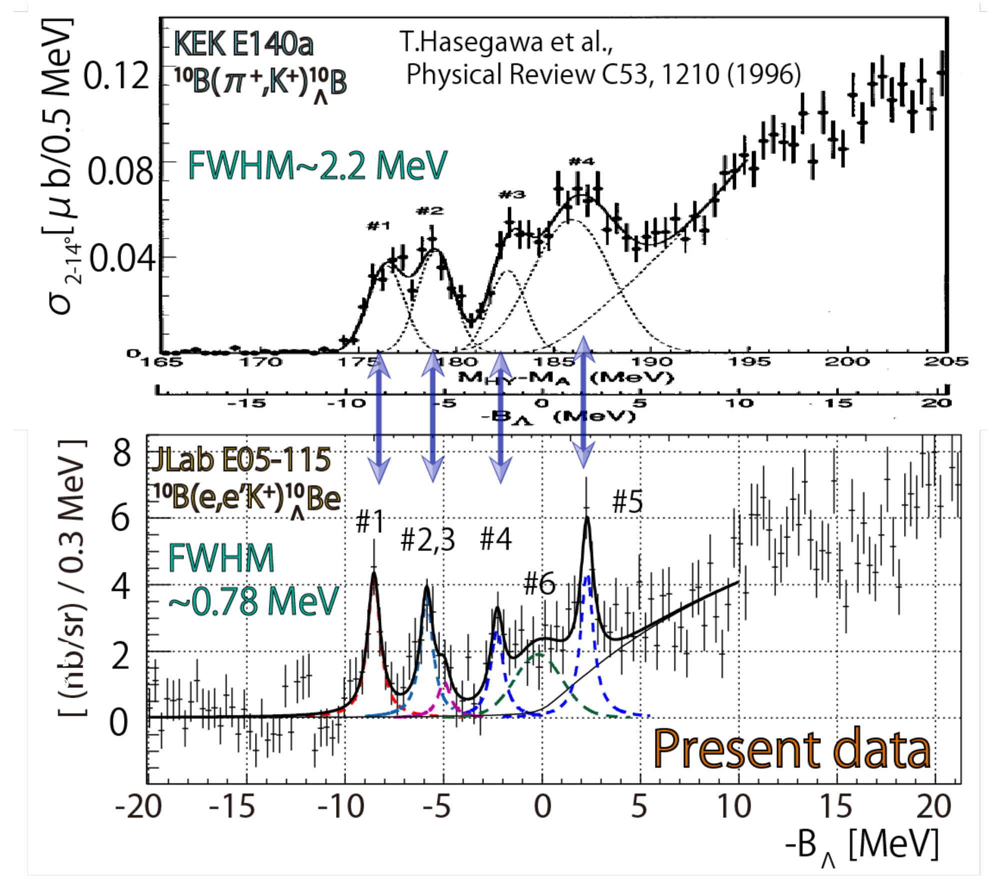
2. Proton target
   ➔ **Absolute calibration (Better accuracy)**

BETTER PRECISION AND ACCURACY

$^{10}B(\pi^+, K^+)^{10}_{\Lambda}B$ @KEK



RPC *93* (2016) 034314



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

THE PROPOSED MEASUREMENT (P12-19-002)

<u>High precision + accuracy measurement at JLab Hall A</u>

- ${}^{3}\mathrm{He}(e, e'K^{+}){}^{3}_{\Lambda}\mathrm{H}$ ➔ Hypertriton puzzle (10 days)
- ${}^{4}\mathrm{He}(e, e'K^{+}){}^{4}_{\Lambda}\mathrm{H}$ ➔ ΛN CSB (1 day)

The same experimental setup as E12-15-008 (${}^{40,48}_{\Lambda}\mathrm{K}$)
➔ Saving a lot of time for spectrometer installation (~0.5 years)

CHARGE SYMMETRY BREAKING (CSB)

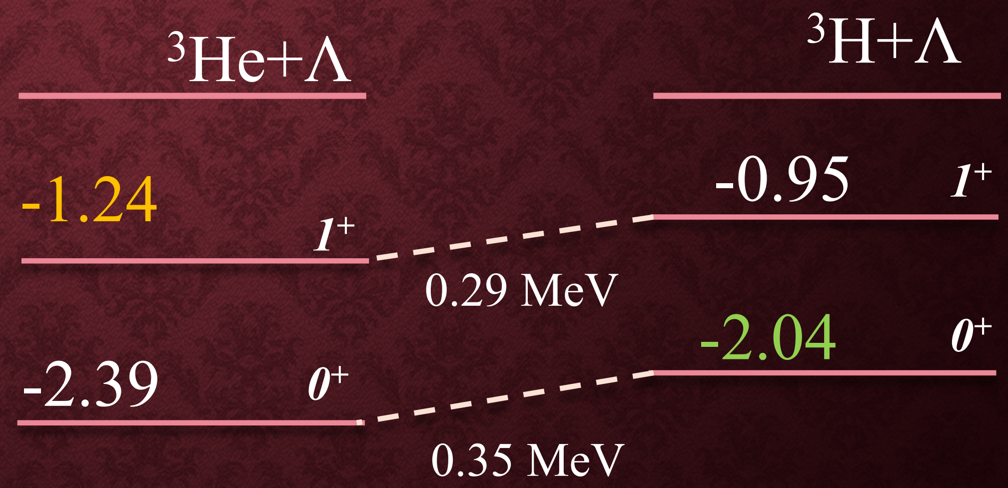
Before 2015

$$\Delta B = 0.76384\ (26)^{*1)}\ \text{MeV}$$
$$\Delta B_{\text{Coulomb}} = 0.683^{*2)}\ \text{MeV}$$

⇨ ***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).



⇨ ***≈0.4 MeV w/ correction***

Five times larger effect!!

CHARGE SYMMETRY BREAKING (CSB)

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

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

$$\begin{cases} \Delta B = 0.76384\ (26)^{*1)}\ \text{MeV} \\ \Delta B_{\text{Coulomb}} = 0.683^{*2)}\ \text{MeV} \end{cases}$$

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*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).

⇨ ***≈0.4 MeV w/ correction***

- ☐ Five times larger effect
- ☐ Spin dependent

CHARGE SYMMETRY BREAKING (CSB)

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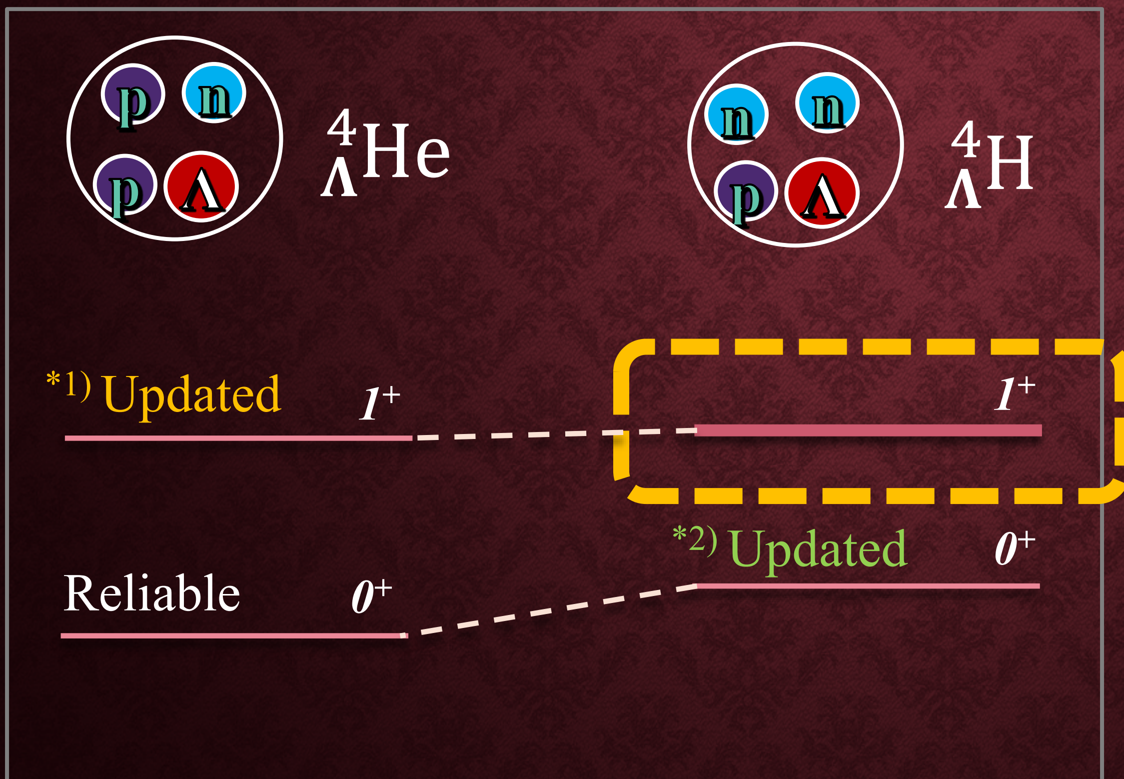


This experiment

$\Delta B_{\Lambda}^{\mathrm{total}} < \pm 0.1$ MeV

(1 day @ 50 μA)

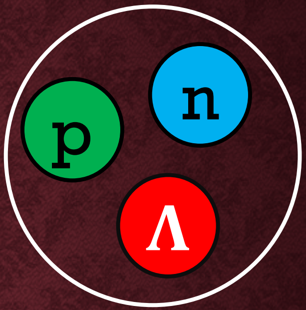
↕

Emulsion or MAMI + J-PARC E63 (γ-ray)

$\Delta B_{\Lambda}^{\mathrm{MAMI}} \simeq \pm 0.1$ MeV

$\Delta B_{\Lambda}^{\gamma-\mathrm{ray}} \simeq \pm 0.02$ MeV

Λ HYPERTRITON



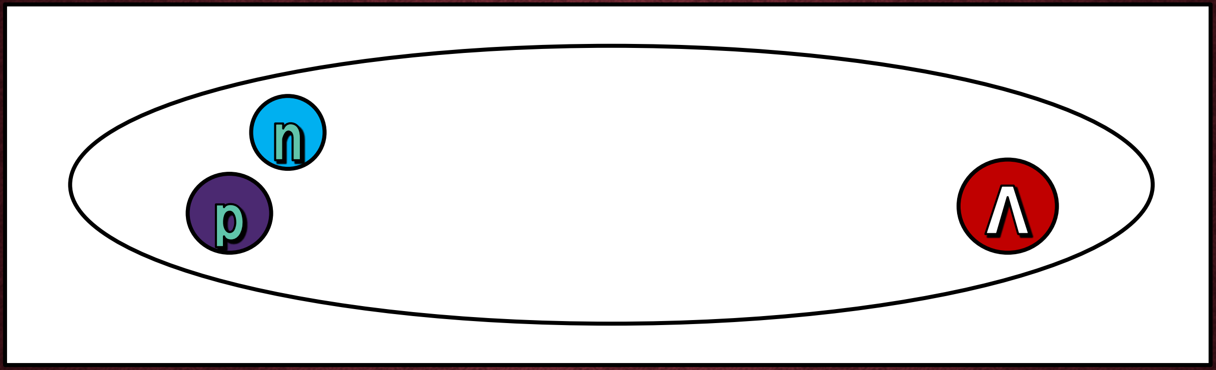
Basic observable for the ΛN interaction study

- No two body bound system with Λ
- The lightest hypernucleus
- Scarce data of scattering experiment

Puzzle

- The small binding energy vs. the short lifetime

LOOSELY BOUND SYSTEM OF ${}^{3}_{\Lambda}\mathrm{H}$



$$\sqrt{< r^2 >} \cong \frac{\hbar}{\sqrt{4\mu B_\Lambda}}$$

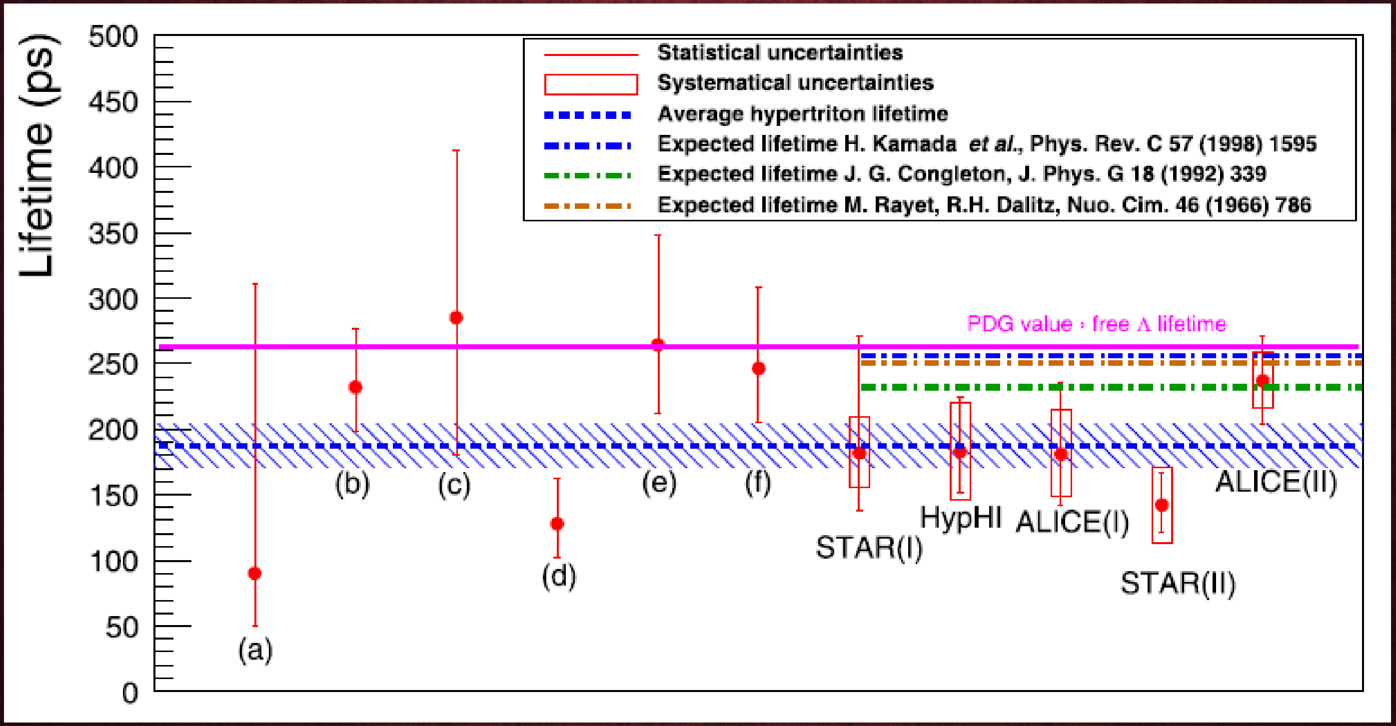
$$\cong 10\ \mathrm{fm} \qquad (\text{where, } B_\Lambda = 130\ \mathrm{keV})$$

Λ is almost free from the interaction with nucleons

➔ Hypertriton lifetime is expected to be similar to Λ

LIFETIME PUZZLE OF Λ HYPERTRITON

Lifetime of Λ hypertriton:
A. Gal and H. Garcilazo,
Phys. Lett. B 791, 48—53 (2019).

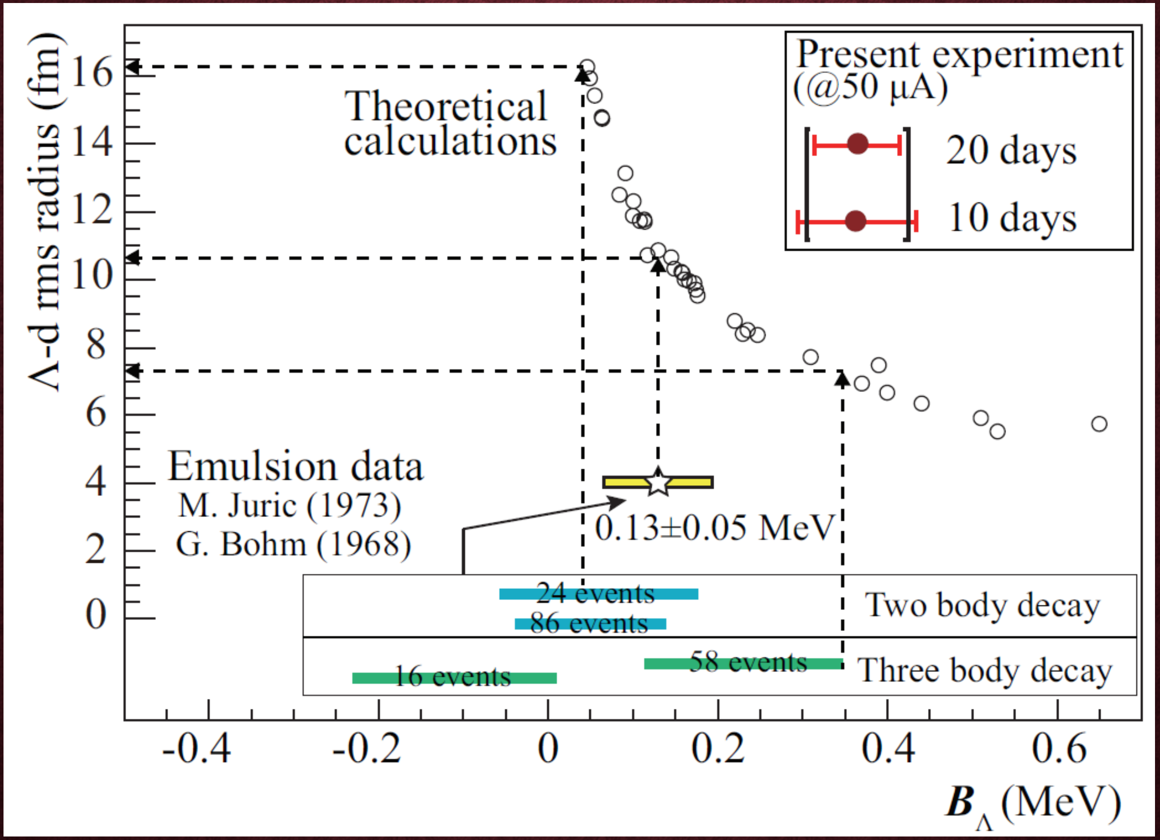


→ Why is the lifetime much shorter than Λ?

- Is the B_Λ measurement wrong?
- π^+ final state interaction with nucleus

Λ HYPERTRITON $^{3}_{\Lambda}H$

Spatial extent of Λ hypertriton:
A. Cobis et al., Phys. G: Nucl. Part. Phys. 23, 401—421 (1997).



B_Λ scattered depending on decay channels
→ **Precise measurement of B_Λ are awaited**

Λ HYPERTRITON ${}^{3}_{\Lambda}H$

Spatial extent of Λ hypertriton:
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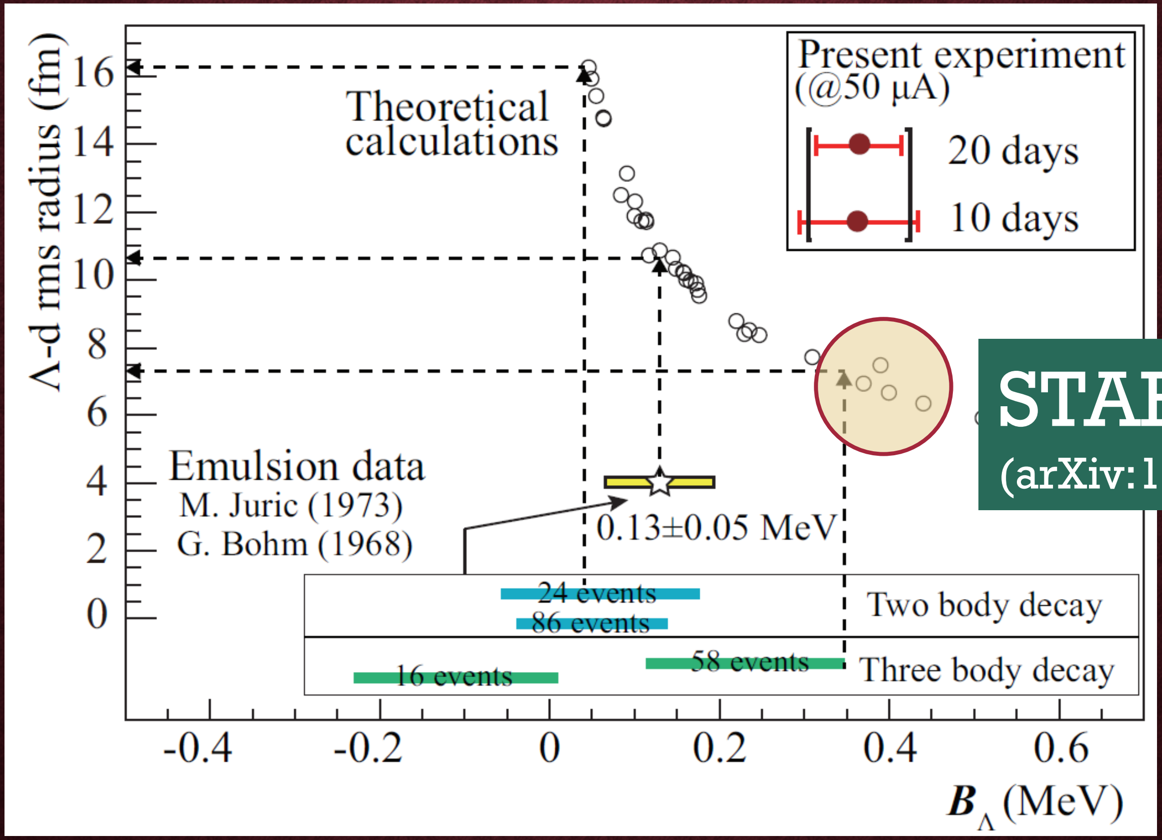


STAR @RHIC
(arXiv:1904.10520v1)

B_Λ scattered depending on decay channels

→ **Precise measurement of B_Λ are awaited**

EFFORTS TO SOLVE THE Λ HYPERTRITON PUZZLE

Lifetime measurement

- J-PARC (Two proposals were submitted recently)
- ELPH (the experiment is being prepared)
- Heavy ion (higher statistics will be available in the future)

Binding energy measurement

- Heavy ion beam experiments (g.s.)
- MAMI (g.s.)
- **THIS PROPOSAL (g.s. and/or $3/2^+$ states)**

Theory

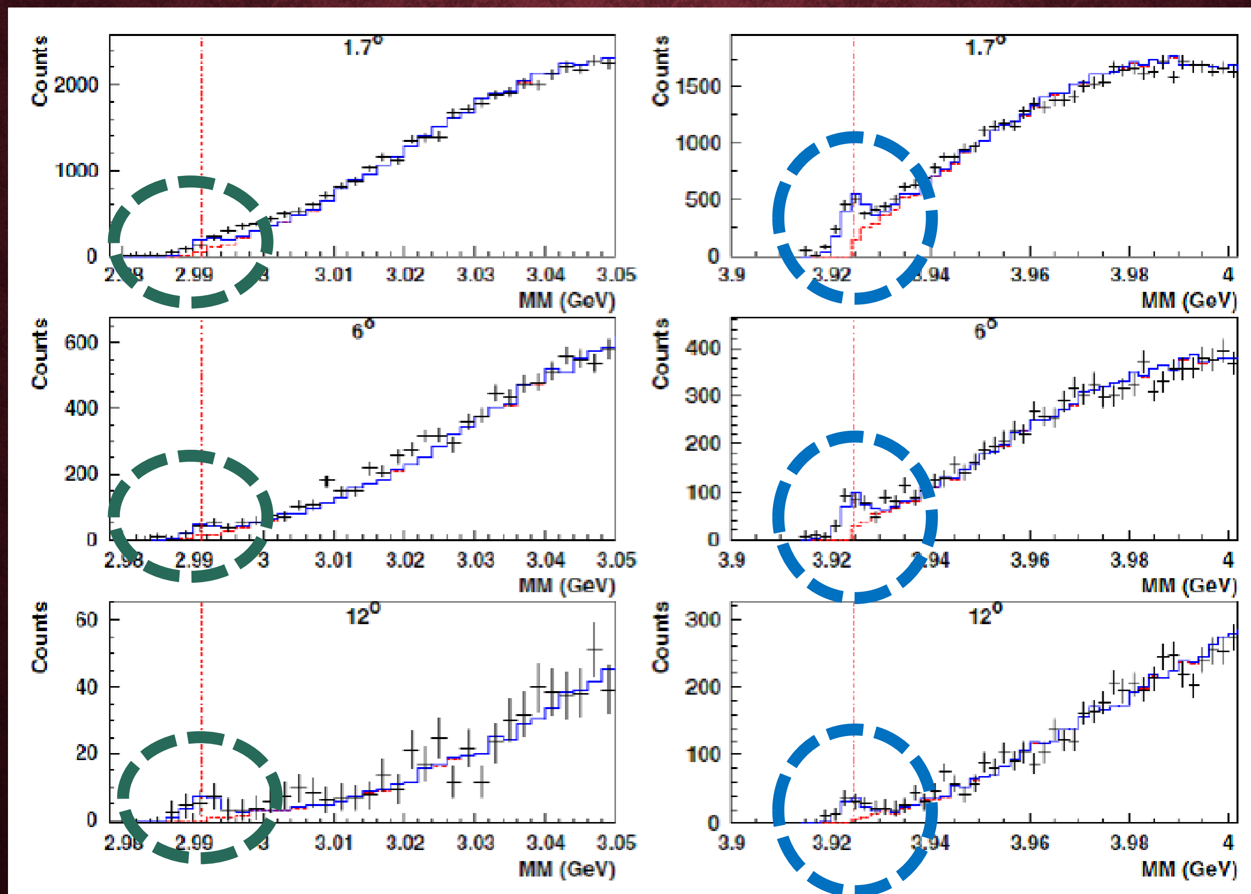
- π^+ final state interaction + realistic interaction model

PREVIOUS EXPERIMENT

F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).

(e,e'K$^+$) experiment at Hall C

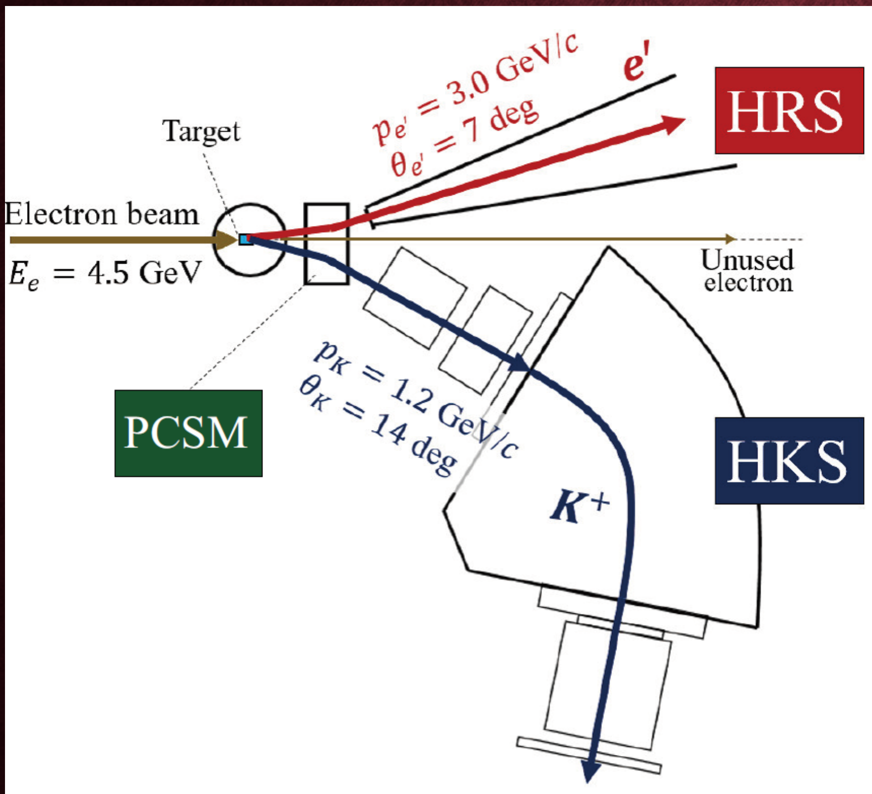
$^{3}_{\Lambda}$H



$^{4}_{\Lambda}$H

EXPERIMENTAL SETUP

Setup of E12-15-008 (approved)



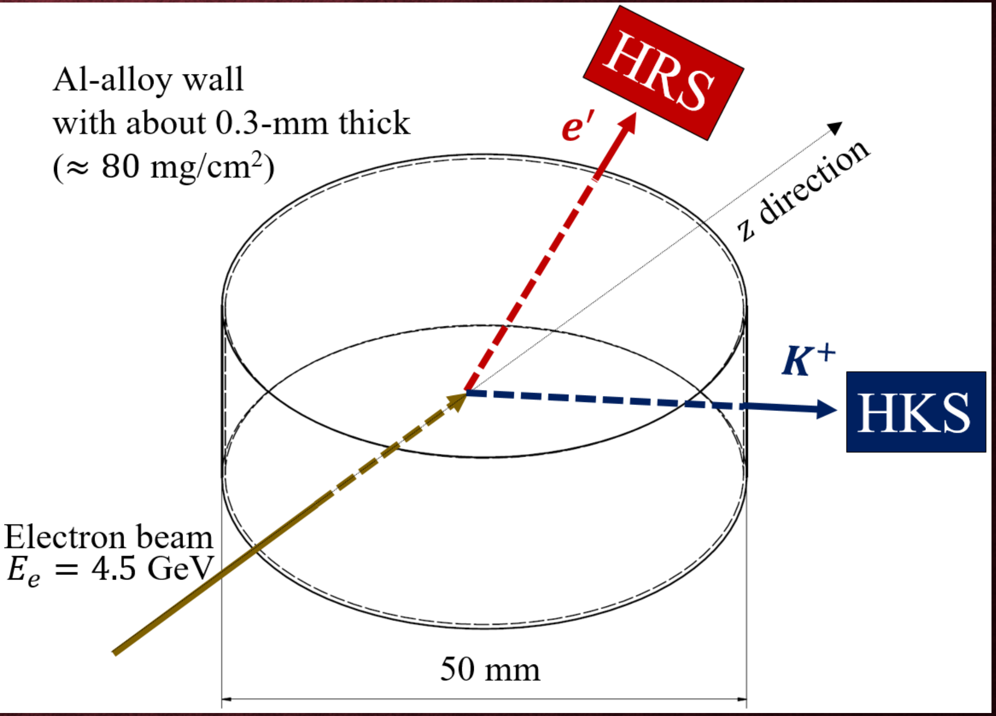
Beam	$\Delta p/p$	$< 1 \times 10^{-4}$ FWHM
	E_e	4.5 GeV
PCSM + HRS (e')	D(PCSM) + QQDQ	
	$\Delta p/p$	$\simeq 2 \times 10^{-4}$ FWHM
	$p_{e'}$	3.0 GeV/$c \pm 4.5\%$
	$\theta_{ee'}$	7.0 ± 1.5 deg
	Solid angle $\Omega_{e'}$	5 msr
PCSM + HKS (K^+)	D(PCSM) + QQD	
	$\Delta p/p$	$\simeq 2 \times 10^{-4}$ FWHM
	p_K	1.2 GeV/$c \pm 10\%$
	θ_{eK}	14.0 ± 4.5 deg
	Solid angle Ω_K	3 msr
	Optical length	12 m
	K^+ survival ratio	26%

The experimental setup will be shared with E12-15-008

➔ Saving installation time

TARGET

Assumed spec of cryogenic targets:
J. Alcorn et al., NIMA 522 (2004) 294—346

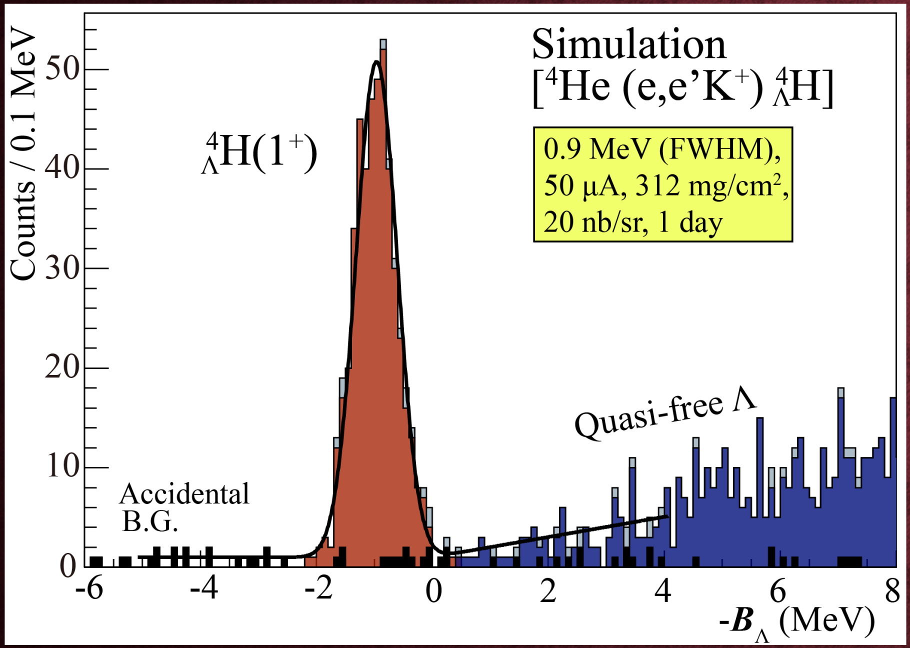


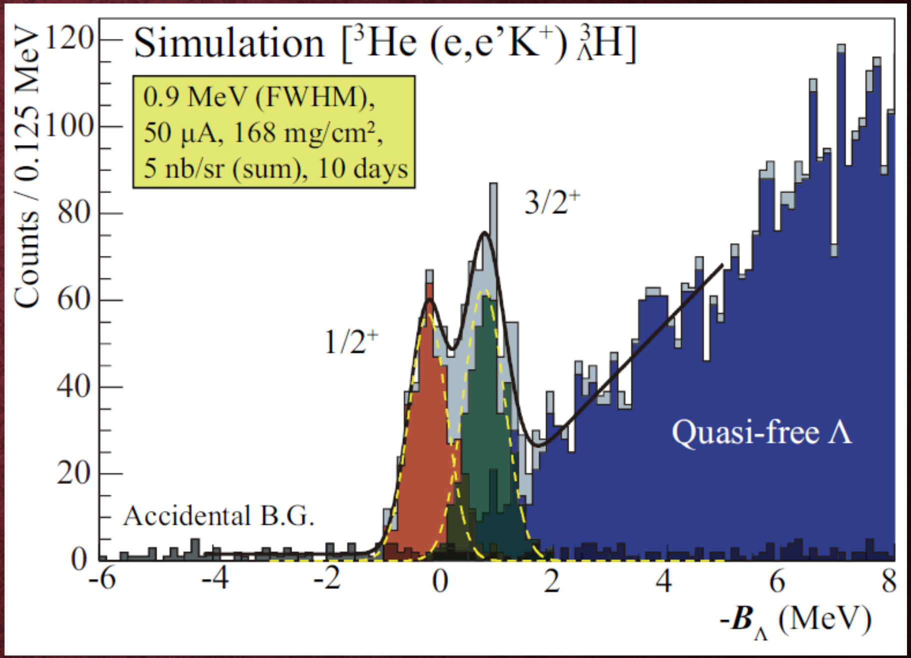
Proposed measurements

- ☐ Cryogenic targets
  - ✓ LH_2
  - ✓ ^{3}He and ^{4}He (gas)
- ☐ Multi foil target

Solid targets and cryogenic targets can be on the same ladder

EXPECTED SPECTRA



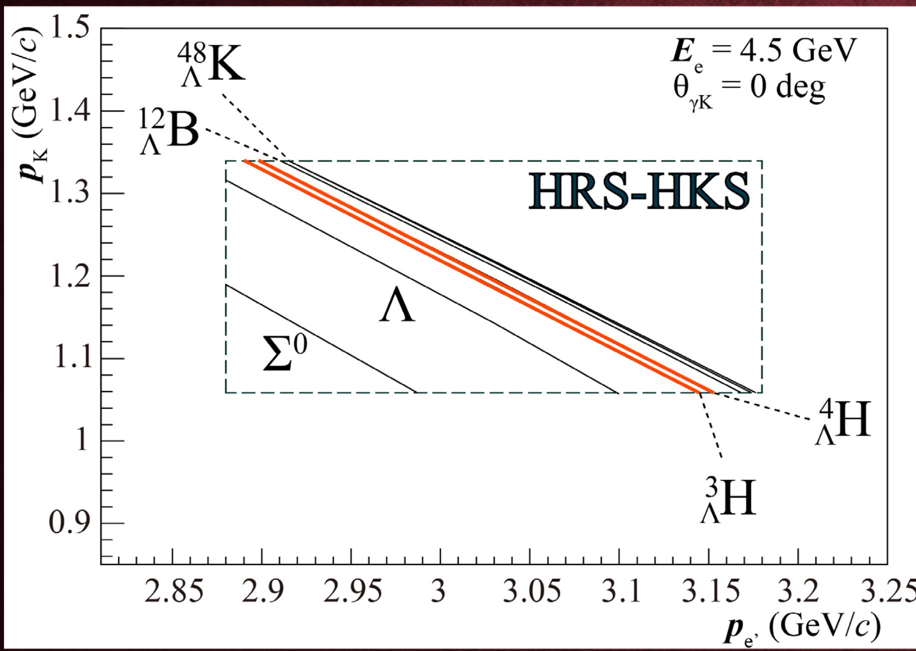


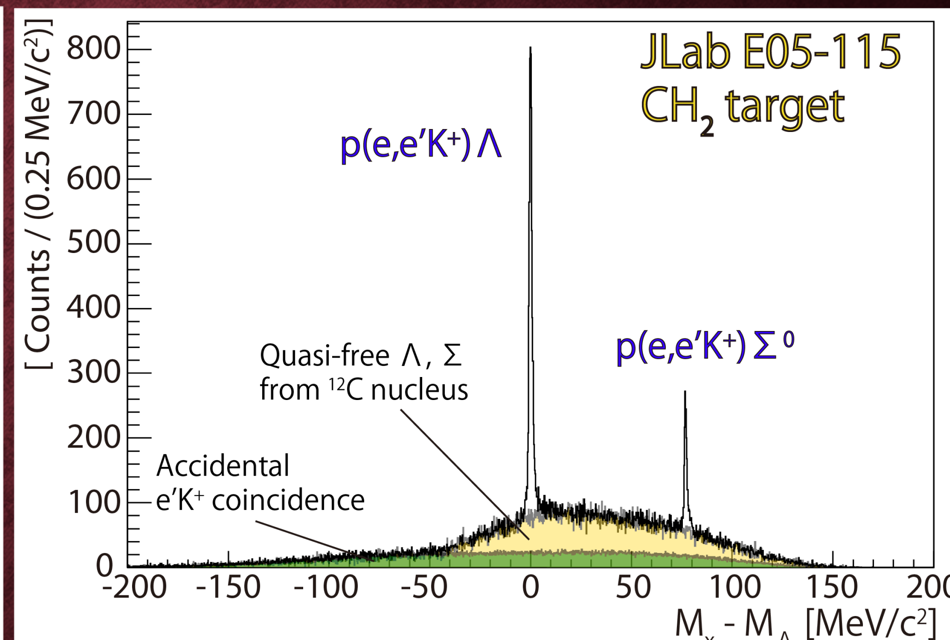
$\Delta B_\Lambda^{\mathrm{stat.}} = \pm 20\,\mathrm{keV}$ $\Delta B_\Lambda^{\mathrm{stat.}} = \pm 70\,\mathrm{keV}$

- Cross section of signals: simulated based on E91-016 results
- Distribution of quasi free Λ: E91-016
- Accidental background: E05-115
- Resolution: MC simulation assuming spectrometers' specifications

ENERGY CALIBRATION

NIMA 900 (2018) 69—83





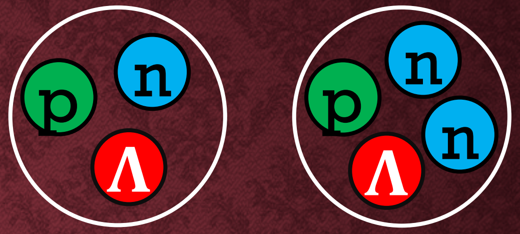
Λ and Σ^0 from LH2 target will be used for the absolute energy calibration → Systematic error < 100 keV

REQUESTED BEAMTIME

Mode	Hypernucleus	Target (mg/cm^2)	Beam current (μA)	Beam time (day)	Yield
Physics	${}^{3}_{\Lambda}H$	${}^{3}He$ (168)	50	10	840 ($1/2^+$, $3/2^+$)
	${}^{4}_{\Lambda}H$	${}^{4}He$ (312)	50	1	470 (1^+)
	Subtotal			**11**	-
Calibration	Λ Σ^0	LH_2 (174)	20	0.5	Λ: 3000 Σ^0: 1000
	-	Multi foil	20	0.1	-
	-	Multi foil + Sieve slit	20	0.2	-
	-	Empty cell	20	0.2	-
	Subtotal			1	-
Total				**12**	-

Commissioning time can be shared with E12-15-008 (~0.5 year)

SUMMARY (P12-19-002)



Precise B_Λ measurements that are unique at JLab

- $^{3}\mathrm{He}(e,e'K^{+})^{3}_{\Lambda}\mathrm{H}$ (1/2+, 3/2+) → **Hypertriton puzzle** (10 days)
- $^{4}\mathrm{He}(e,e'K^{+})^{4}_{\Lambda}\mathrm{H}$ (1+) → **ΛN CSB** (1 day)

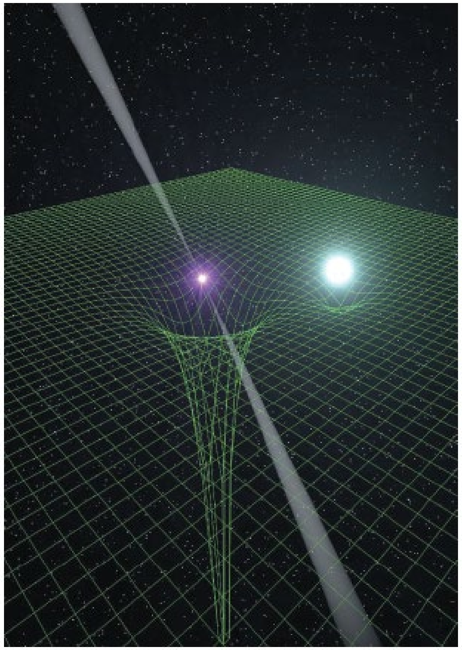
We request additional 12 days to E12-15-008

- Installation time (~0.5 year) can be shared

BACKUP

HYPERON PUZZLE IN NEUTRON STARS

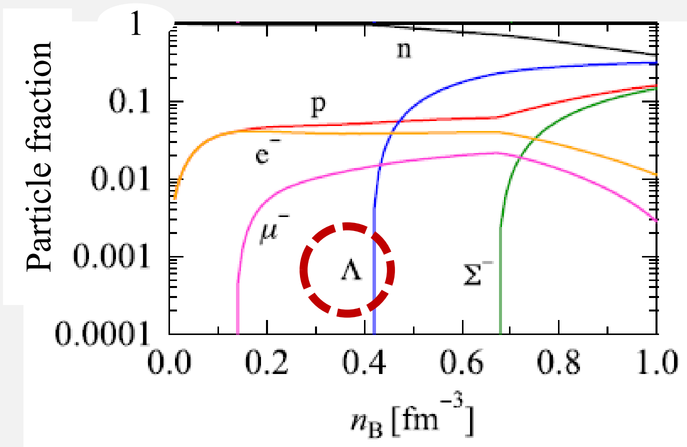
Neutron star (NS):
- ✓ Very dense nuclear matter
- ✓ $\leq 2M_{\odot}$

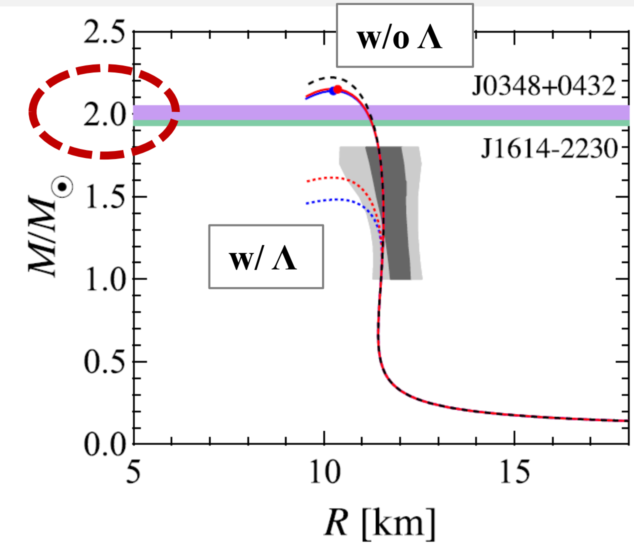


Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic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





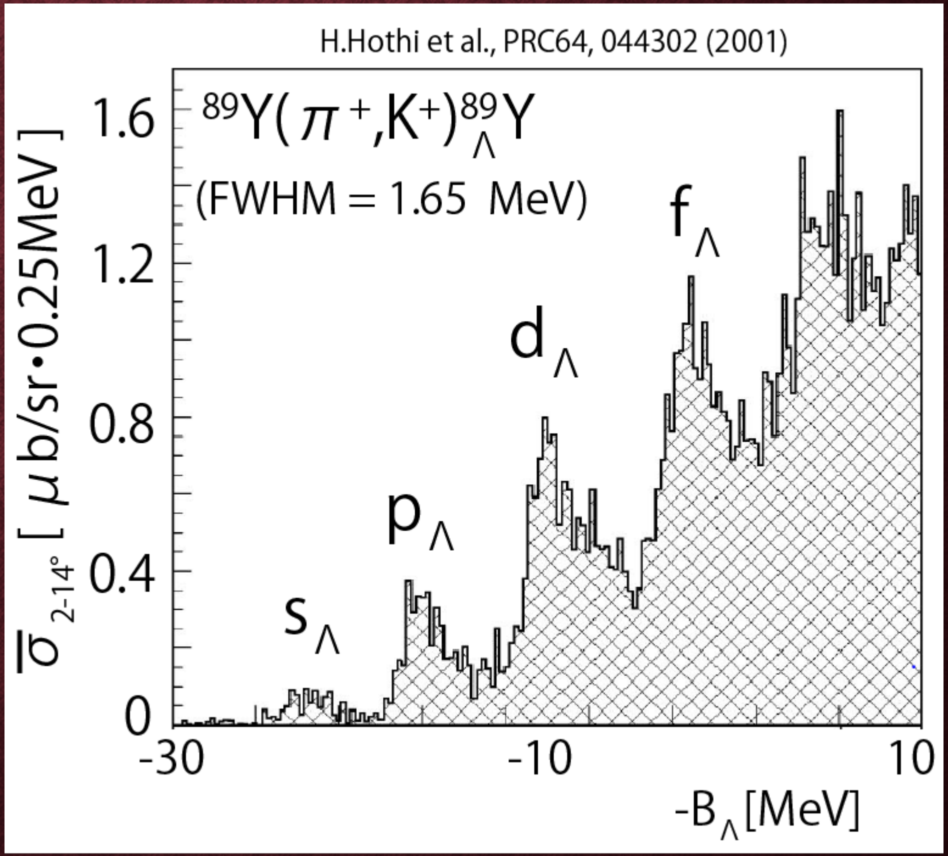
Λ generation in NS ⟷ *CONFLICT!!* ⟷ $2M_{\odot}$ NS

Need improvement our understanding of the ΛN and ΛNN interaction

INNOVATIVE RESULTS TO SEE SHELL STRUCTURE DEEP INSIDE OF NUCLEUS

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

$V^0_{\Lambda} = 30$ MeV

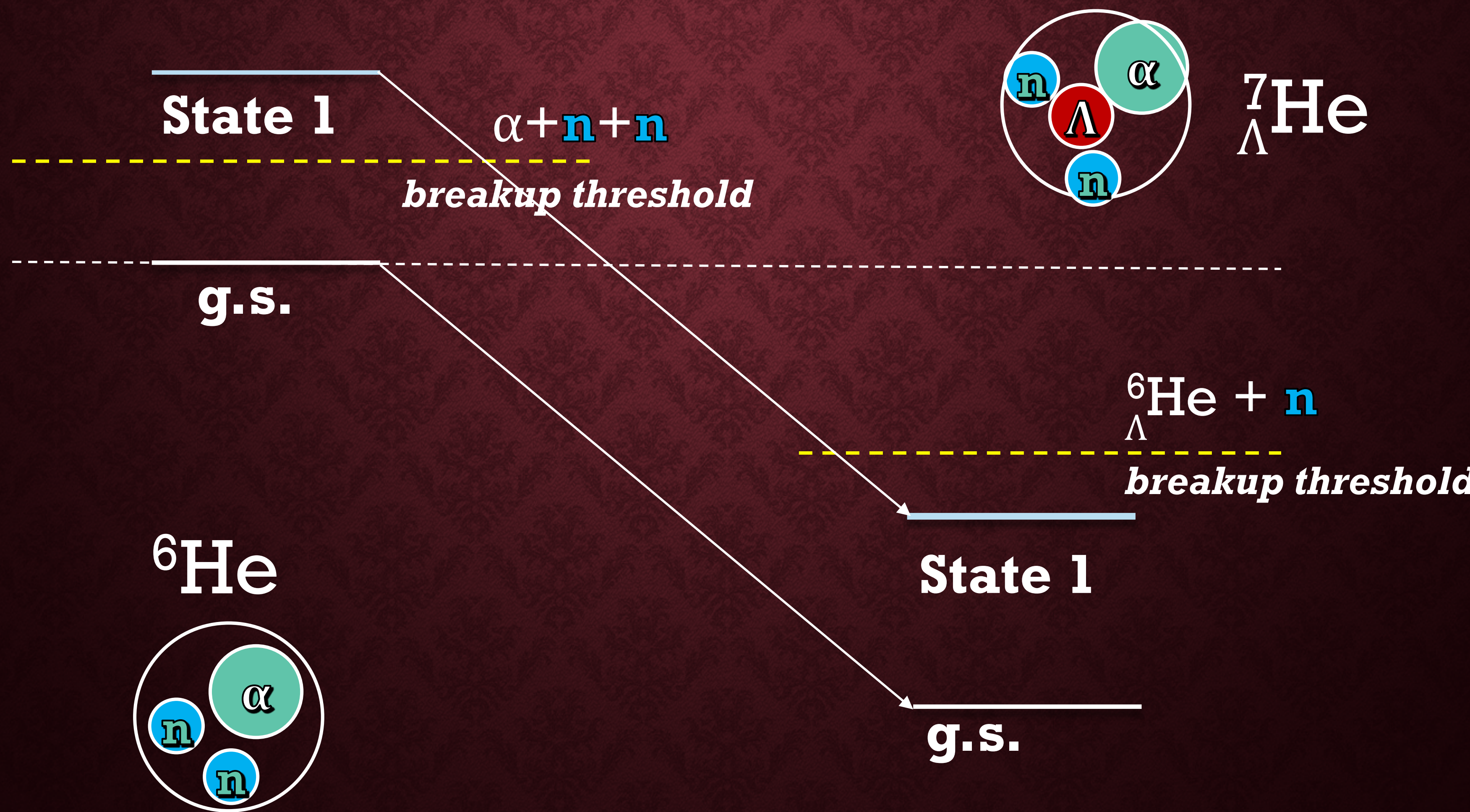


Λ binding energy $\quad B_\Lambda\left({}^{A}_{\Lambda}Z\right) = M\left({}^{A-1}Z\right) + M(\Lambda) - M\left({}^{A}_{\Lambda}Z\right)$

GLUE-LIKE ROLE OF Λ

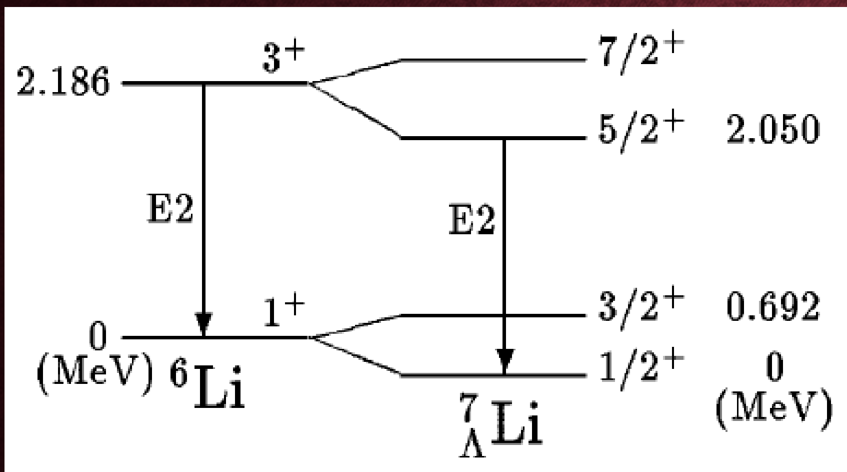
Shrinkage of a nucleus ($^{7}_{\Lambda}$Li) :
K. Tanida et al., PRL 86, 1982 (2001).

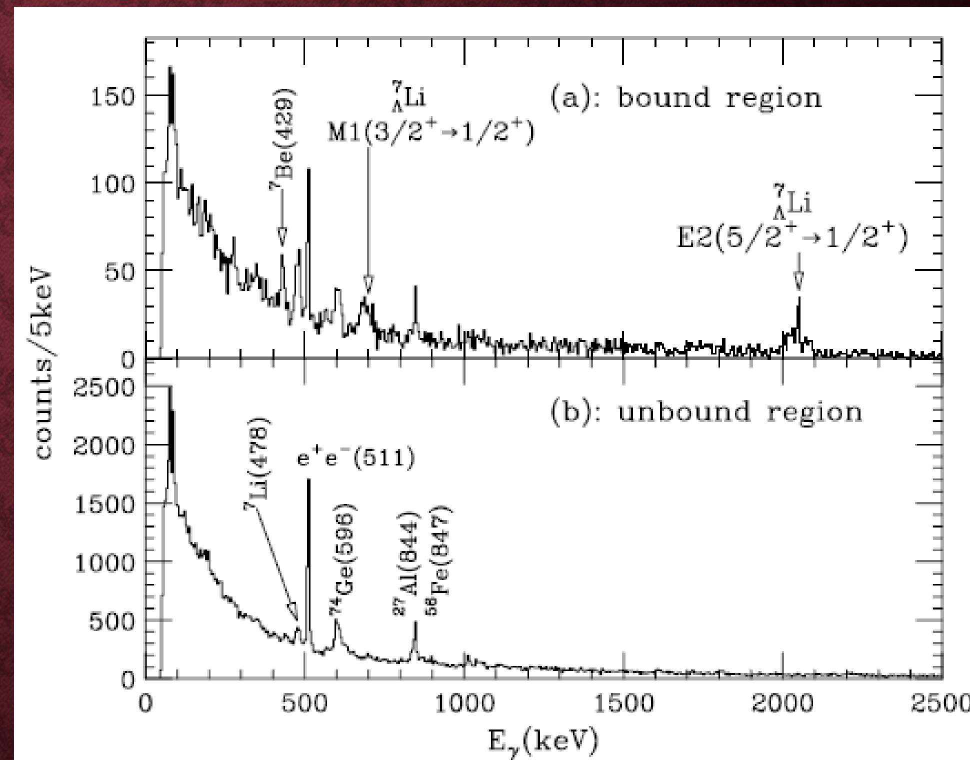
Stabilizing an unstable state ($^{7}_{\Lambda}$He):
T. Gogami et al., PRC 94, 02132(R) (2016).



ラムダの糊効果

$^{7}_{\Lambda}$Li の収縮:
K. Tanida et al., PRL 86, 1982 (2001).

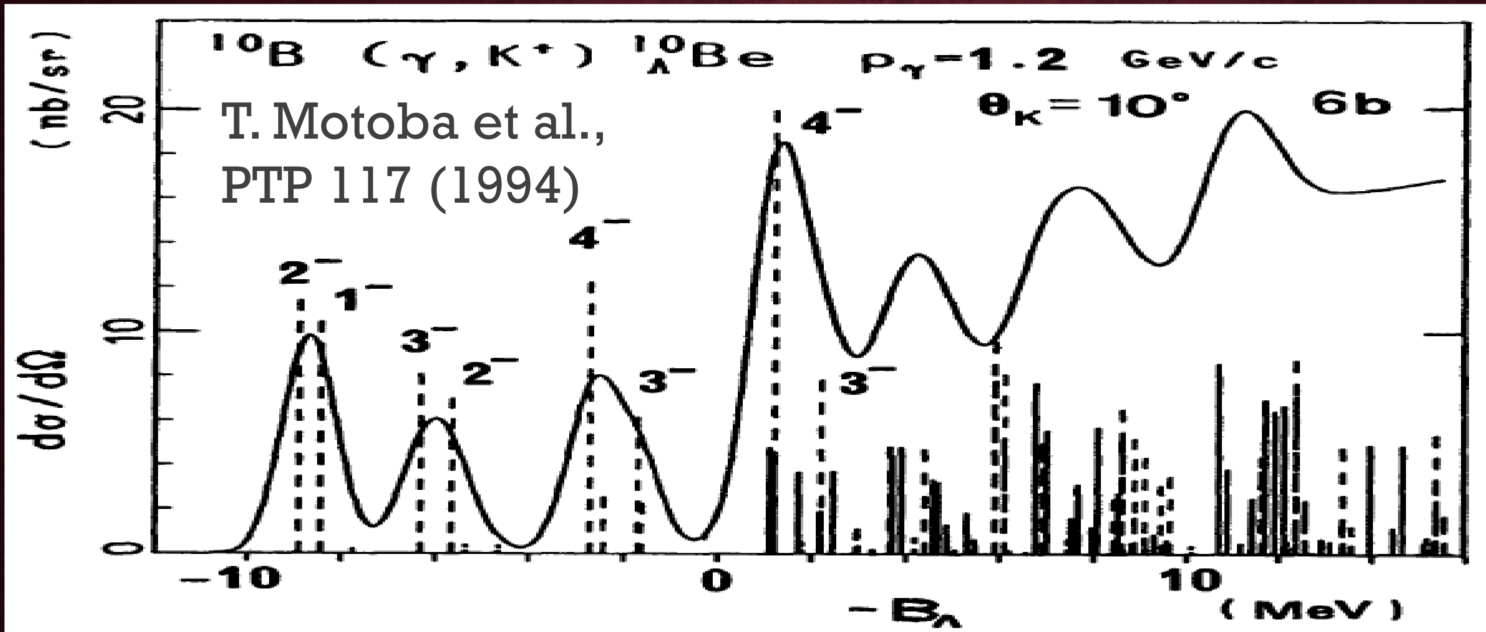


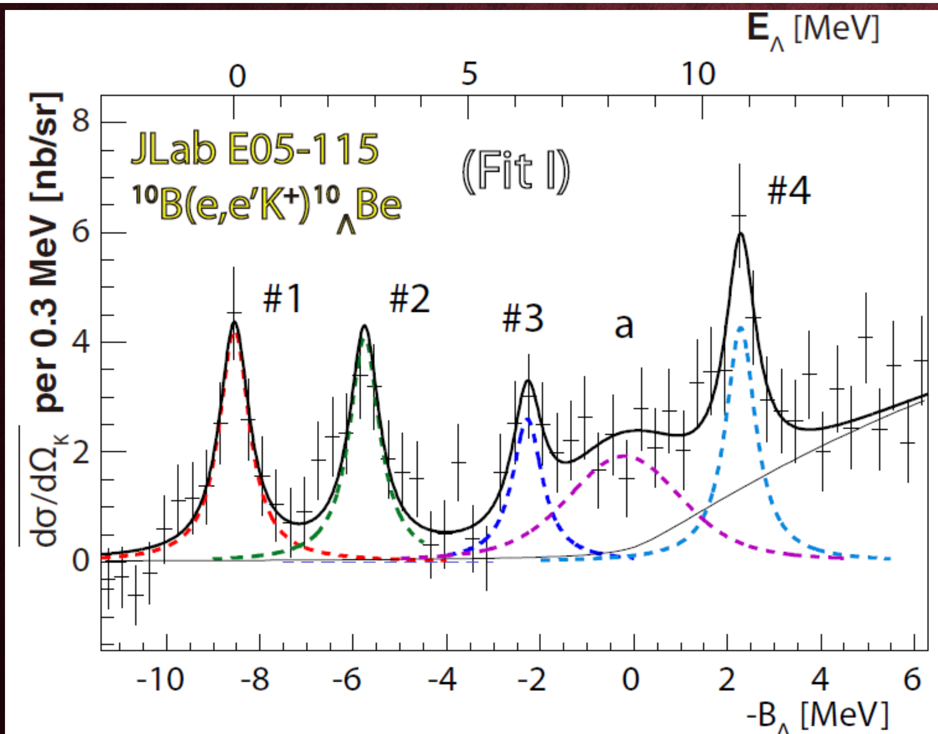


$$S = \left[\frac{9}{7} \frac{B(E2;^{7}_{\Lambda}\mathrm{Li}5/2^{+} \rightarrow 1/2^{+})}{B(E2;^{6}\mathrm{Li}3^{+} \rightarrow 1^{+})} \right]^{1/4}$$

$$S = 0.81 \pm 0.04$$

$^{5}_{\Lambda}$He-d rms radius is shorter than α-d by 19%





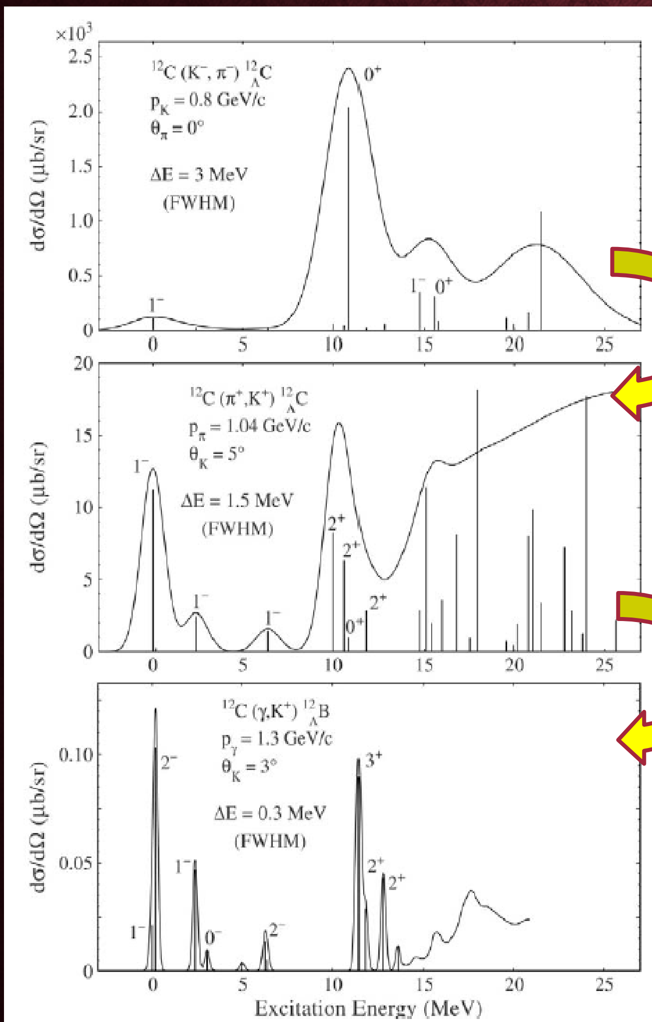
Exceeded events (a) ?

It was not predicted with a conventional shell model

T. Gogami et al.,
Phys. Rev. C 93 (2016) 034314.

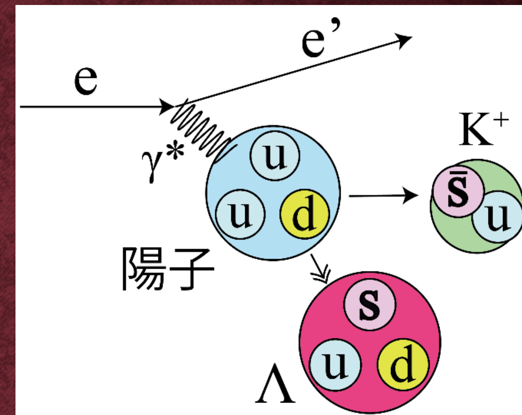
EXPERIMENTAL DIFFICULTY TO OVERCOME

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



$\times 10^{-2}$

$\times 10^{-2}$



- Small Cross section
- Small VP flux ($\Gamma\sim10^{-5}$)
- EM backgrounds (Moller, Bremsstrahlung)
- High precision spectroscopy

  → $\Delta p/p\sim10^{-4}$ for both e' and K$^+$

Unique technique
(It can be done only at JLab)

THE CSB IN P-SHELL Λ HYPERNUCLEI

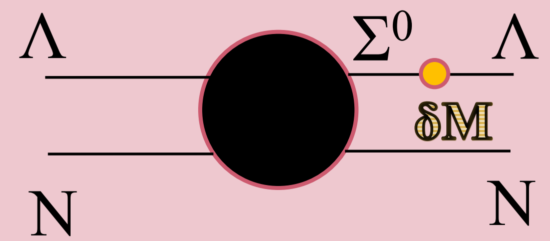
Phenomenological CSB:
E. Hiyama *et al.*, *Phys. Rev. C* **80**, 054321 (2009).

ΛN-ΣN coupling:
A. Gal, Phys. Lett. B 744, 352 (2015).

Phenomenological ΛN CSB interaction

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

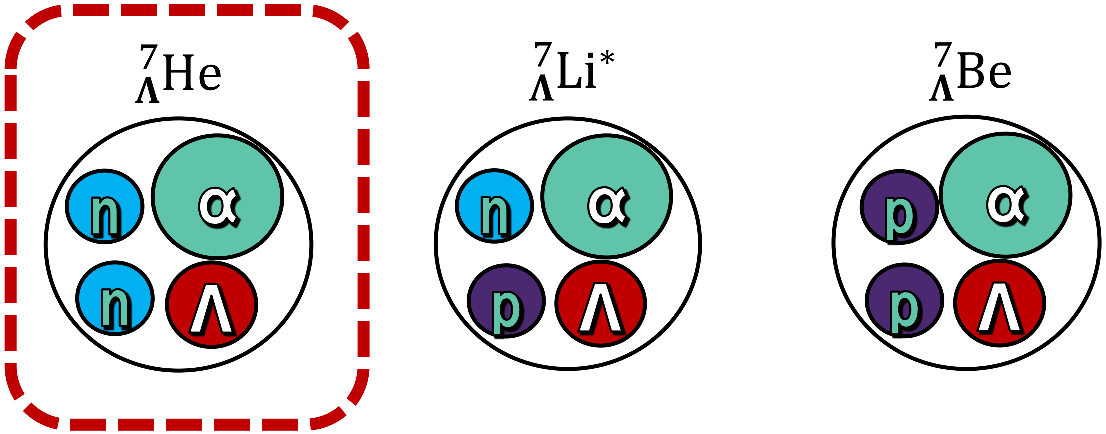
Explicit inclusion of the ΛN-ΣN coupling



- ✓ Little effect on p-shell Λ hypernuclear system
- ✓ Large CSB in the A = 12 system ($^{12}_{\Lambda}$B and $^{12}_{\Lambda}$C) ??

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

emulsion + γ-ray   emulsion

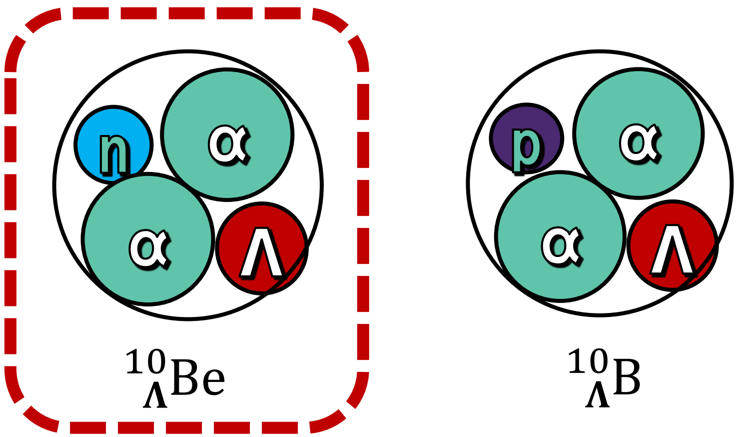


$A = 7, T = 1$

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

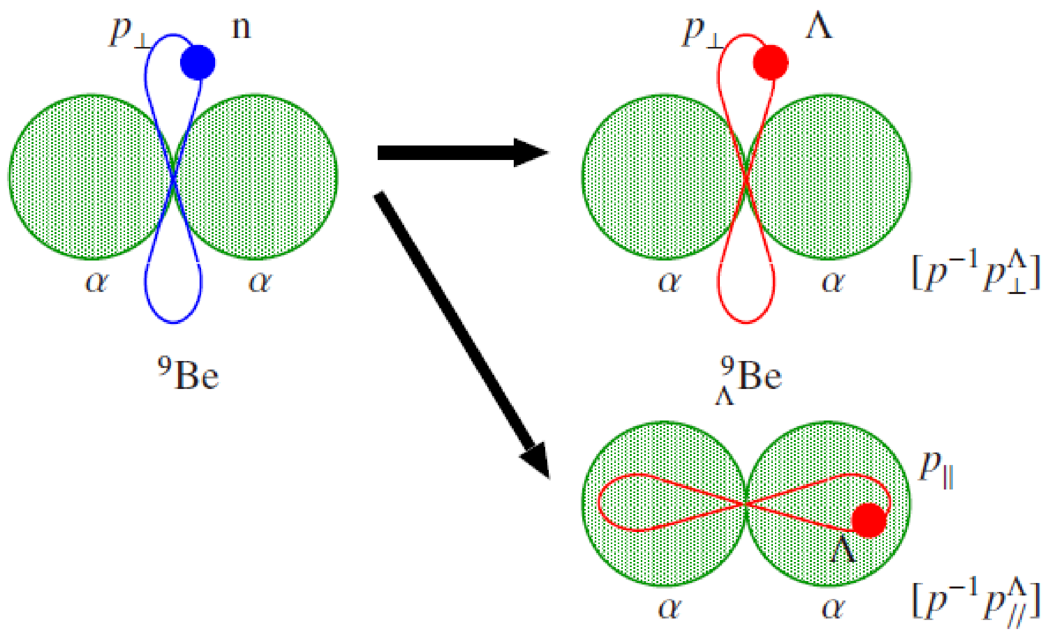


emulsion (3 events)

emulsion (10 events)

$A = 10, T = 1/2$

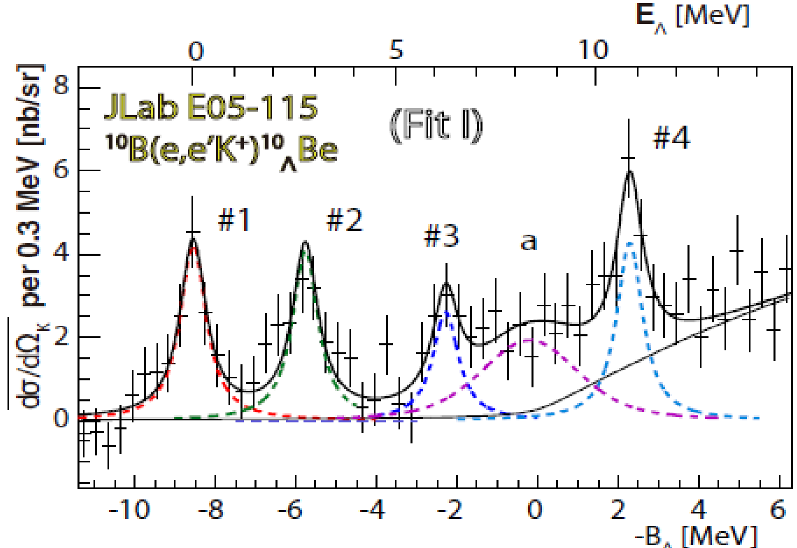
$[p^{-1}p_{\perp}^{\Lambda}]$ and $[p^{-1}p_{//}^{\Lambda}]$ states of ${}^{9}_{\Lambda}$Be (1)



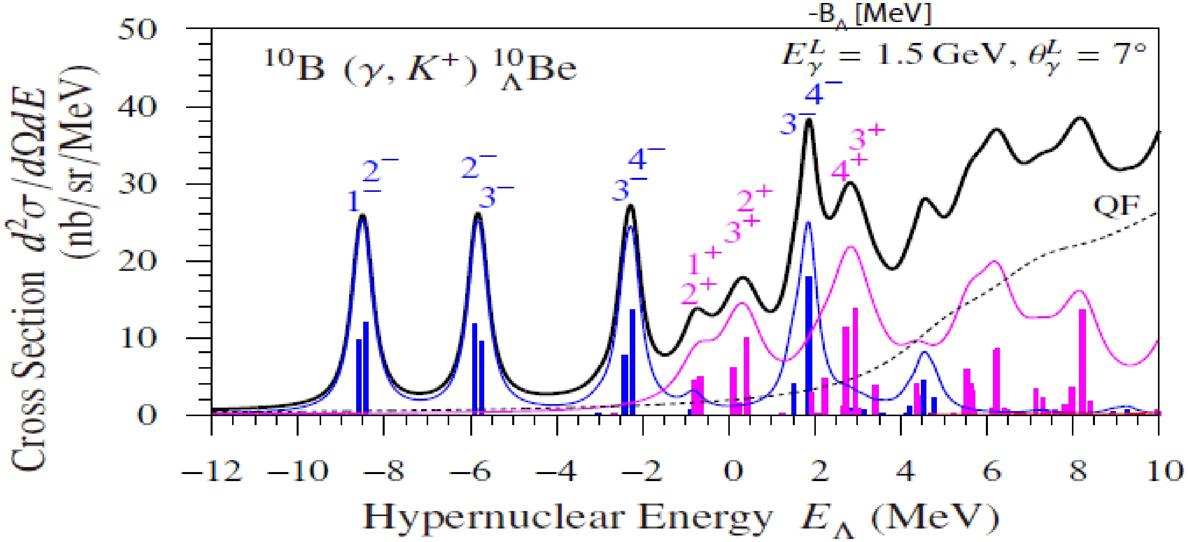
In ${}^{9}_{\Lambda}$Be, it is well known that the p_{Λ}-state splits into two orbital states expressed by $p_{\perp}$ and $p_{//}$, which is due to the strong coupling with nuclear core deformation having the α-α structure. **T. Motoba *et al.*, PTPS81, 42 (1985)**

The $p_{//}$ state tends to the configuration with an SU(3) classification $[f](\lambda\mu) = [54](50)$ called supersymmetric.
R. H. Dalitz, A. Gal, PRL36, 362 (1976); AP131, 314 (1981)

Results : Cross sections of the $^{10}\mathrm{B}\ (\gamma, K^{+})\ ^{10}_{\Lambda}\mathrm{Be}$ reaction (2)



T. Gogami *et al.*, PRC93, 034314 (2016)

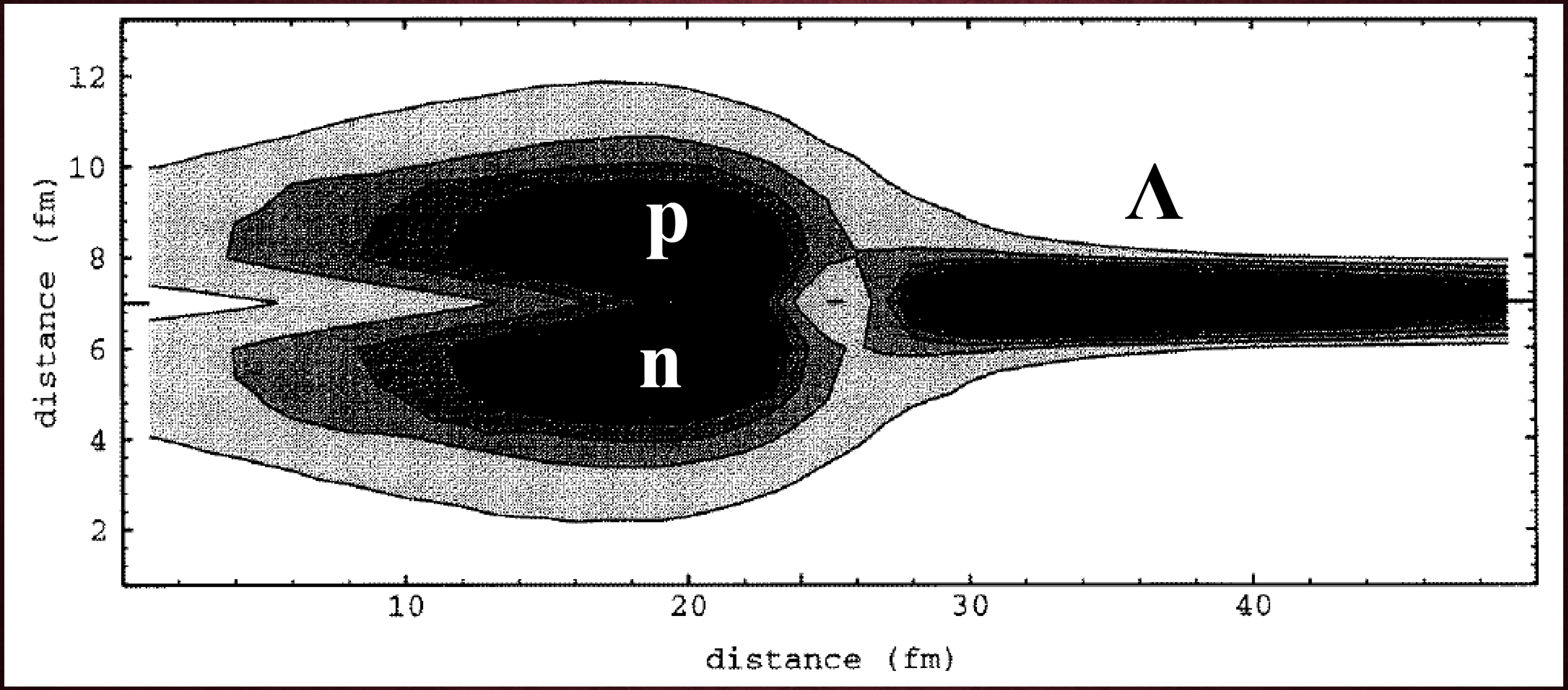


Our new calculation reproduces the four major peaks (#1, #2, #3, #4).

Our new calculation explains the new bump (a) as a sum of cross sections of some J^{+} states.

ハイパートライトン ラムダハロー

ハイパートライトンの空間的広がり:
A. Cobis et al., Phys. G: Nucl. Part. Phys. 23, 401—421 (1997).



$$\sqrt{< r^2 >} \cong \frac{\hbar}{\sqrt{4\mu B_\Lambda}}$$

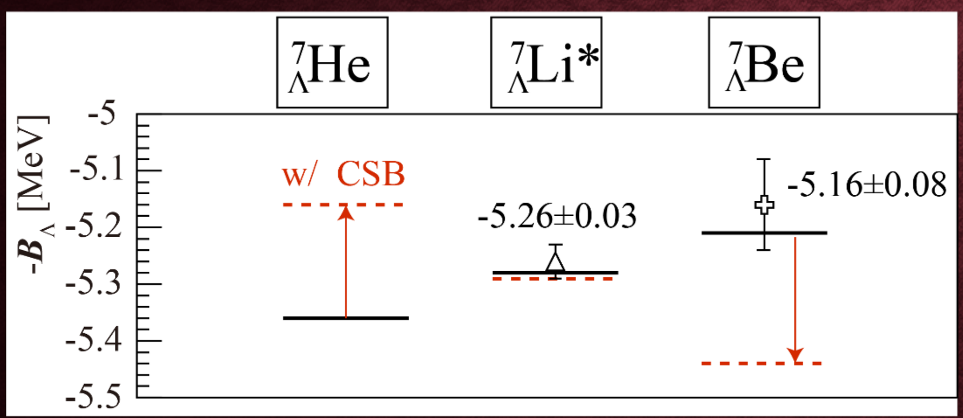
Root mean square radius ≈ 10 fm
(重陽子の5倍！)

THE P-SHELL HYPERNUCLEAR CSB

Phenomenological potential of the ΛN CSB interaction

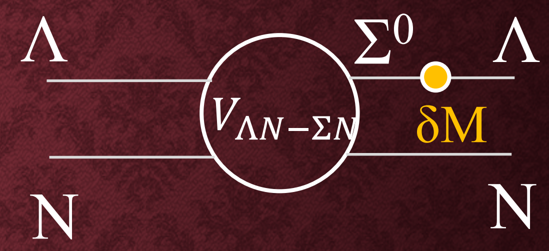
E. Hiyama *et al.*, *Phys. Rev. C* **80**, 054321 (2009).

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



$^7_\Lambda$He: S.N. Nakamura et al., PRL 110, 012502 (2013).

Explicit inclusion of the ΛN ↔ΣN coupling



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

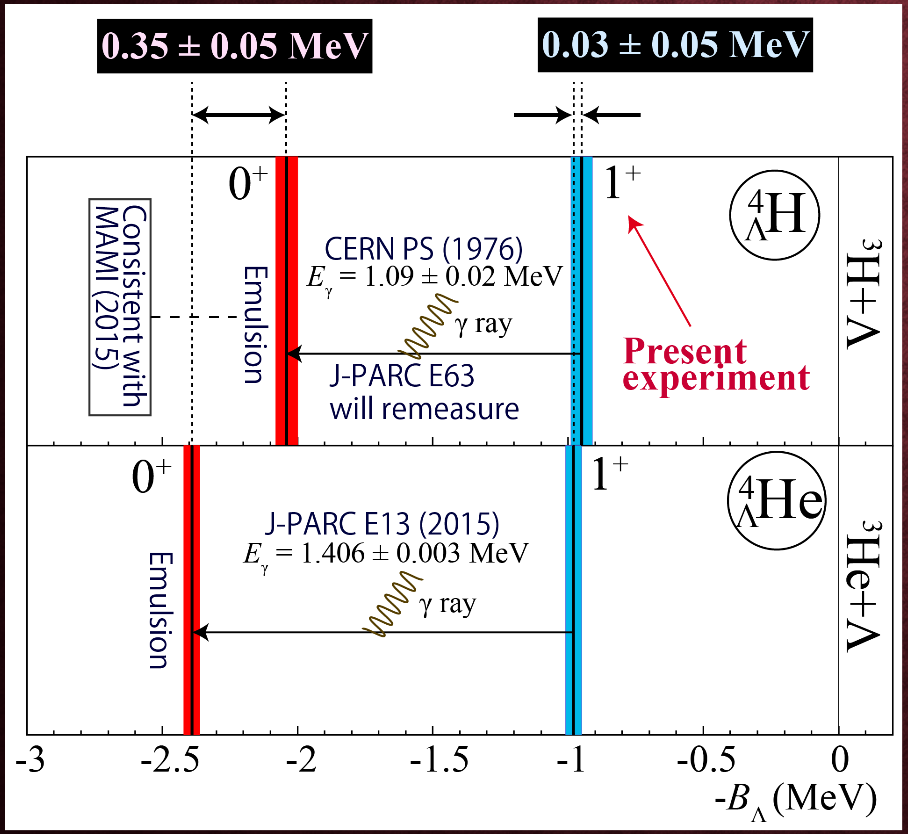
Isomultiplet	$\Delta B_\Lambda^{\rm exp}$ (MeV)	Prediction (MeV)
$^4_\Lambda$He − $^4_\Lambda$H (0^+)	270±60	+226
$^4_\Lambda$He − $^4_\Lambda$H (1^+)	30±50	+39
$^7_\Lambda$Li* − $^7_\Lambda$He	−420 ± 250	-
$^{10}_\Lambda$B − $^{10}_\Lambda$Be	−220 ± 250	-136
$^{12}_\Lambda$C − $^{12}_\Lambda$B	~~−790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

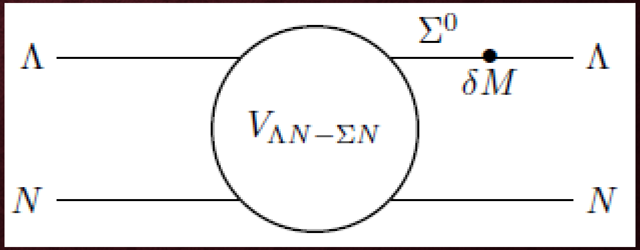
ラムダ-核子間の荷電対称性の破れ

ΛN CSB についての最近の理解:
A. Gal and D. Gazda, *J. Phys.: Conf. Ser.* **966** 012006 (2018).



ラムダ – 陽子
≠
ラムダ – 中性子

✓ 核子間は ほぼ 荷電対称 (CS)
✓ ラムダ-核子間は荷電対称性が破れている… (CSB)



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

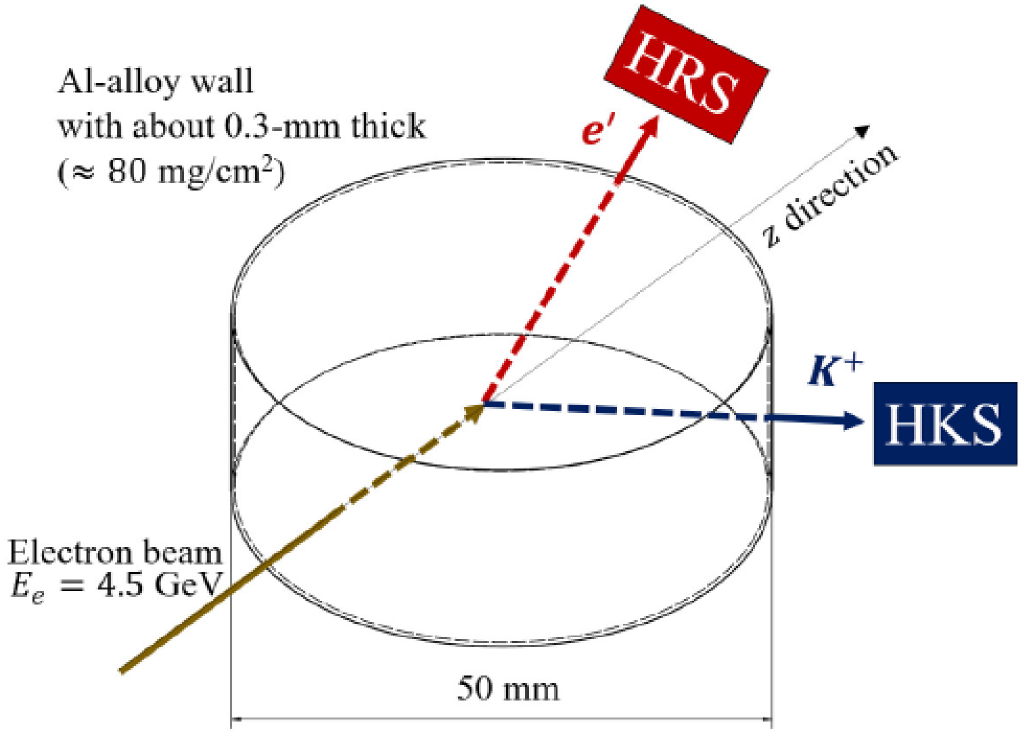
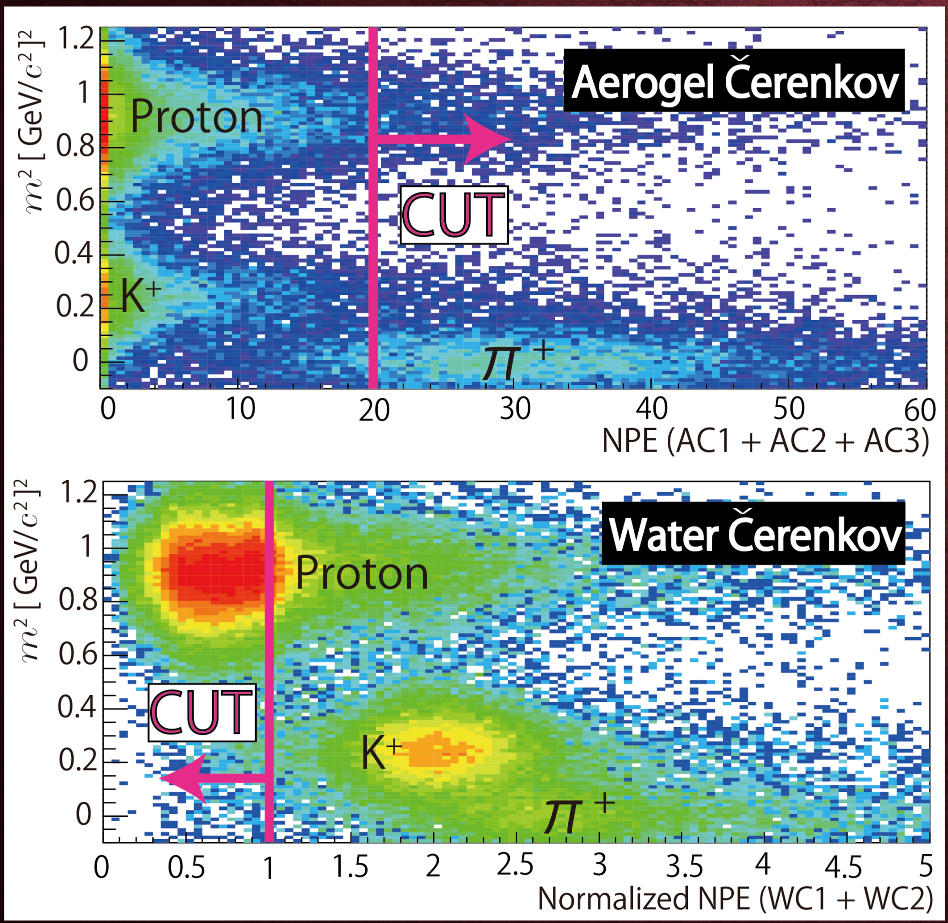


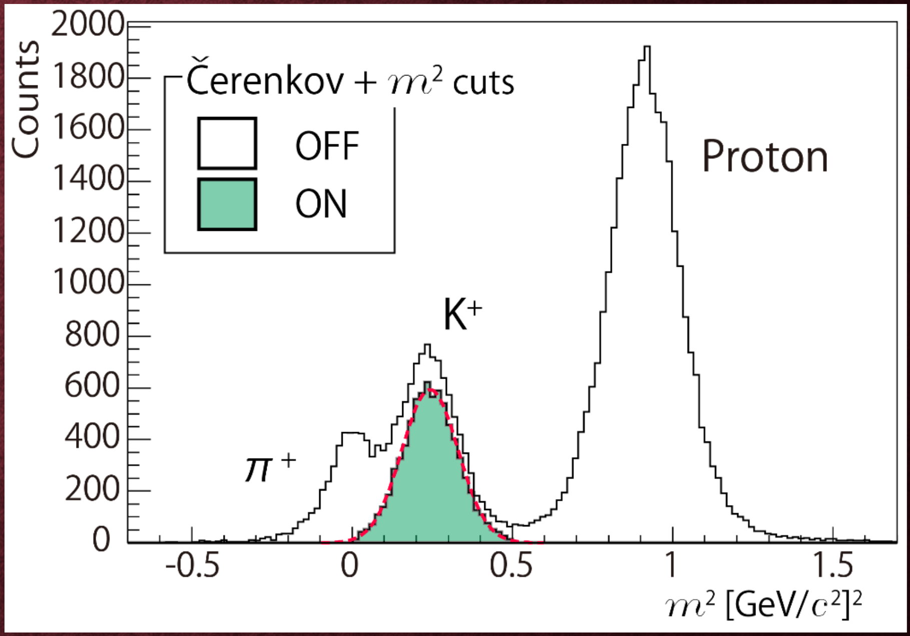
FIG. 9. A schematic of a target cell for a gaseous helium (^{3,4}He) and a liquid hydrogen (LH$_2$). A diameter of the target cell which defines the target length in the beam direction (z-direction) is 50 mm. If events in $|z_{\rm react}| \leq 12$ mm are used for analyses, about 2σ events ($\Delta z_{\rm react} \simeq 15$-mm FWHM [39]) coming from the target cell are rejected. The 24-mm length in z corresponds to 174, 312 and 168 mg/cm^2 assuming the densities are 72, 130 and 70 mg/cm^3, respectively [39].

KAON IDENTIFICATION IN HKS

KID in HKS:

T. Gogami et al., NIMA **729 (2013)** 816–824.



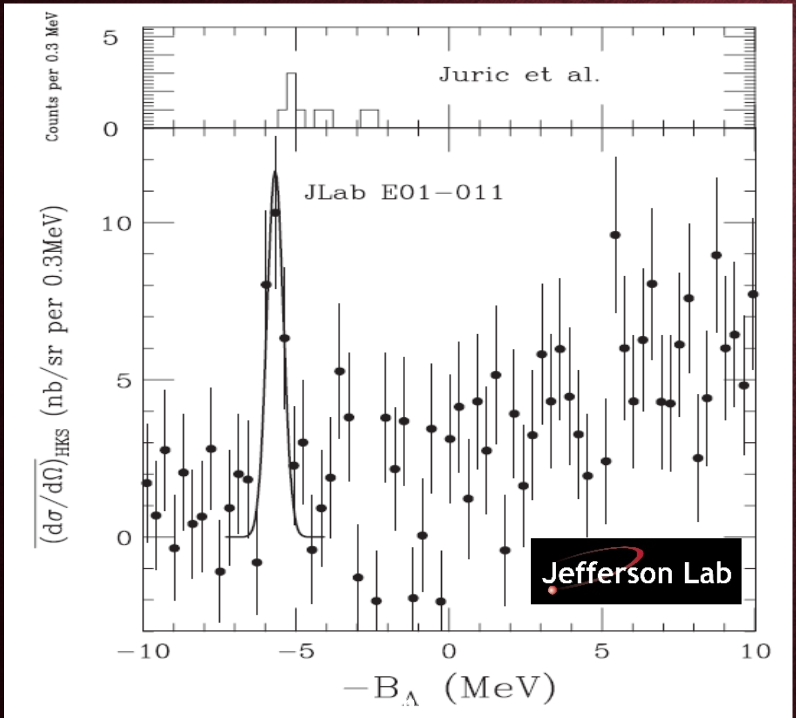


Survival ratios (on- and off-lines)

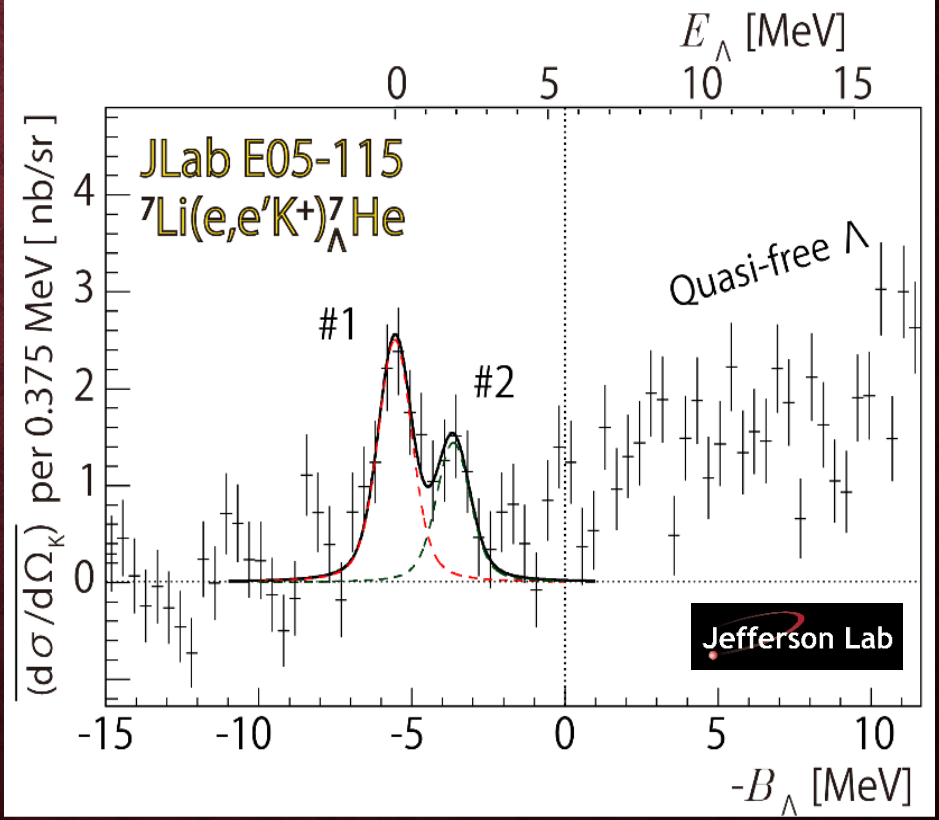
- ✓ K^+ : 83%
- ✓ π^+: 4.7×10^{-4}
- ✓ p : 1.9×10^{-4}

$^{7}_{\Lambda}$He MEASUREMENTS AT JLAB

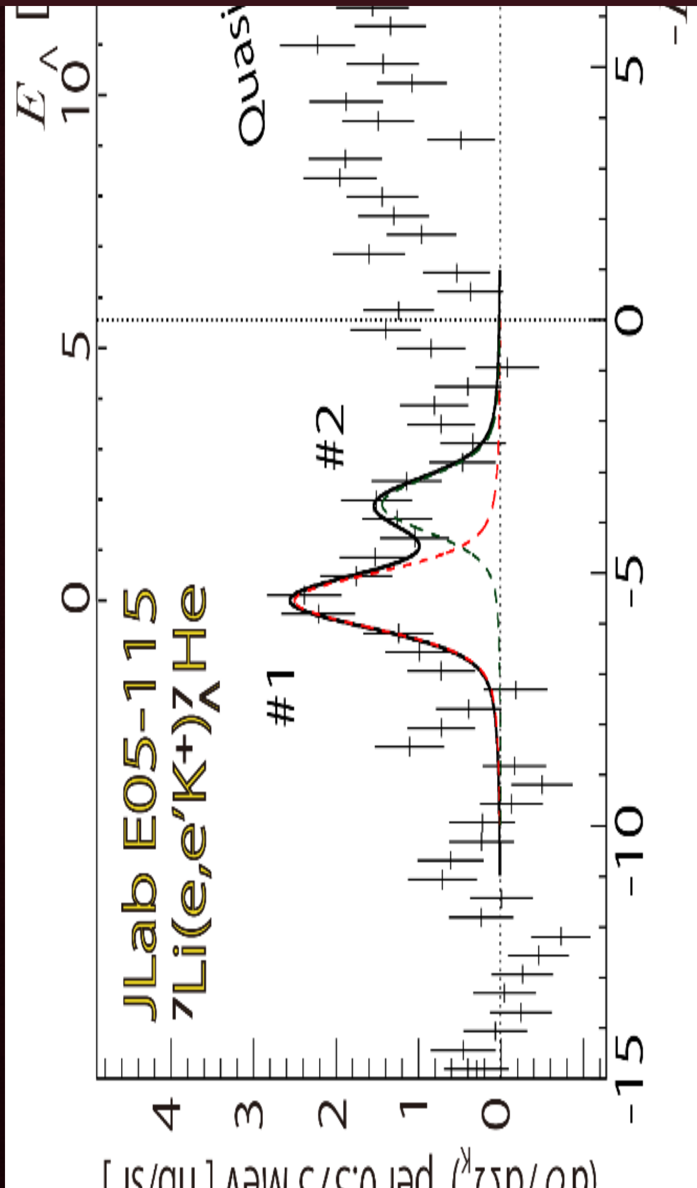
S. N. Nakamura *et al.*
(HKS(JLab E01-011 Collaboration)),
Phys. Rev. Lett. **110**, 012502 (2013).



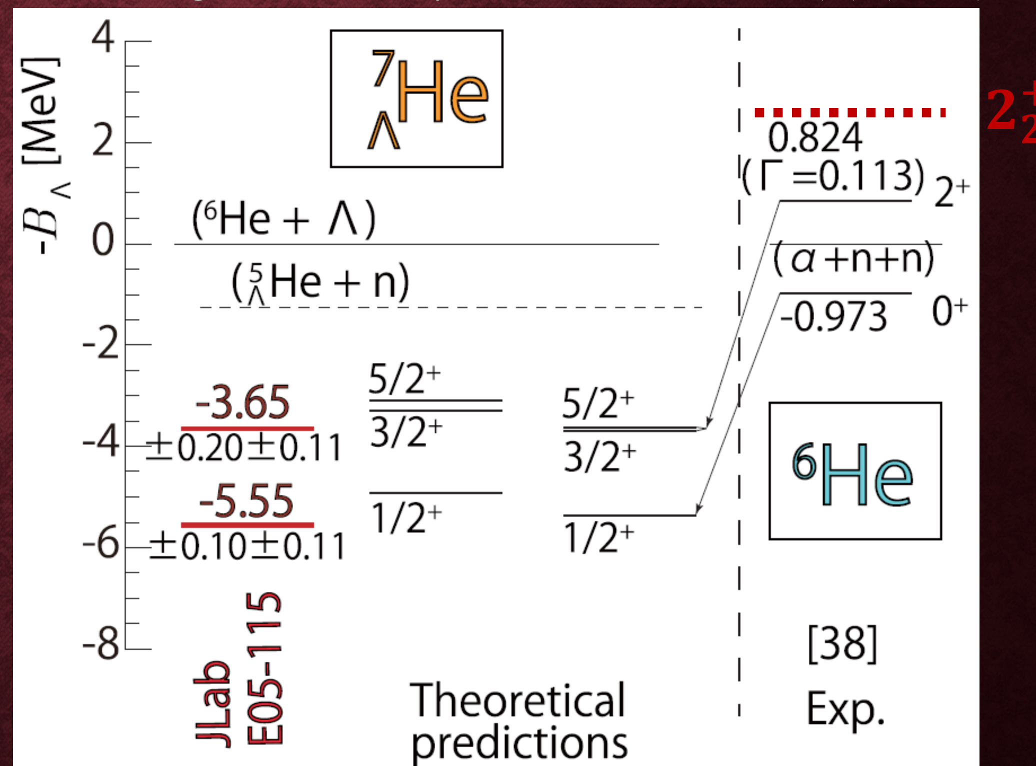
T. Gogami *et al.*
(HKS(JLab E05-115 Collaboration)),
Phys. Rev. C **94**, 021302(R) (2016).



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).