東北大学

SPHERE MEETING
9TH SEPTEMBER 2014

Satoshi N Nakamura, Tohoku University

Experimental study of hypernuclei with electron beams

JLab E05-115 collaboration, 2009, JLab Hall-C

Characteristics of
Λ hypernuclear study by (e,e'K^+) reaction

EM Interaction

p to Λ

primary e beam

Electron BG

Small C.S.

Coin. measure

High Quality Beam
Sophisticated Detectors

Three generation experiments at Hall-C

E89-009 (2000) : Existing spectrometers, SOS + Enge

Proof of Principle

E01-011 (2005) : Construction of HKS, Tilt Method

Λ, Σ^0, $^{7}_{\Lambda}$He, $^{12}_{\Lambda}$B, $^{28}_{\Lambda}$Al

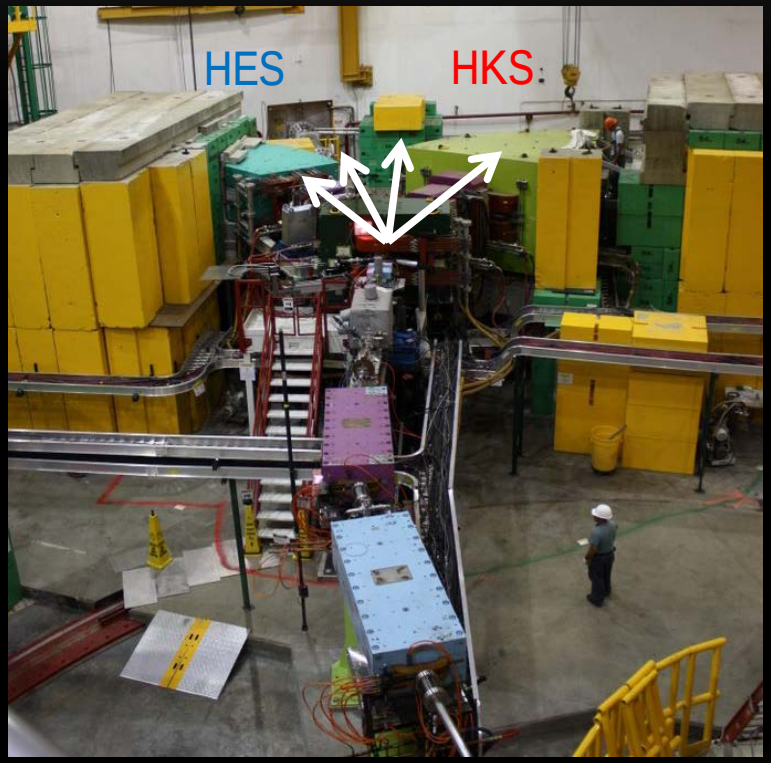
Light Hypernuclei

E05-115 (2009) : HKS+HES, new Beamline, Splitter

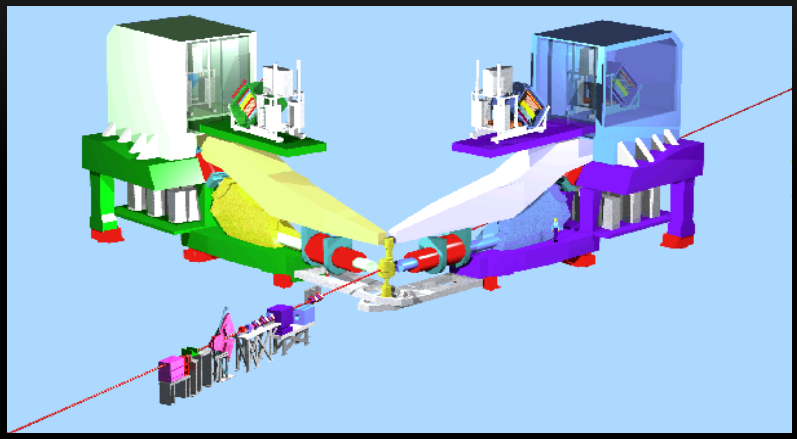
Λ, Σ^0, $^{7}_{\Lambda}$He , $^{12}_{\Lambda}$B, $^{52}_{\Lambda}$V

Light to medium-heavy Hypernuclei

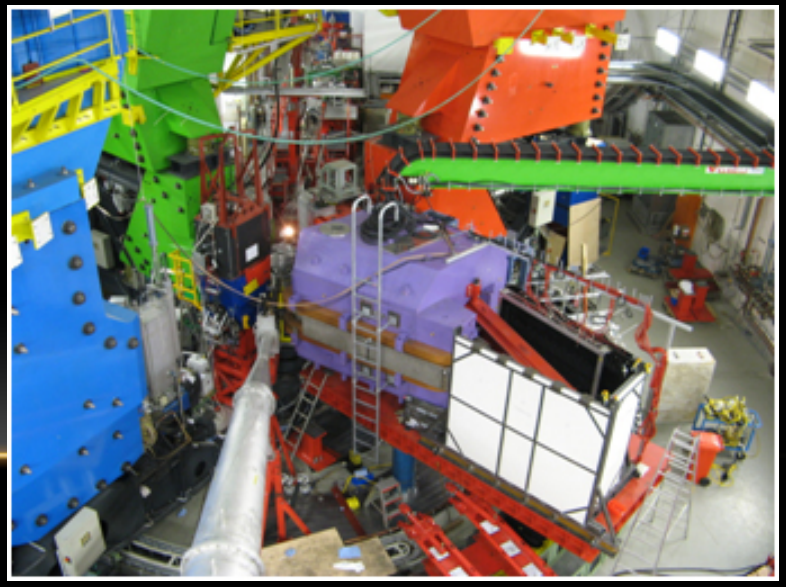
Facilities for (e,e'K^+) HY study



JLab Hall-C
HNSS (2000)
HKS (2005)
HKS+HES (2009)



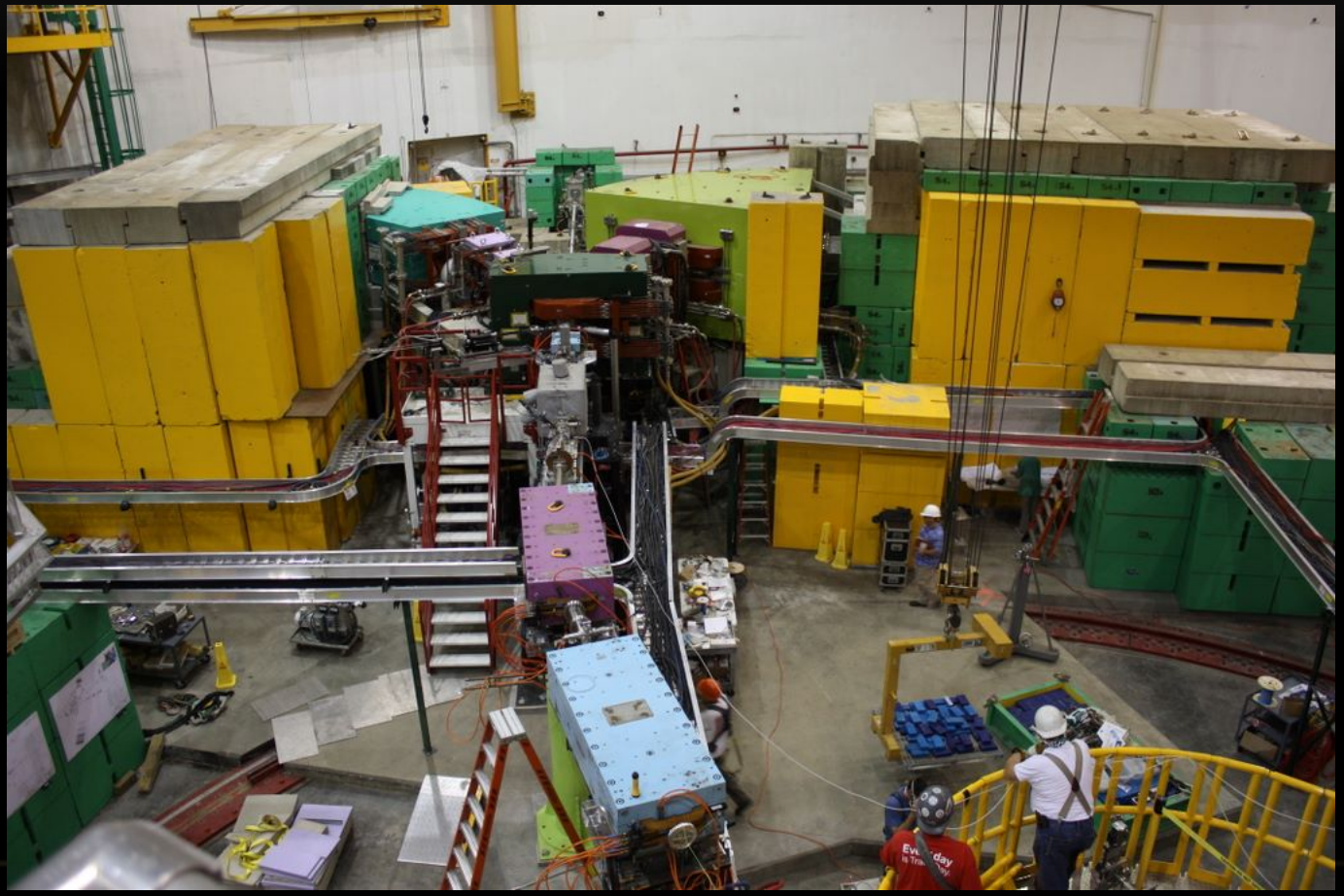
JLab Hall-A HRS+HRS (2004)



Mainz MAMI-C A1 KaoS (2008-)

JLab E05-115 (Hall-C) setup

EXPERIMENTAL SETUP



$^{12}C(e,e'K^+)^{12}_{\Lambda}B$

0.54 MeV (FWHM)

Absolute MM calibration

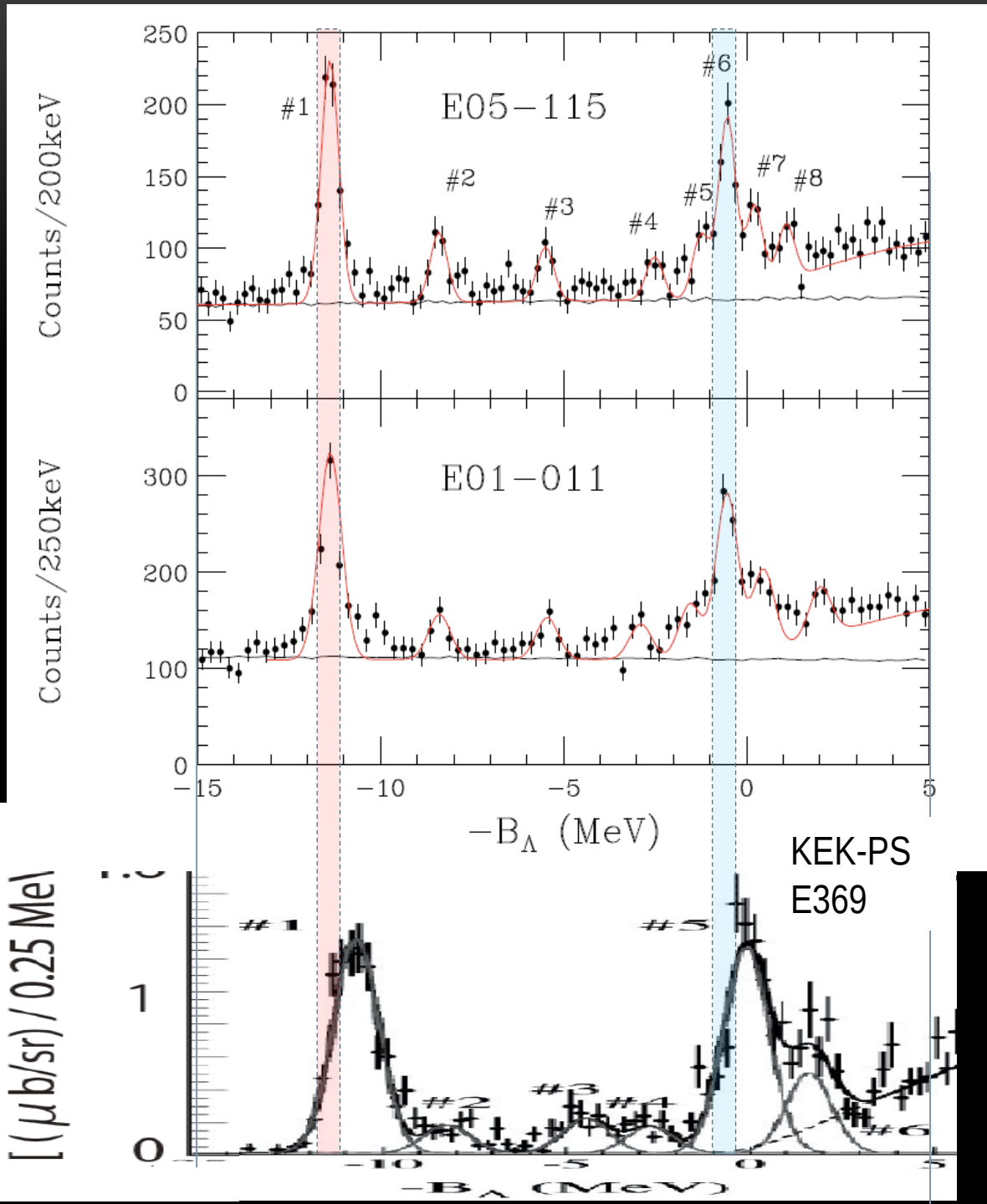
0.71 MeV (FWHM)

L.Tang, C.Chen, T.Gogami et al.
PRC in press
ArXiv 1406.2353.

$^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

1.45 MeV (FWHM)

$^{12}_{\Lambda}C_{gs}$ energy
from emulsion



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

Nuclear Physics **A484** (1988) 520–524

TABLE 1 [a])

	Decay mode	Range of the hypernucleus (μm)	B_Λ (as $^{12}_{\Lambda}$C) (MeV)	Ref.
1.	$^{12}_{\Lambda}C \rightarrow \pi^- + {}^{12}N$(g.s.)	—	11.14 ± 0.57	[4]
2.	$^{12}_{\Lambda}C \rightarrow \pi^- + p + {}^{4}He + {}^{7}Be$	3.0 ± 0.8	10.45 ± 0.33	[3]
3.	$^{12}_{\Lambda}C \rightarrow \pi^- + p + {}^{11}C$	4.3 ± 0.7	10.50 ± 0.47	[3]
4.		3.5 ± 0.4	10.65 ± 0.33	[1,2]
5.		3.5 ± 0.5	10.85 ± 0.44	[1,2]
6.		3.4 ± 0.5	11.59 ± 0.45	[1,2]
7.		3.2 ± 0.4	15.67 ± 0.50	[1,2]

^{11}C (3/2-) : Ex = 4.8MeV

situation is not the case for π^- mesonic decay modes of $^{12}_{\Lambda}$C: ($\pi^-{}^{12}$N), (π^-p^{11}C), (π^-p^{3}He^{4}He^{4}He) and (π^-p^{4}He^{7}Be). Every one of these decay topologies is easily confused with those of other hypernuclei.

The value obtained for B_Λ of $^{12}_{\Lambda}$C, (10.80 ± 0.18) MeV

Statistical errors quoted, systematic errors (~0.04 MeV) reduced by measuring M_Λ in same emulsion stack.

Nuclear Physics **A547** (1992) 369

$^{12}_{\Lambda}C$	**10.76 ± 0.19**

Statistical error only

Reference for all (π, K) B_Λ data:

B_Λ ($^{12}_{\Lambda}$Cg.s.) = 10.76 +-0.19MeV

$^{12}_{\Lambda}$B EMULSION DATA

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

		(# of events)	
$^{12}_{\Lambda}$B	$\pi^- + {}^4\mathrm{He} + {}^4\mathrm{He} + {}^4\mathrm{He}$	61	11.45 ± 0.07

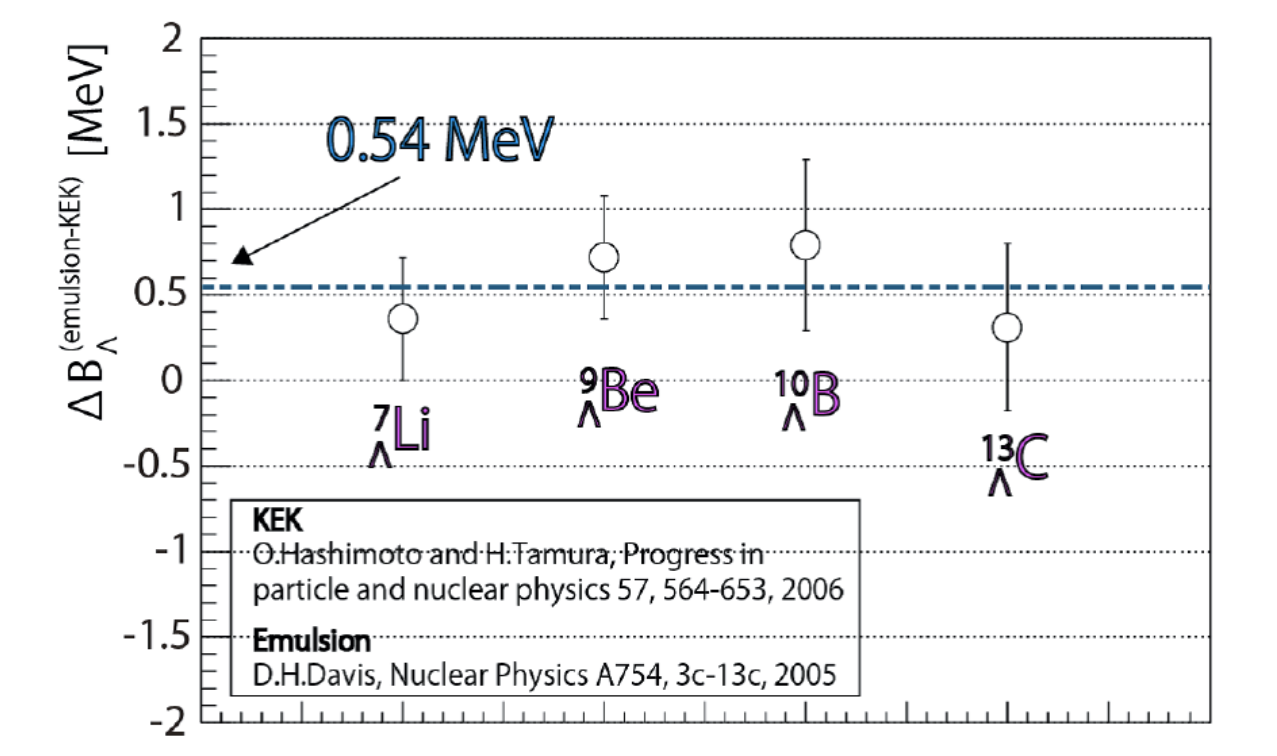
B_Λ ($^{12}_{\Lambda}$Bg.s.) = 11.45 +-0.07 MeV Emulsion Result (M.Juric et al.)

B_Λ ($^{12}_{\Lambda}$Bg.s.) = 11.38 +- 0.02 (stat) MeV (JLab E05-115)

Totally independent measurement

POSSIBLE SHIFT OF ${}^{12}_{\Lambda}C_{GS}$ B_{Λ}

${}^{12}_{\Lambda}C - {}^{12}_{\Lambda}B$	-0.57 ± 0.19 $-0.62 \pm 0.19 \pm 0.11$	${}^{12}_{\Lambda}C$: 6 events, ${}^{12}_{\Lambda}B$: 87 events present data for ${}^{12}_{\Lambda}B$



T. Gogami, Doctor thesis, (2014) Tohoku U.

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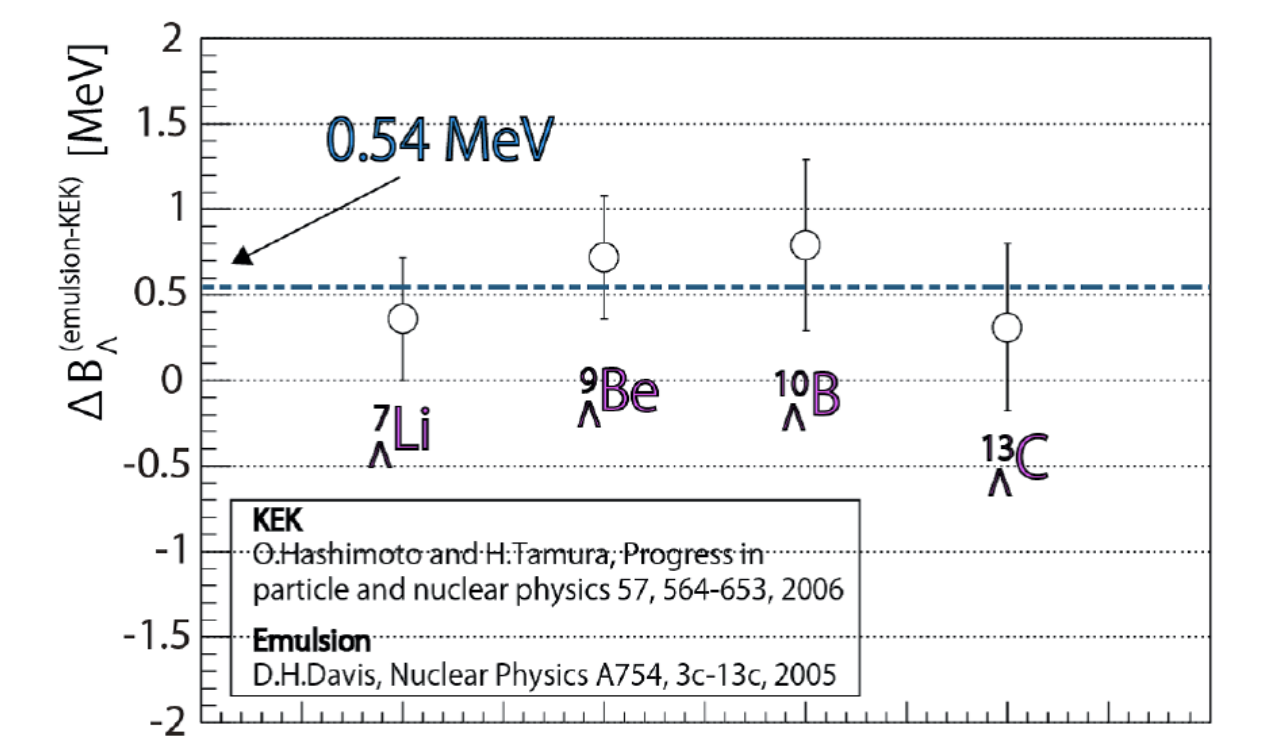


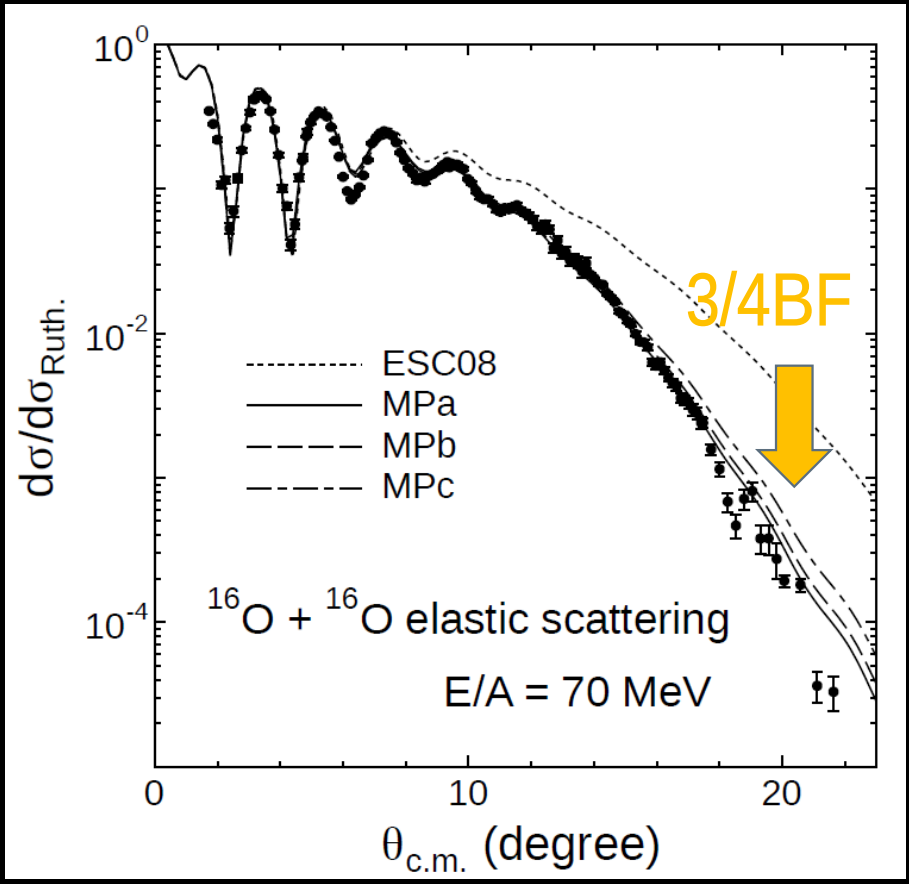
T. Gogami, Doctor thesis, (2014) Tohoku U.

Comparison between $^{51}_{\Lambda}V$ by (π,K) and $^{52}_{\Lambda}V$ by (e,e'K^{+}) supports the existence of the shift.

EOS OF NUCLEAR MATTER WITH HYPERONS

To solve hyperon puzzle

Microscopic nuclear force model @ $\rho_0 \rightarrow 2\,\rho_0$



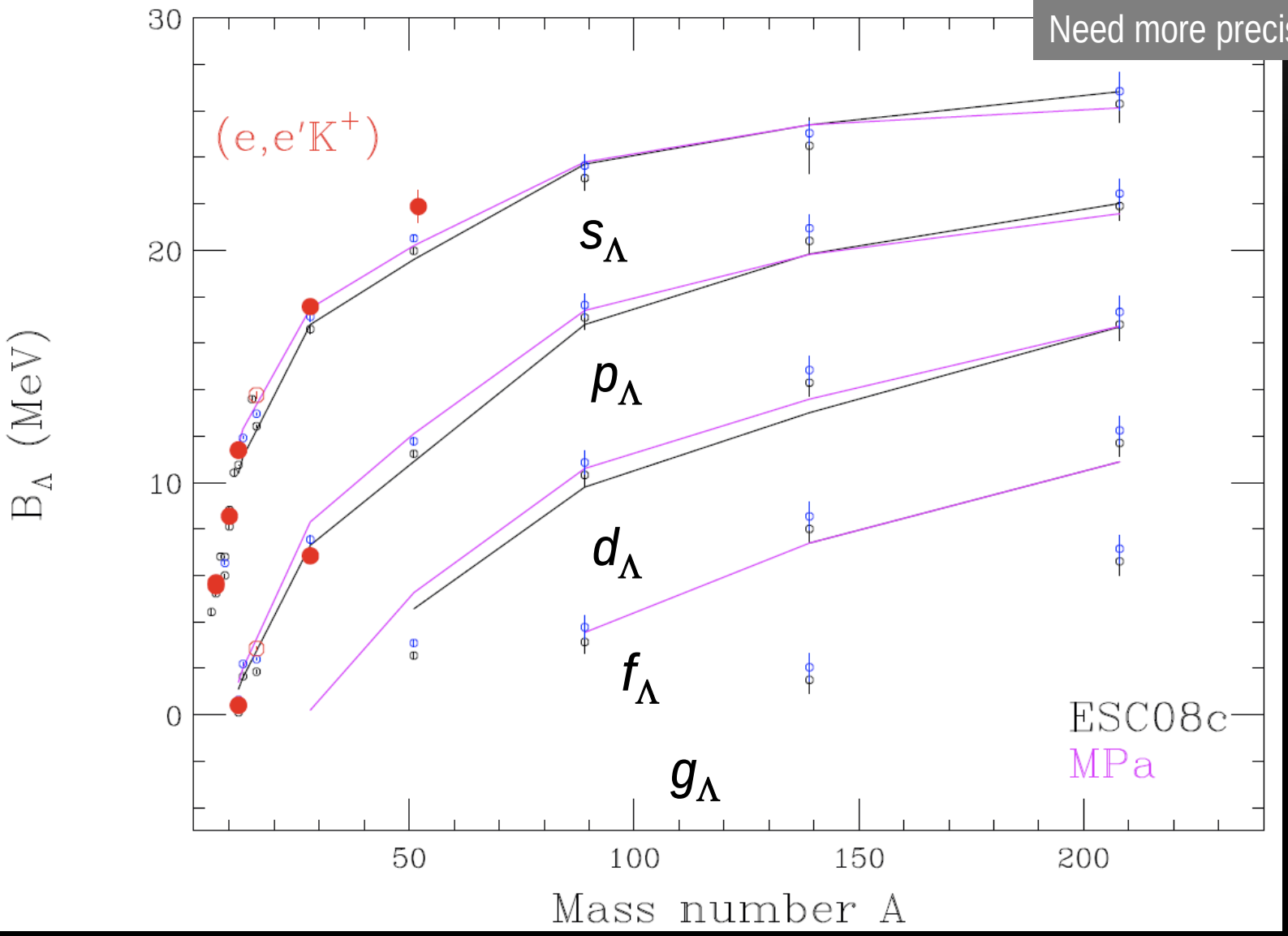
Density dependence with hyperons

Importance of 3B/4BF

Furumoto, Sakuragi, Yamamoto, PRC 79 (2009) 0011601(R)

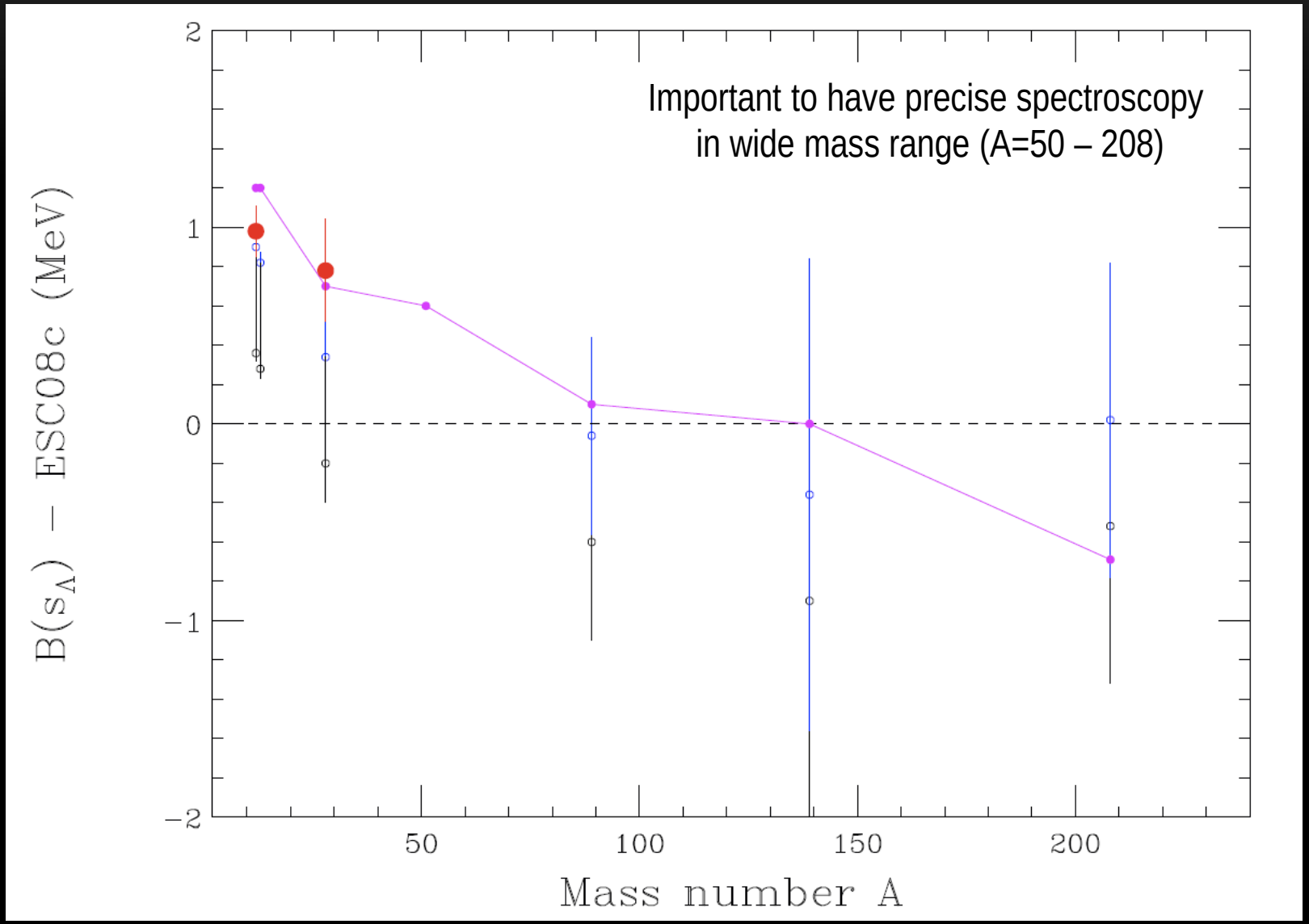
Mass dependence of B_Λ

General tendency is well understood.
Need more precise data.

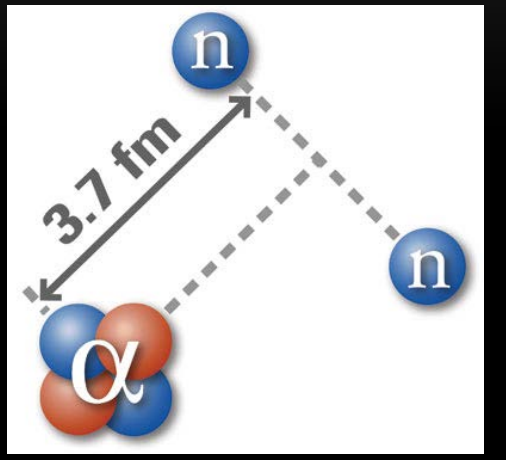


Lines: Calc. by Yamamoto & Rijken

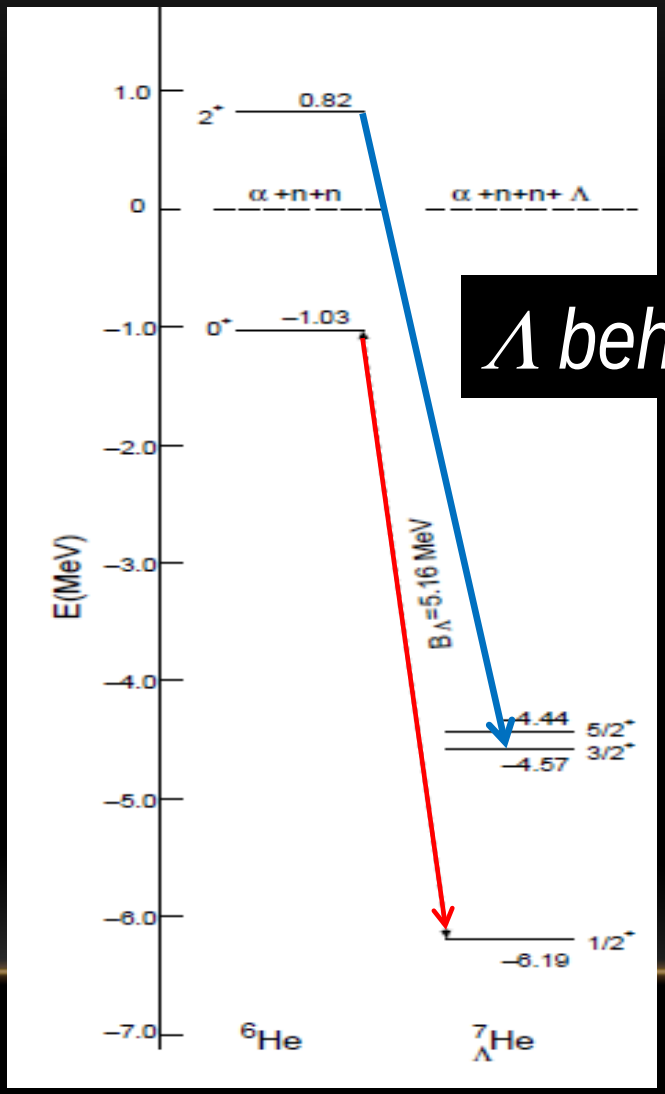
Mass dependence of B_Λ



$^{7}_{\Lambda}\mathrm{He} = {}^{6}\mathrm{He} + \Lambda$



^{6}He : 2n halo

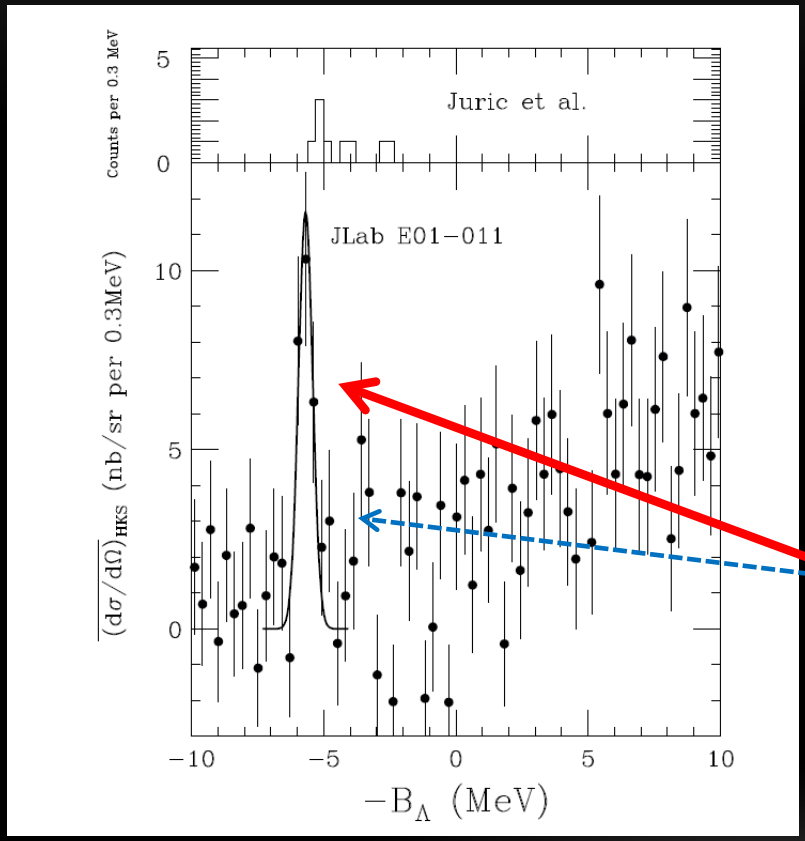


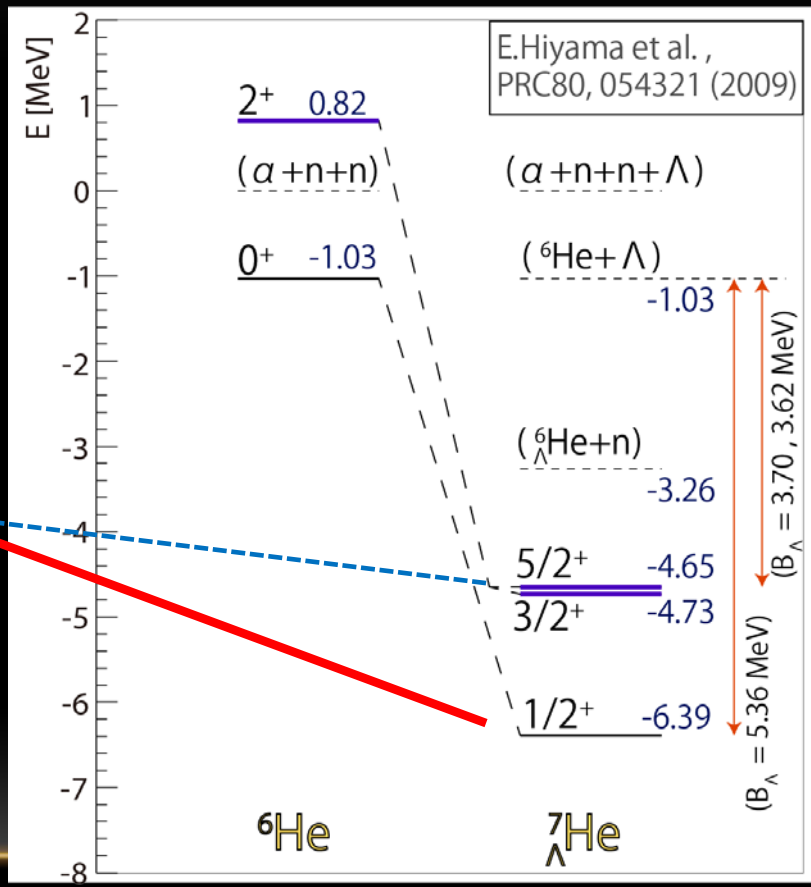
Λ behaves like glue

E.Hiyama et al. PRC 80, 054321 (2009)

$^{7}_{\Lambda}$He spectrum of E01-01

SNN et al., PRL 110, 012502 (2013)





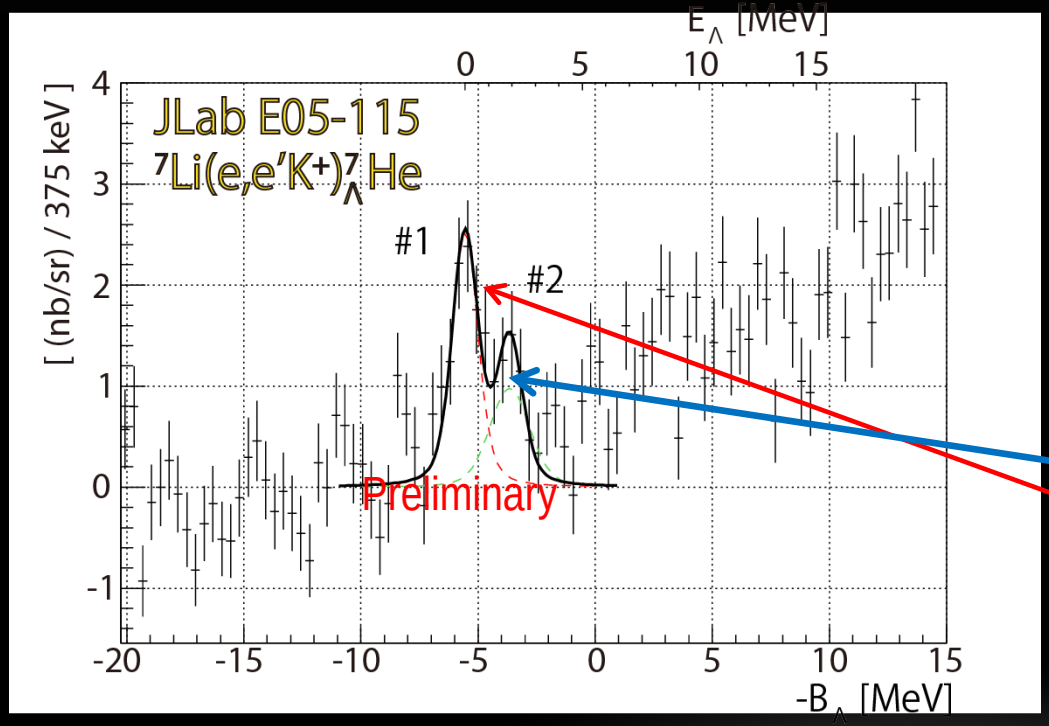
E01-011(HKS) 90 counts

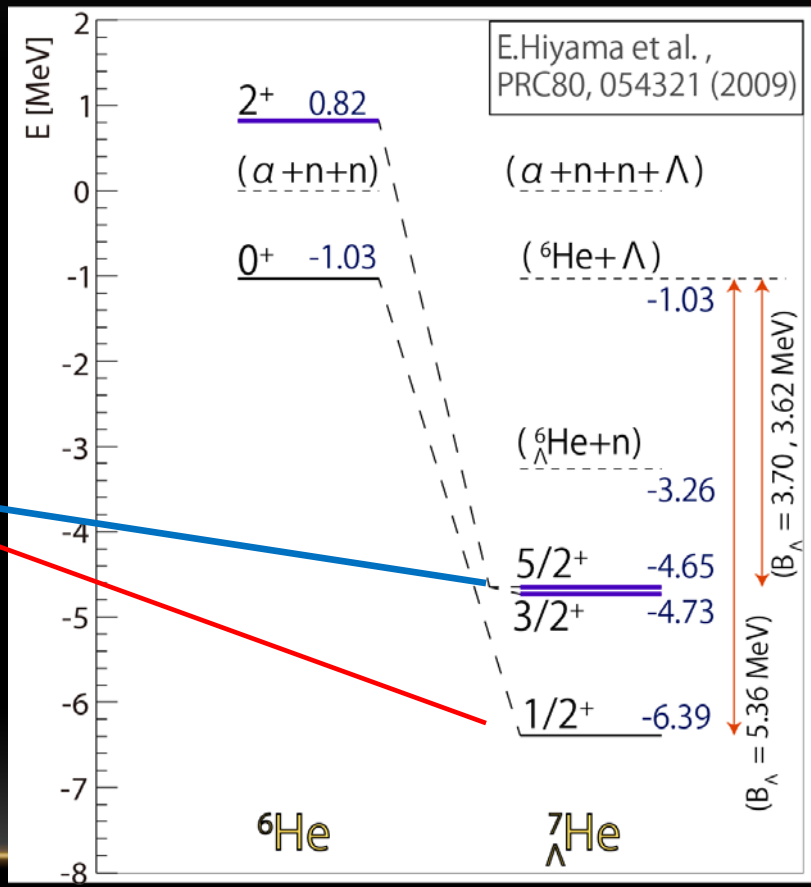
E05-115(HKS-HES) >500 counts

unbound ^{6}He excited state + Λ = bound $^7_\Lambda$He excited state

$^{7}_{\Lambda}$He spectrum of E05-115

T.Gogami, Doctor Thesis (2014) Tohoku Univ.





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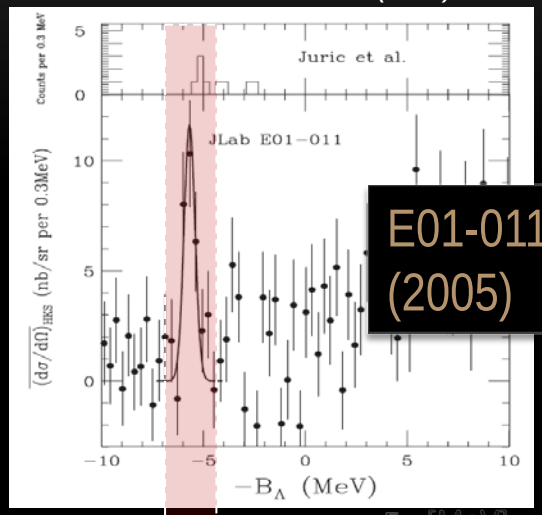
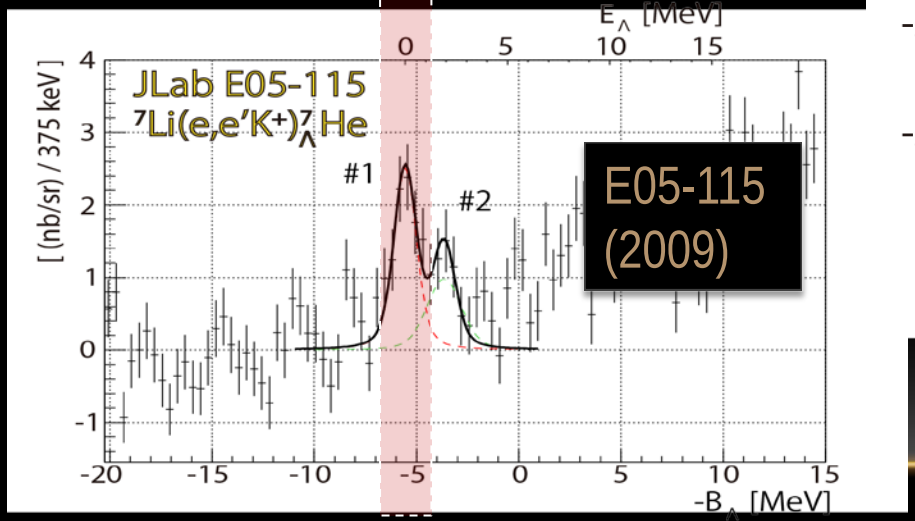
unbound ^{6}He excited state + Λ = bound $^{7}_{\Lambda}$He excited state

CSB INTERACTION TEST IN A=7 ISO-TRIPLET COMPARISON

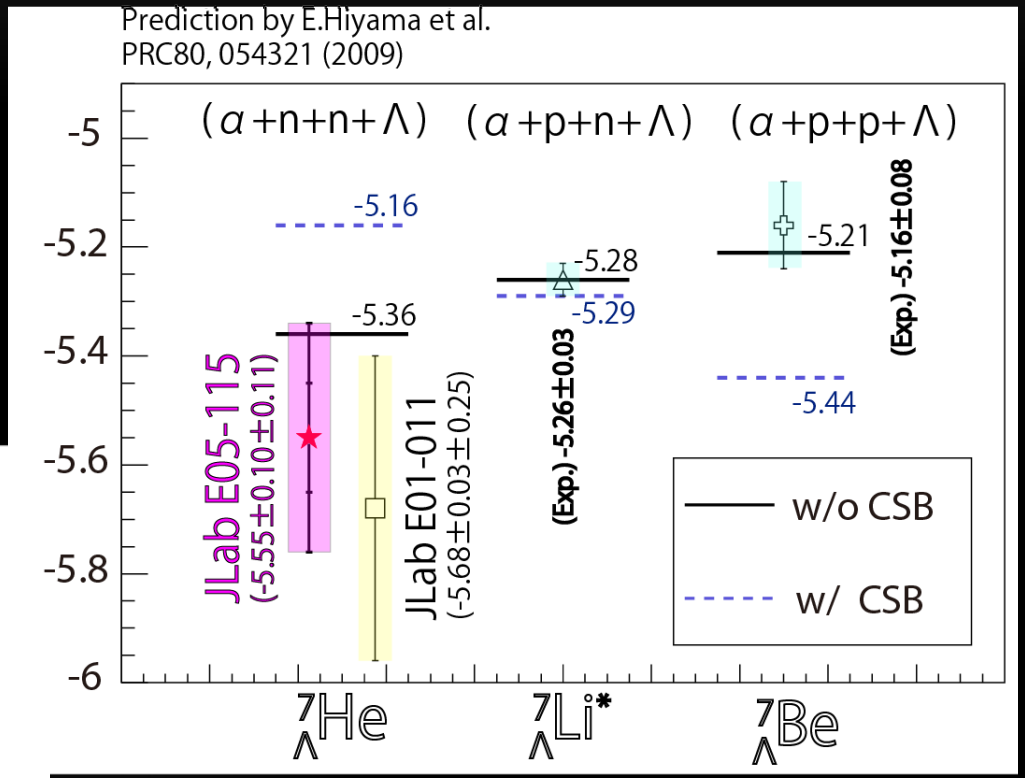
SNN et al., PRL 110, 012502 (2013)



E01-011 (2005)

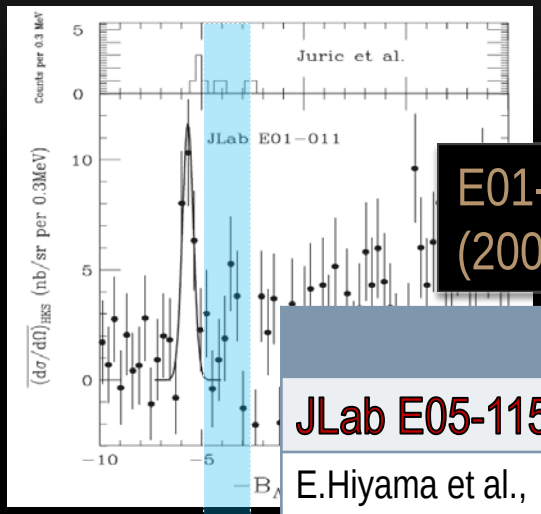


E05-115 (2009)

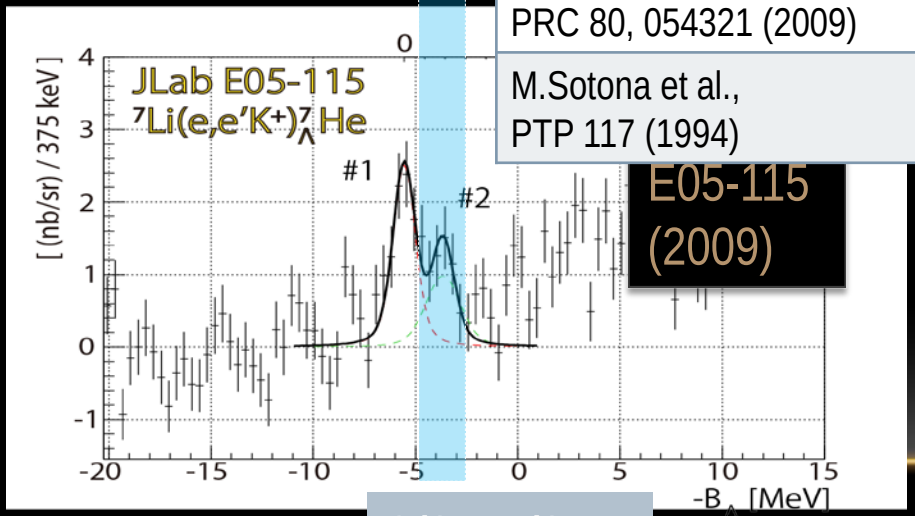


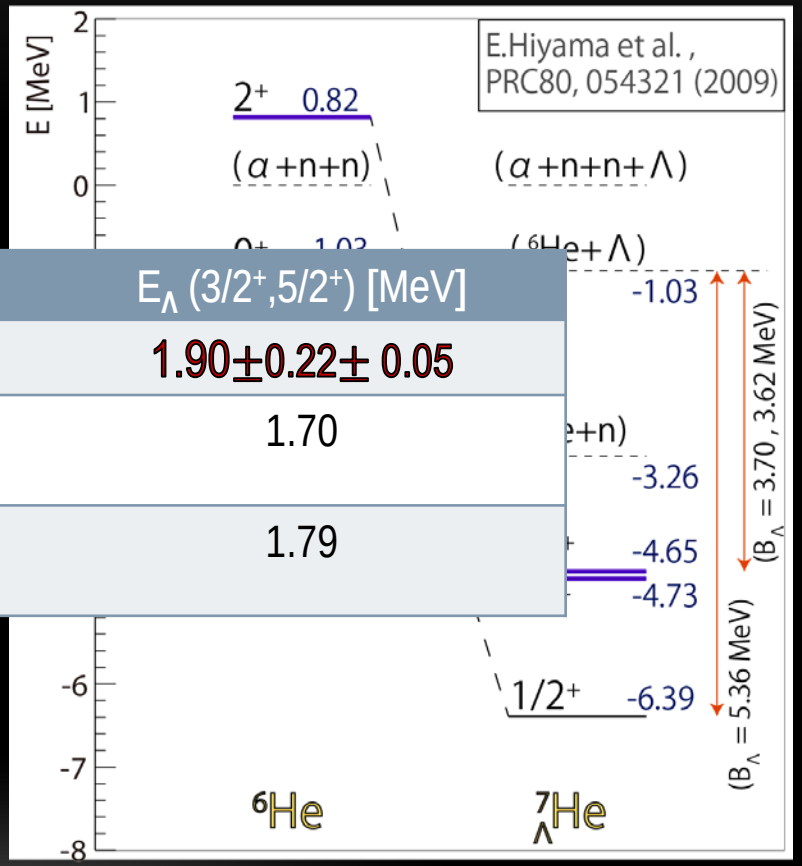
T.Gogami, Doctor Thesis (2014) Tohoku Univ.

CSB INTERACTION TEST IN A=7 ISO-TRIPLET COMPARISON



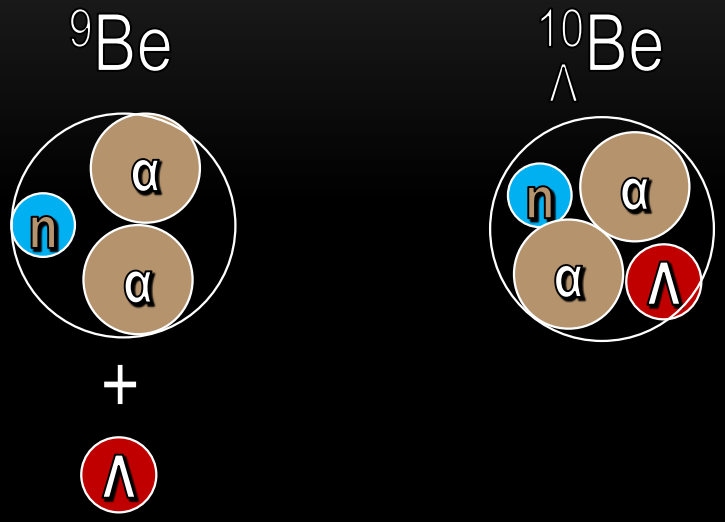
	E_Λ ($3/2^+$,$5/2^+$) [MeV]
JLab E05-115	**$1.90 \pm 0.22 \pm 0.05$**
E.Hiyama et al., PRC 80, 054321 (2009)	1.70
M.Sotona et al., PTP 117 (1994)	1.79

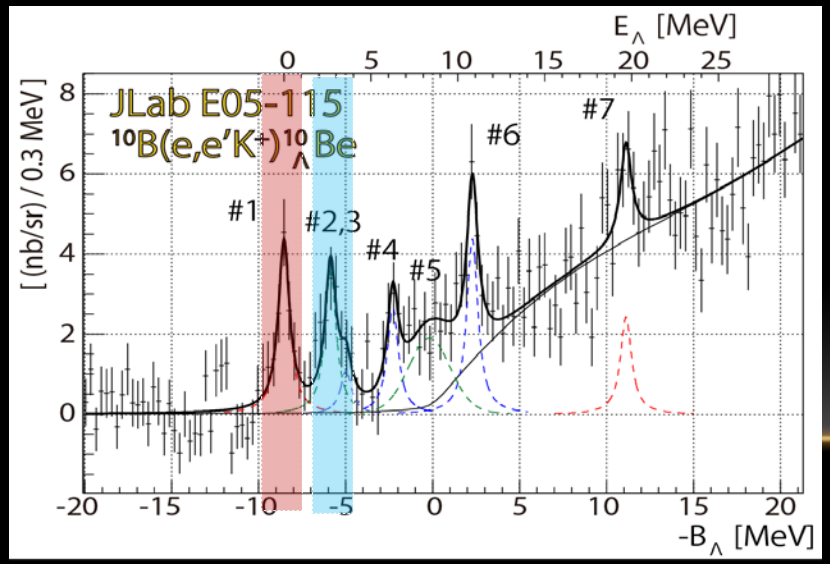


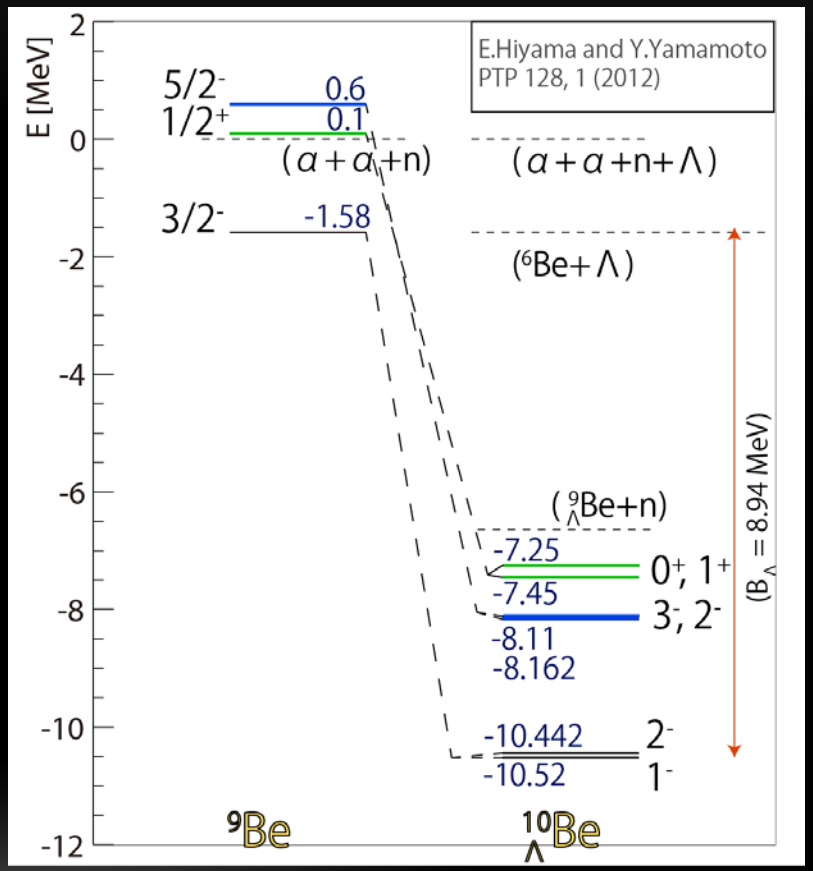


T.Gogami, Doctor Thesis (2014) Tohoku Univ.

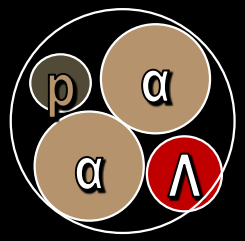
$^{10}B(e,e'K^+)^{10}{}_{\Lambda}Be$



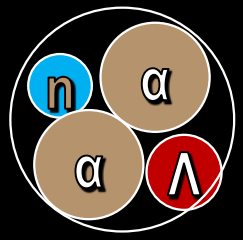




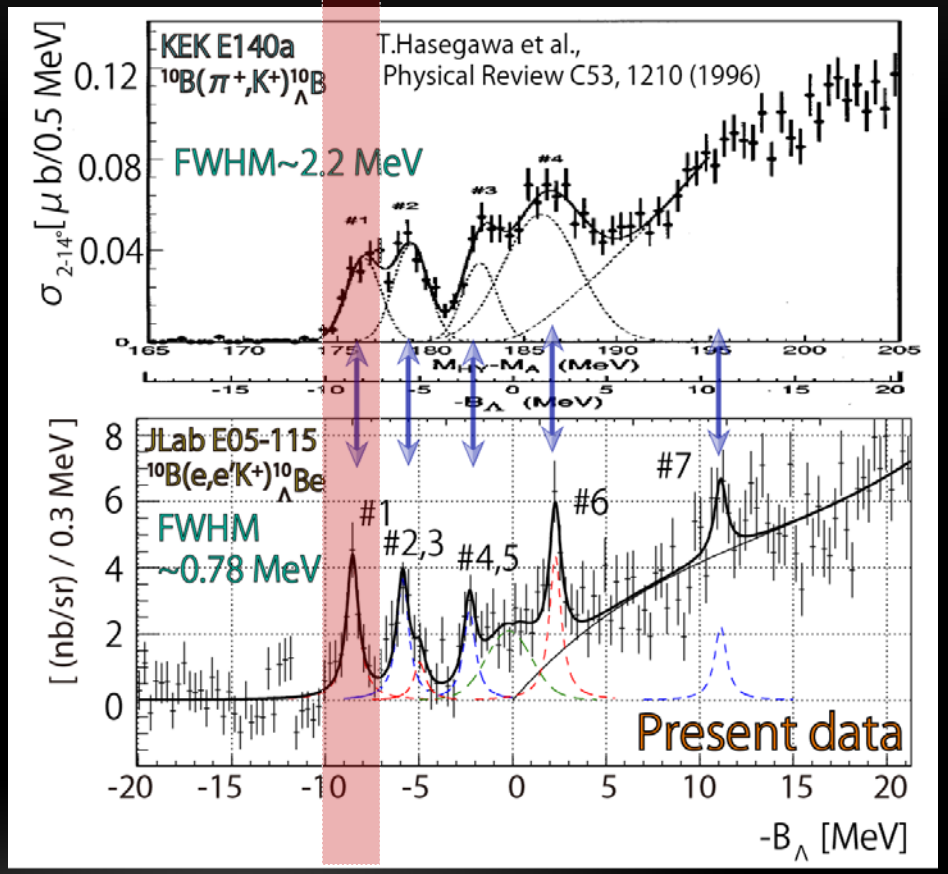
$^{10}_{\Lambda}$B and $^{10}_{\Lambda}$Be



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

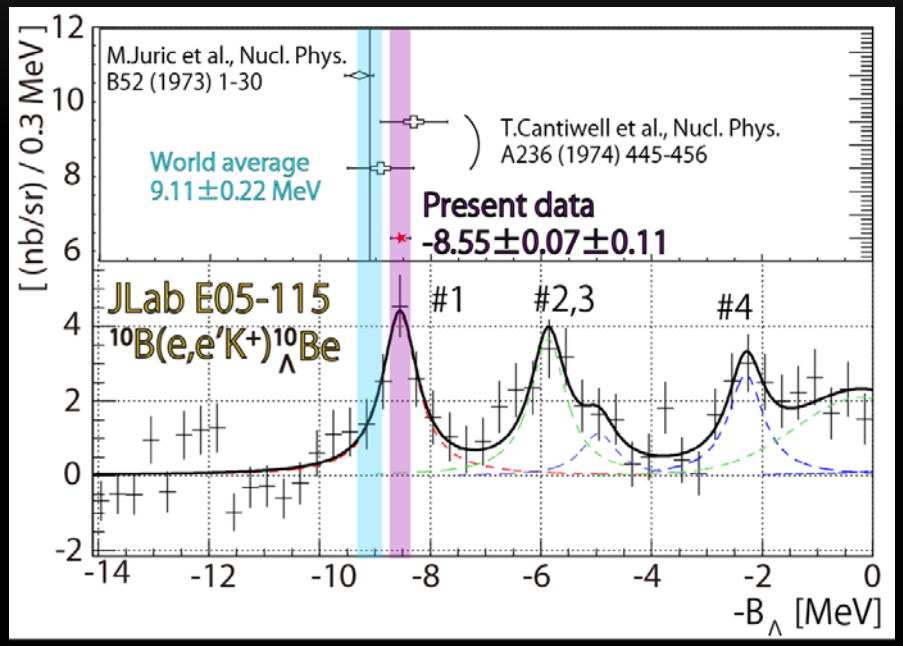


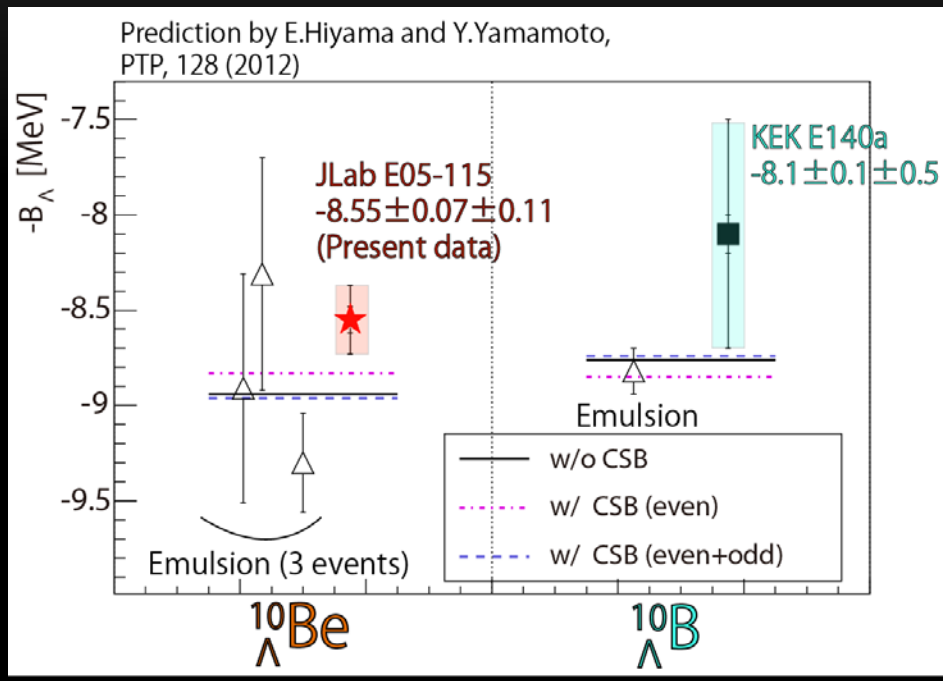
$^{10}_{\Lambda}$Be



T.Gogami, Doctor Thesis (2014) Tohoku Univ.

COMPARISON OF THE GROUND STATES (A=10)





$$
\begin{aligned}
& B_\Lambda(^{10}_{\Lambda}\mathrm{Be}) - B_\Lambda(^{10}_{\Lambda}\mathrm{B}) \\
= \; & 0.45 \pm 0.12(\mathrm{stat.}) \pm 0.61(\mathrm{sys.})\ \mathrm{MeV}\ \ (\mathrm{JLab} - \mathrm{KEK}), \\
& -0.27 \pm 0.07(\mathrm{stat.}) \pm 0.23(\mathrm{sys.})\ \mathrm{MeV}\ \ (\mathrm{JLab} - \mathrm{emulsion}),
\end{aligned}
$$

⇔

CSB(even) on : 20 keV
CSB off: -180 keV

A=4 SYSTEM
CSB ΛN POTENTIAL

$B_\Lambda({}^4_\Lambda\mathrm{H},1^+) = 1.00 \pm 0.06$ MeV

1^+

$B_\Lambda({}^4_\Lambda\mathrm{He},1^+) = 1.24 \pm 0.06$ MeV

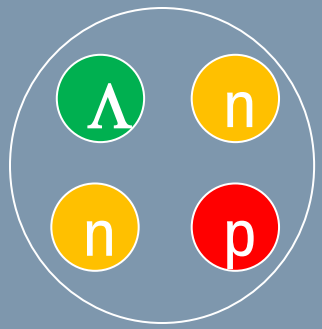
0.24 MeV

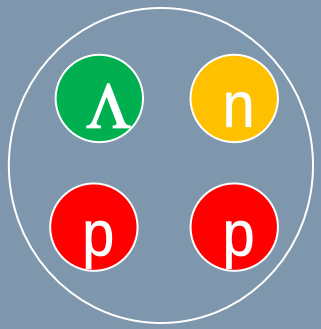
0.35 MeV

$B_\Lambda({}^4_\Lambda\mathrm{H},0^+) = 2.04 \pm 0.04$ MeV

0^+

$B_\Lambda({}^4_\Lambda\mathrm{He},0^+) = 2.39 \pm 0.03$ MeV





A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.

Coulomb effect is very small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

$$V^{\mathrm{CSB}} = -\tau_3 T_\pi^2 \tfrac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B_\Lambda^*) + (0.568\Delta B_\Lambda - 0.756\Delta B_\Lambda^*)\sigma_\Lambda \cdot \sigma_N]$$

${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

Emulsion Result (M.Juric et al.)

		(# of events)	B_Λ (MeV)
${}^{4}_{\Lambda}$H	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
${}^{4}_{\Lambda}$He	$\pi^- + {}^1H + {}^3He$	83	2.42 ± 0.05
	$\pi^- + {}^1H + {}^1H + {}^2H$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04

$$2.14 \pm 0.07$$
$$1.92 \pm 0.12$$

$$\longrightarrow \quad CSB = 0.35\ MeV$$
$$\Delta = 0.22\ MeV$$

A=4 SYSTEM
CSB ΛN POTENTIAL

$B_\Lambda(^4_\Lambda\mathrm{H},1^+) = 1.00 \pm 0.06$ MeV

^{4}He(e,e'K$^+$) $^4_\Lambda$H(1$^+$)

$B_\Lambda(^4_\Lambda\mathrm{H},0^+) = 2.04 \pm 0.04$ MeV

Decay π

1$^+$

0.24 MeV

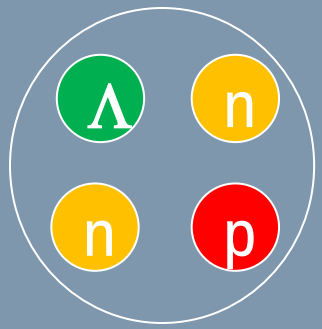
0.35 MeV

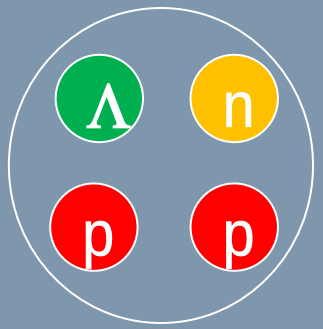
0$^+$

$B_\Lambda(^4_\Lambda\mathrm{He},1^+) = 1.24 \pm 0.06$ MeV

J-PARC E13

$B_\Lambda(^4_\Lambda\mathrm{He},0^+) = 2.39 \pm 0.03$ MeV





A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.

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$$V^{\mathrm{CSB}} = -\tau_3 T_\pi^2 \tfrac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B_\Lambda^*) + (0.568\Delta B_\Lambda - 0.756\Delta B_\Lambda^*)\sigma_\Lambda \cdot \sigma_N]$$

POSSIBLE FUTURE PROGRAMS @ JLAB

1. Elementary Λ, Σ^0

   Reliable data ^{1}H(e,e'K$^+$)Λ, Σ^0 in low Q^2 ^{3}t(e,e'K)[nnΛ]

2. Few-body ^{6,7}Li(e,e'K)$^6_\Lambda$He, $^7_\Lambda$He

   ^{2}D(e,e'K$^+$) [ΛN] Exotic bound state, ΛN int.

   ^{4}He(e,e'K$^+$)$^4_\Lambda$H ΛN CSB

3. Medium-heavy ^{19}F(e,e'K)$^{19}_\Lambda$O

   ^{40,44,48}Ca(e,e'K$^+$) $^{40,44,48}_\Lambda$K Λ's S.E., iso-spin

   ^{27}Al(e,e'K$^+$) $^{27}_\Lambda$Mg Tri-axial deformation

   ^{48}Ti(e,e'K$^+$) $^{48}_\Lambda$Sc Level inv. due to Λ

4. Heavy

   ^{208}Pb(e.e'K$^+$) $^{208}_\Lambda$Tl Λ in heaviest nucleus

5. Decay π

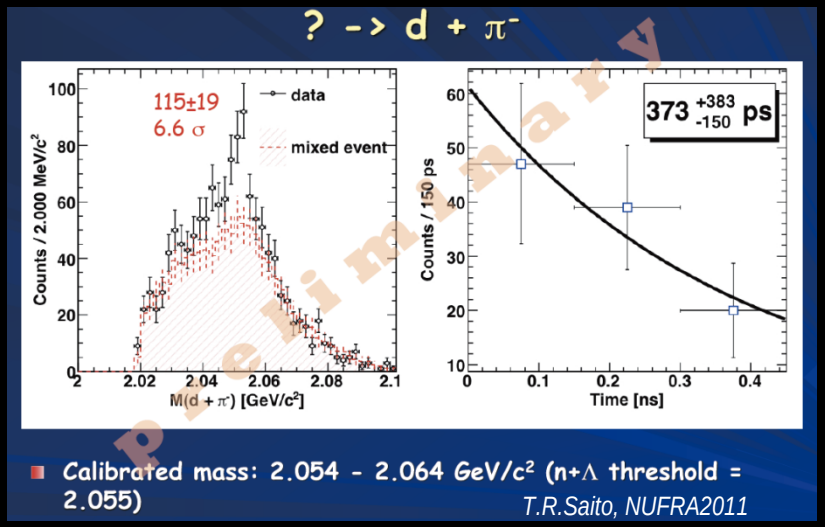
   Weak decay of light hyper-fragments

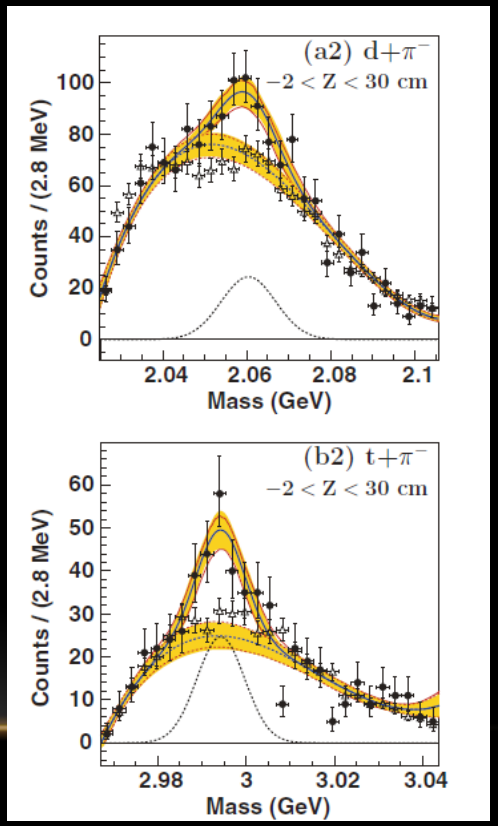
FEW-BODY PHYSICS WITH STRANGENESS

Search of [nΛ] bound state and study of n-Λ interaction through FSI.

Established lightest hypernyclei = $^{3}_{\Lambda}$H

Hyp-HI experiment at GSI a structure in d + π^- , t + π^- invariant mass





C.Rappold et al. PRC88, 041001(R) (2013)

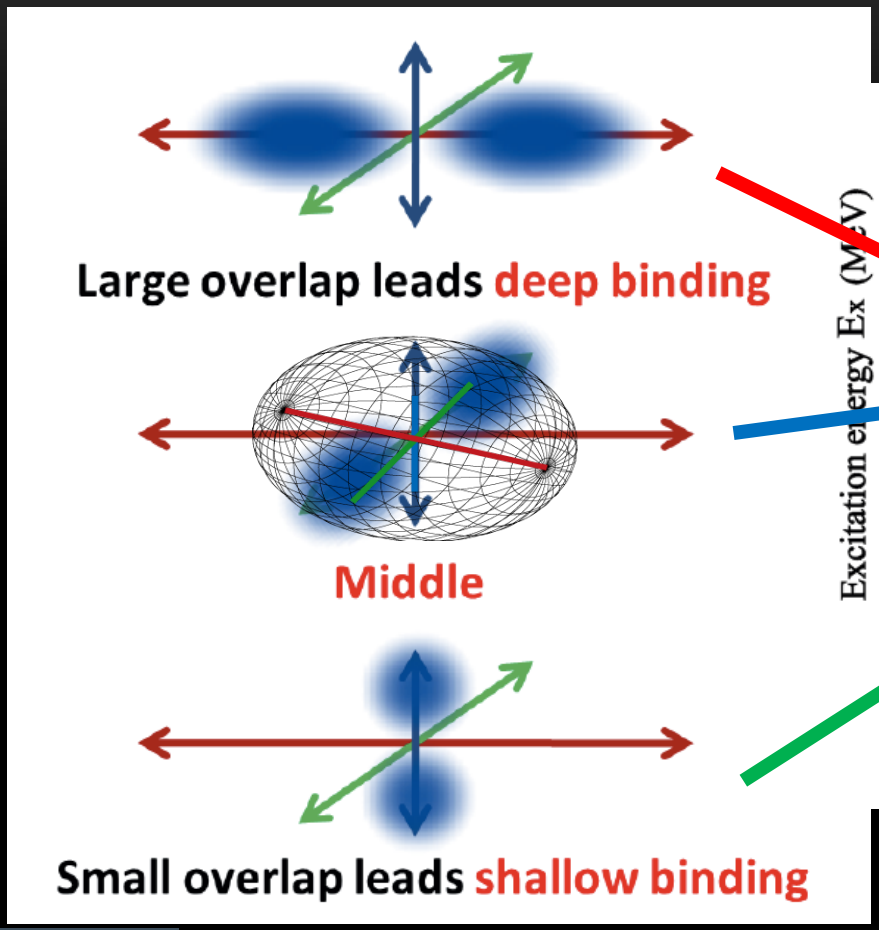
Indication of a nΛ , nnΛ bound state ?

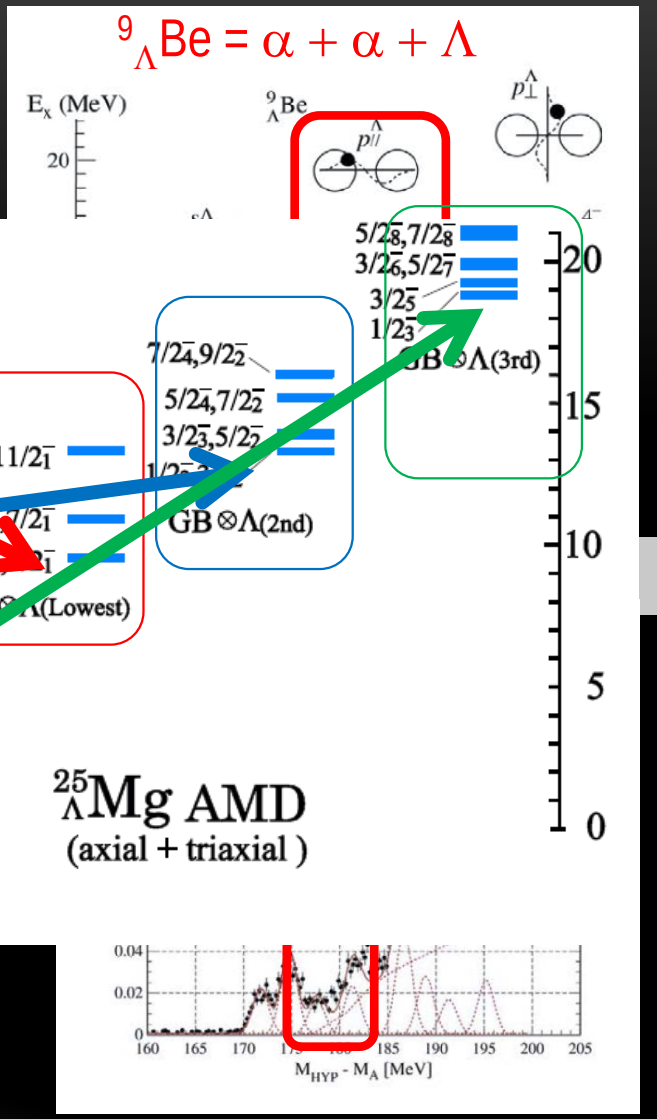
^{2}d(e,e'K^{+})[nΛ]

^{3}t(e,e'K^{+})[nnΛ]

Direct method to search these exotic systems.

2. ^{27}Al (e,e'K$^+$) $^{27}_{\Lambda}$Mg





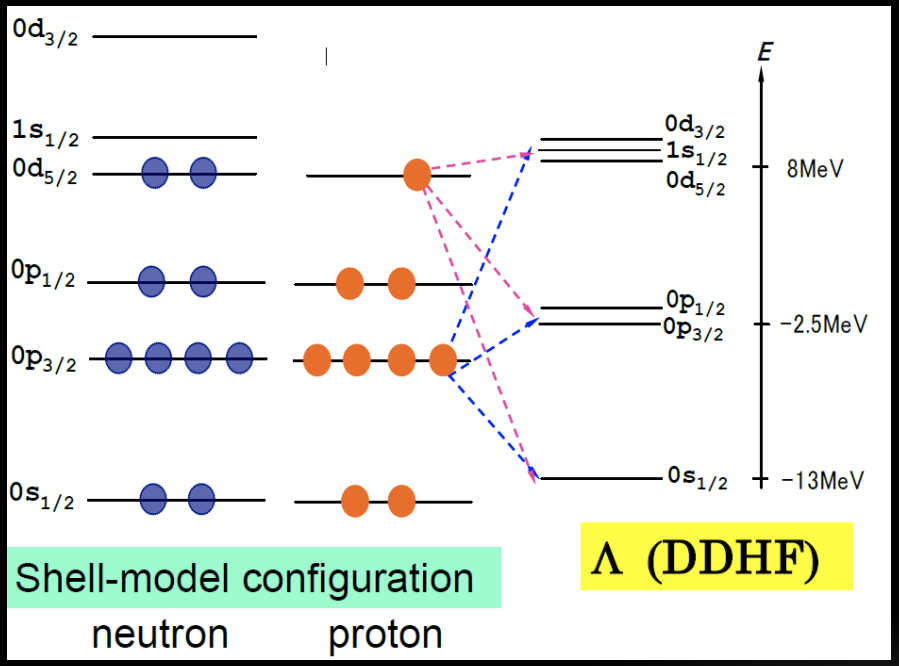
M.Isaka

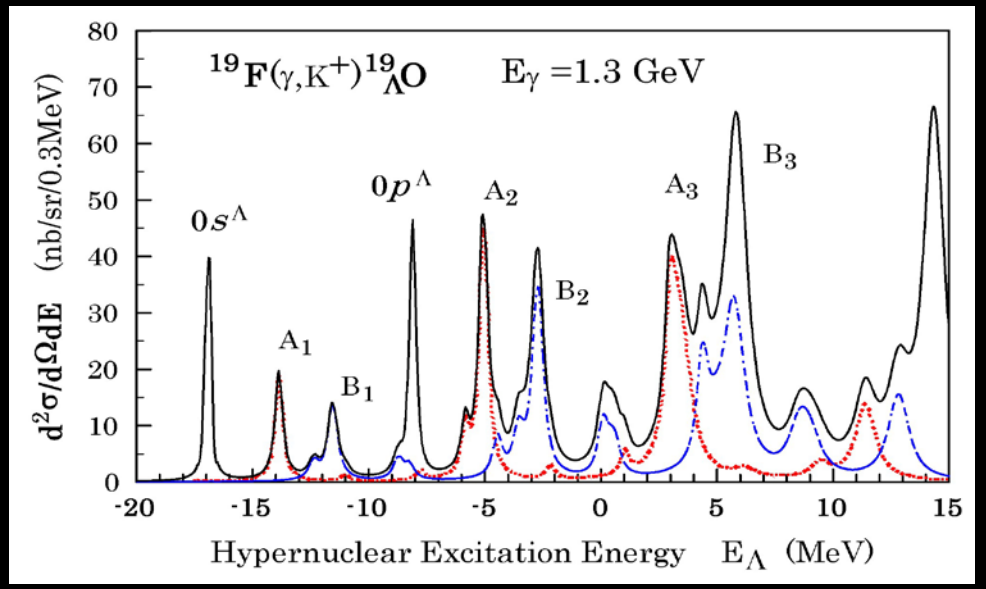
Tri-axially deformed ^{26}Mg core + Λ in p-shell

Totally new method to search shape of nucleus with Λ!

3. ^{19}F TARGET : SIMPLEST SD-SHELL

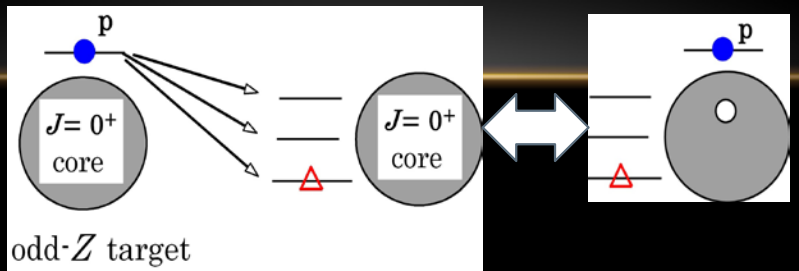
T. Motoba, C2C WS Barcelona (2012)



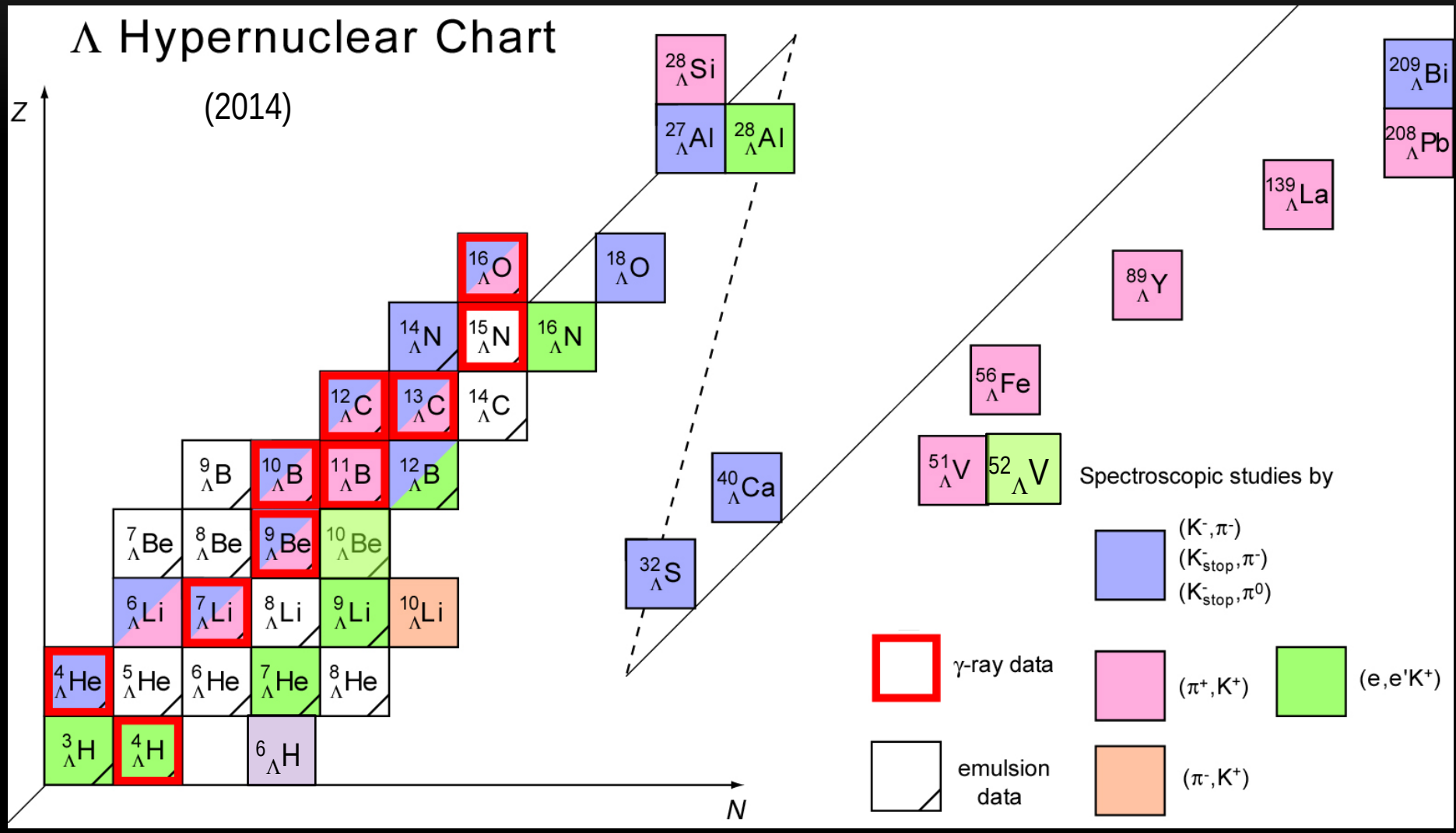


A's: $p_{1/2}$-hole series B's: $p_{3/2}$-hole series

Study of core-dynamics



PRESENT STATUS OF Λ HYPERNUCLEAR SPECTROSCOPY



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

SUMMARY

- We have been developing large magnetic spectrometers (HKS, HES) and techniques in the last decade at JLab and (e,e'K^+) HY spectroscopy is *now established*.

- Best spectroscopy of $^{12}_{\Lambda}B$ was performed and absolute binding energy calibration implies a shift of $^{12}_{\Lambda}C$ emalsion B_{Λ} which is the reference to all (π^+,K^+) spectrosopy binding energies.

- Binding energy of $^{7}_{\Lambda}He_{gs}$ was determined. Important input for ΛN CSB potential. Excited state of $^{7}_{\Lambda}He$ was clearly observed.

- New data on $^{10}_{\Lambda}Be_{gs}$ was obtained.

We are designing next program at JLab.
systematic study of B_{Λ} for wide A range up to 208,
tri-axial deformed HY ,
CSB study with light HY and
elementary study with exotics (nnΛ)