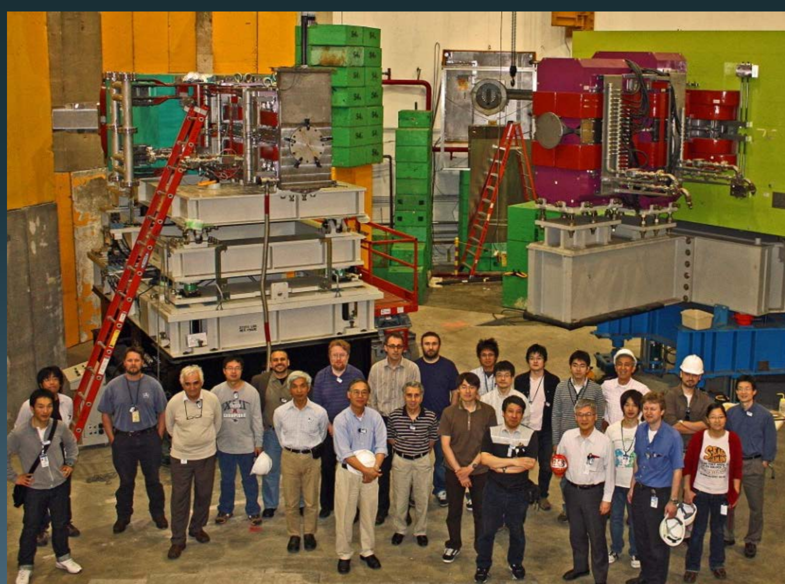
HYP2015, Sendai, Japan
7th September 2015

The 12th International Conference on Hypernuclear and Strange Particle Physics
HYP2015
September 7 – 12, 2015
Tohoku University, Sendai, Japan

Satoshi N Nakamura, Tohoku University

Hypernuclear spectroscopy via the (e,e'K$^+$) reaction



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

Analysis Details:
T.Gogami parallel 1a-5

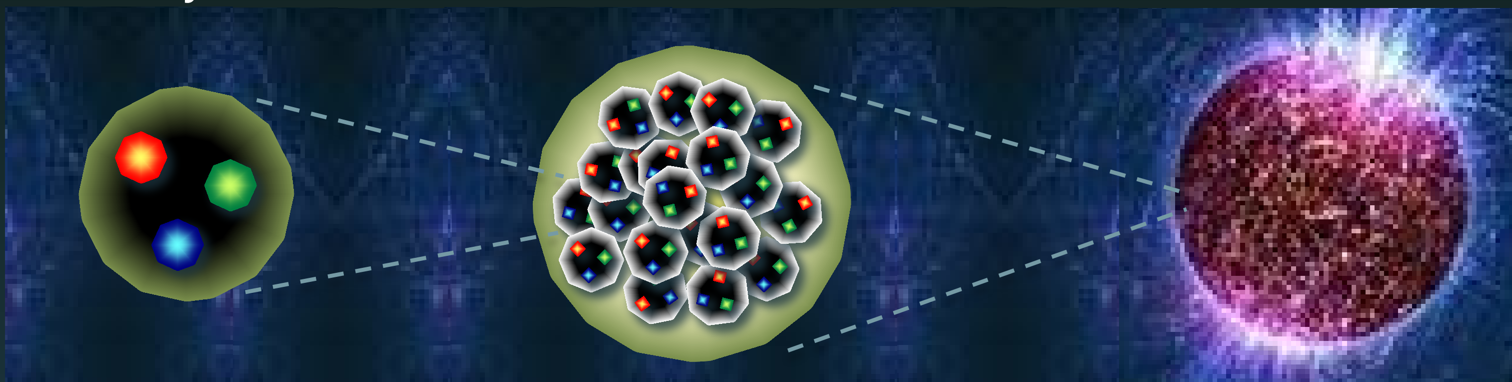
Future Programs at JLab
L.Tang, plenary 11th Sep.

Quantum Many-body System Bound by the Strong Int.

Baryon

(Hyper) Nucleus

Neutron Star



10^{-15} m

10^{4} m

Spectroscopy of Hypernuclei

NN scat.

Obs. $2\ M_{\odot}$

Hyperon Puzzle

Baryon Interaction

LQCD

Production of Λ Hypernuclei

Large C.S.
Small ***q***

s-quark exch.

(K⁻,π⁻)

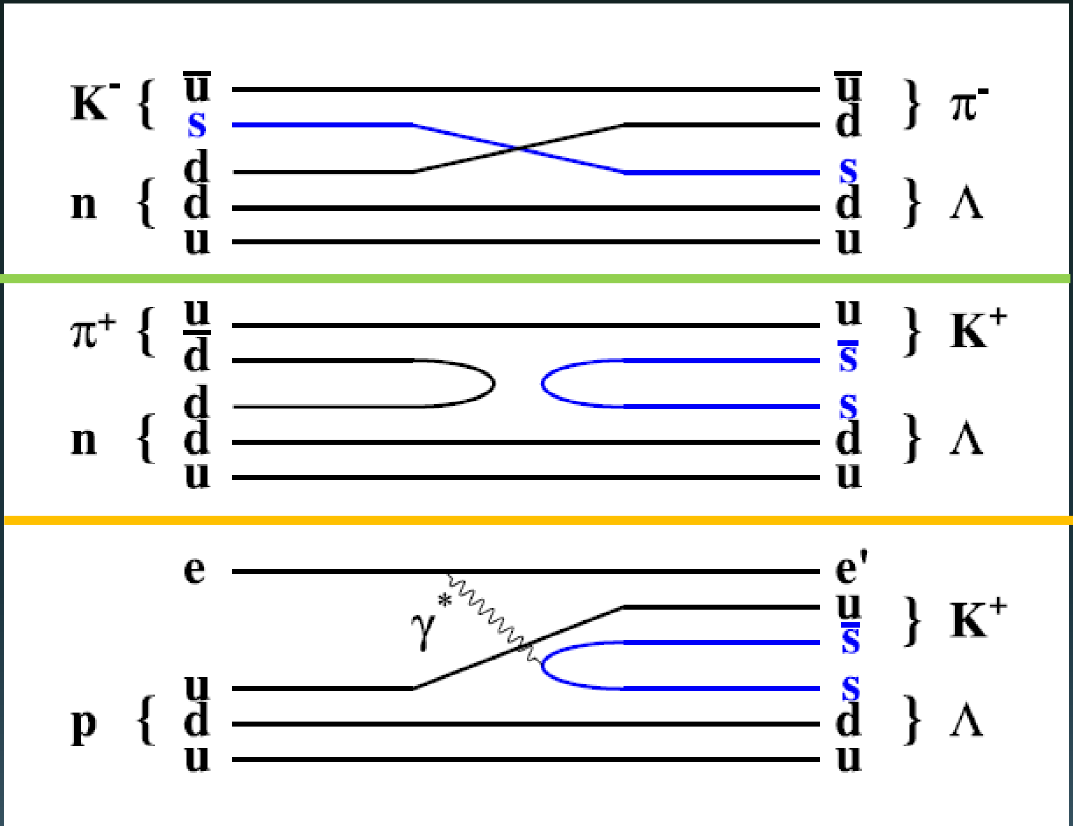
$s, \bar{s}$ pair creation

(π⁺,K⁺)

(e,e'K⁺)

Small C.S.

Large ***q***



n to Λ

No ^{7}He target

~~^{7}He(K⁻,π⁻) $^{7}_{\Lambda}$He~~

~~^{7}He(π⁺,K⁺) $^{7}_{\Lambda}$He~~

p to Λ

^{7}Li(e,e'K) $^{7}_{\Lambda}$He

Spectroscopic techniques of Hypernuclei

Method	Resolution	Absolute E	Yield	comments
(e,e'K$^+$)	0.5 MeV	◎	× 100nb/sr	$p \rightarrow \Lambda$
(π^+,K$^+$)	1.5 – 2 MeV	○ (norm $^{12}_{\Lambda}$C)	○ 10μb/sr	$n \rightarrow \Lambda$
(K$^-$, π^-)	~2 MeV	○ (norm $^{12}_{\Lambda}$C)	◎ 10mb/sr	$n \rightarrow \Lambda$
γ-ray	0.003 MeV	×	-	-
Decay π	0.1 MeV	○ (only g.s.)	-	Fragments

Characteristics of (e,e'K$^+$) HY study

- Electromagnetic production
- Convert Proton to Lambda :

  Mirror to well studied HY by (π,K), (K, π)

  Absolute energy calibration

  with Λ and Σ^0 masses

- High quality primary beam

  High energy resolution (< 1MeV)

  Thin enriched target

Challenge of (e,e'K) HY Study

- Huge e' Background due to

  Bremsstrahlung and Mϕller scattering

  Signal/Noise, Detector

- Less Hypernuclear Cross Section
- Coincidence Measurement (e', K^+)

  Limited Statistics

  DC beam is necessary

High Quality Electron Beam is Essential !

Hypernuclear experiments at JLab

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

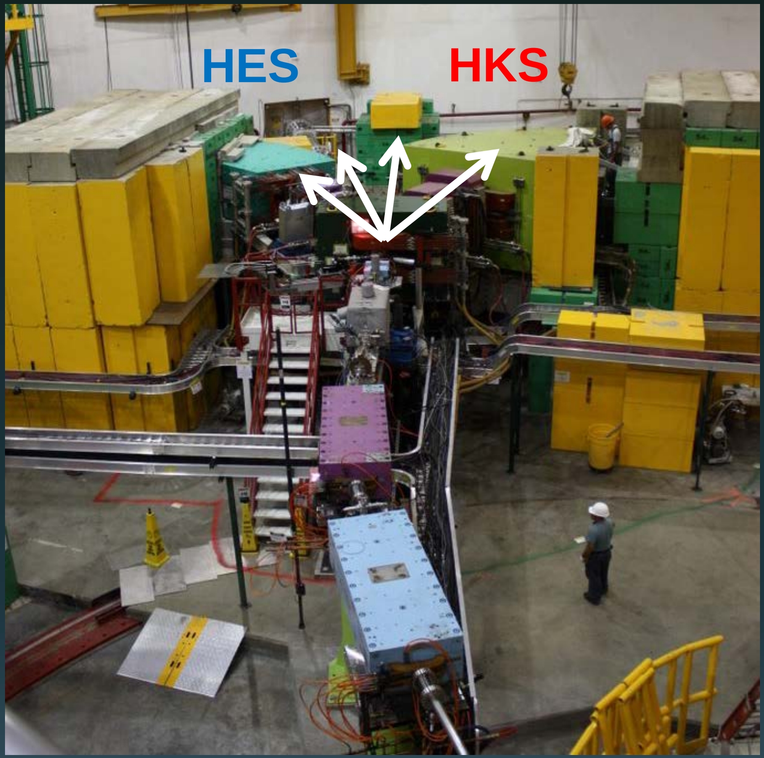
E94-107 (2004-5)
Two HRSs + SC Septum
Λ, Σ^0, $^{9}_{\Lambda}$Li, $^{12}_{\Lambda}$B, $^{16}_{\Lambda}$N

Light Hypernuclei

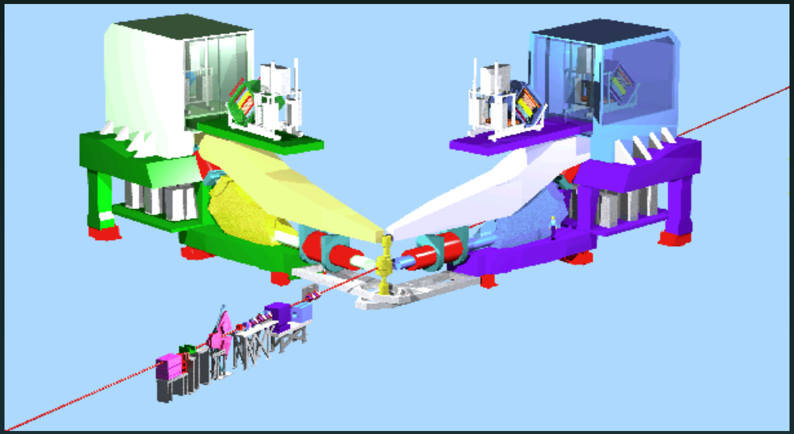
E05-115 (2009) :
HKS+HES, new Chicane beamline, Splitter
Λ, Σ^0, $^{7}_{\Lambda}$He , $^{12}_{\Lambda}$B, $^{52}_{\Lambda}$V

Light to medium-heavy Hypernuclei

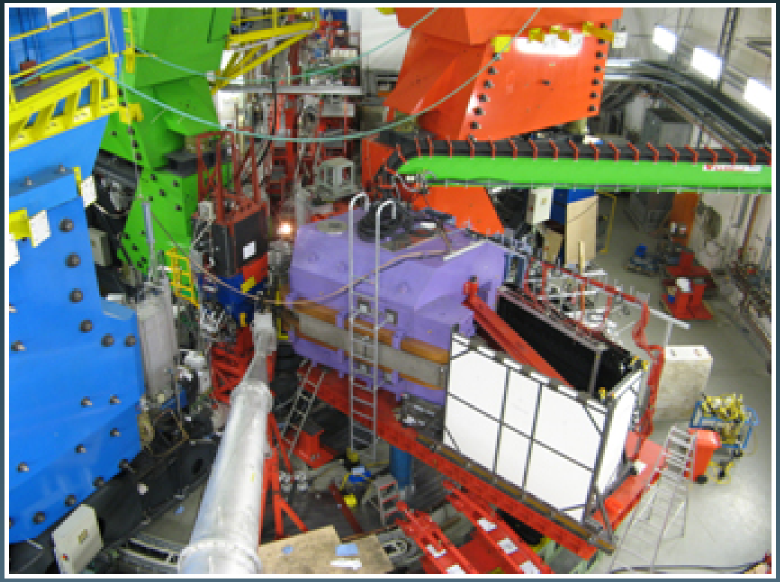
Facilities for (e,e'K$^+$) HY study



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

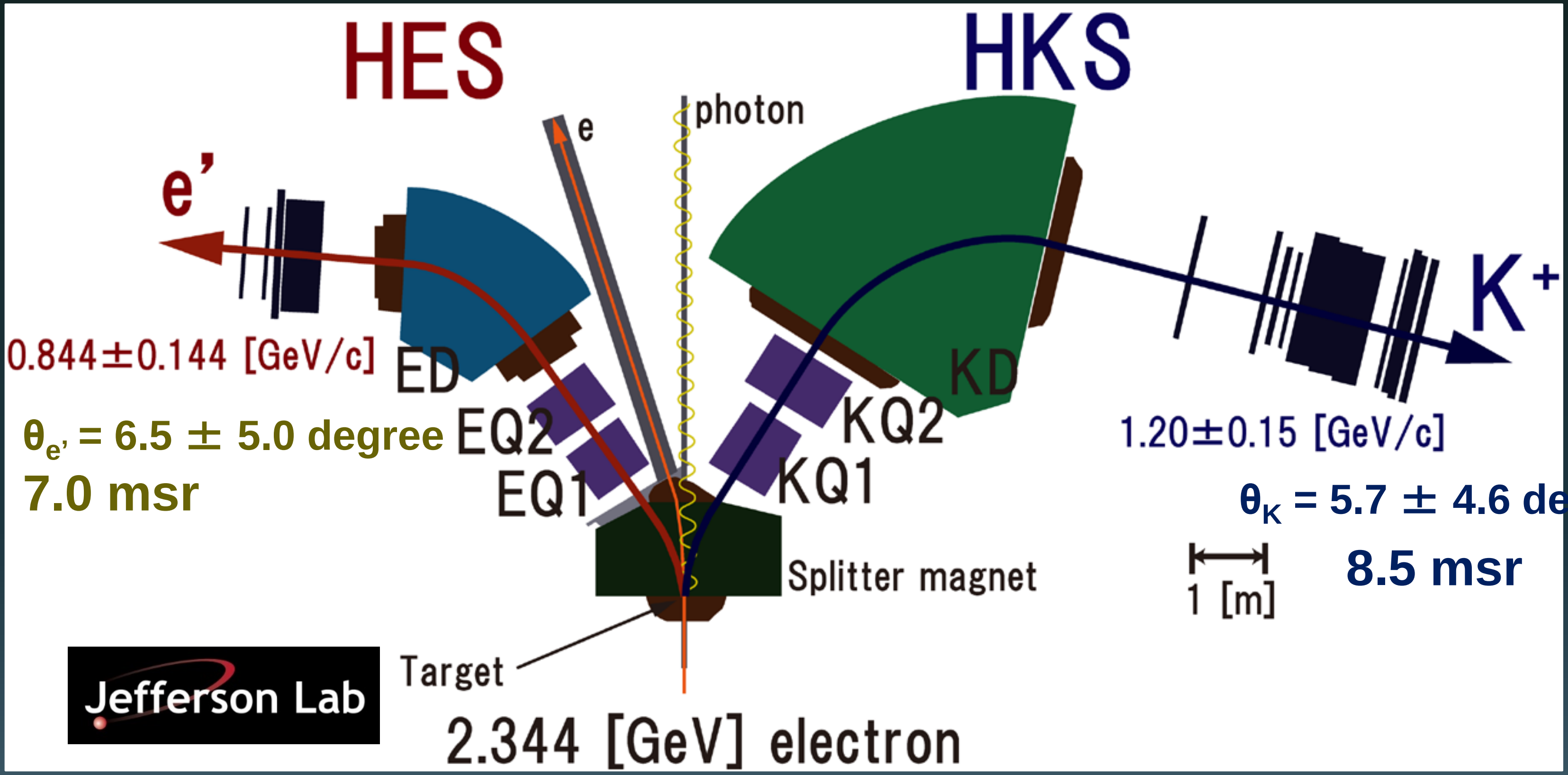


JLab Hall-A HRS+HRS (2004)



Mainz MAMI-C A1 KaoS (2008-)

JLab E05-115 (Hall-C) setup



$\theta_{e'}$ = 6.5 ± 5.0 degree

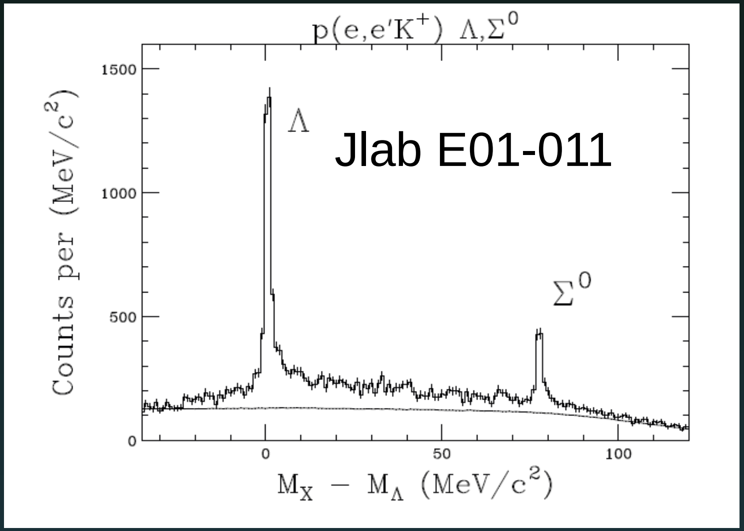
7.0 msr

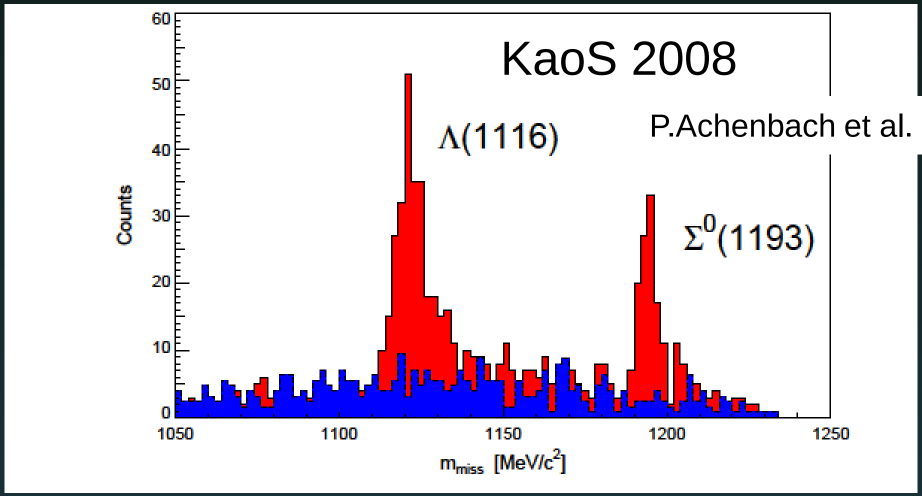
θ_K = 5.7 ± 4.6 degree

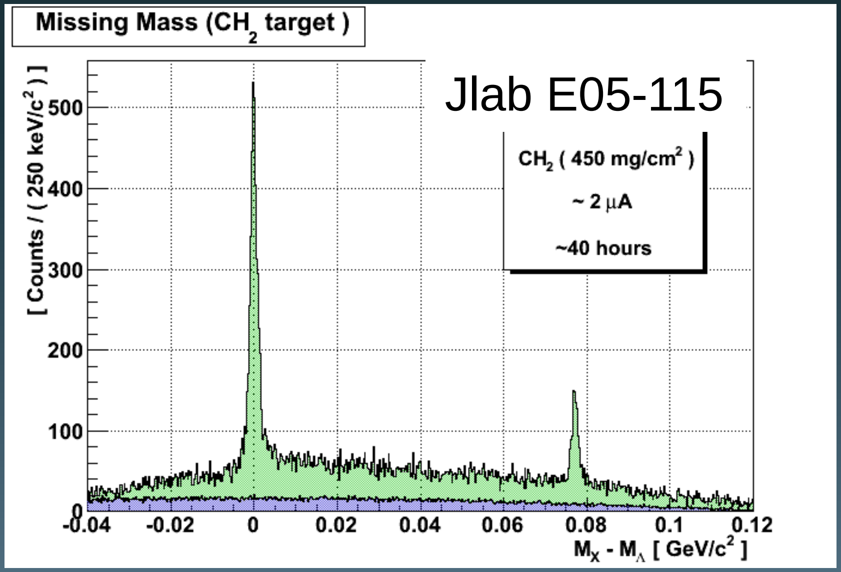
8.5 msr

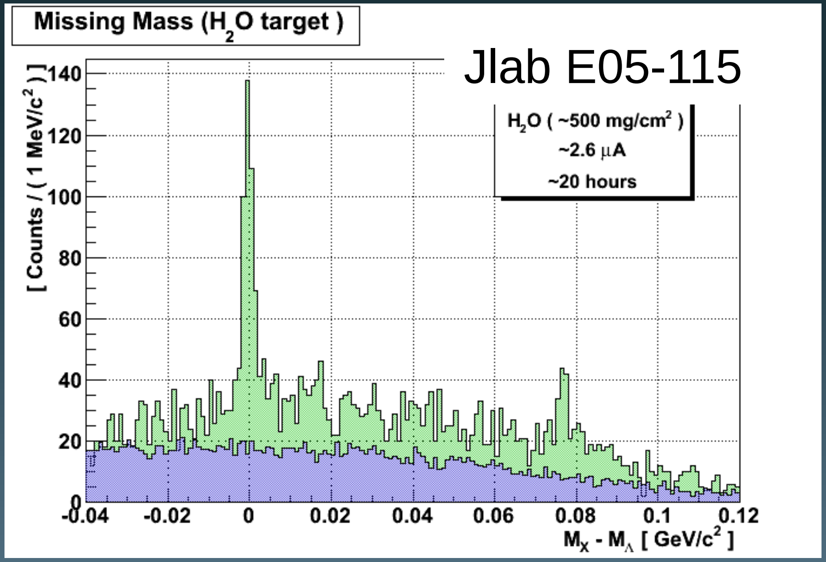
$\Delta p/p \sim 2 \times 10^{-4}$

p(e,e'K⁺)Λ, Σ⁰: Elementary Process

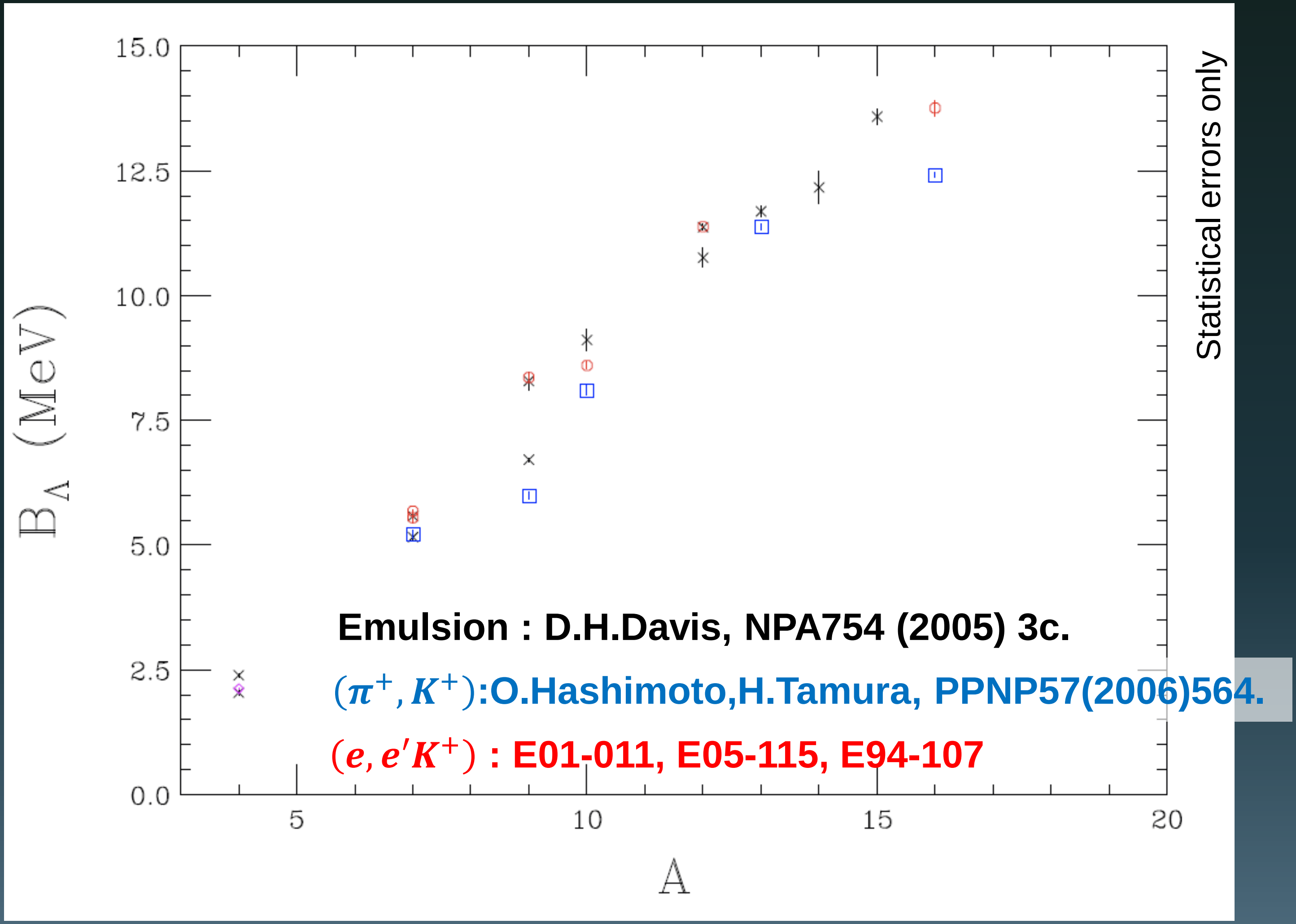




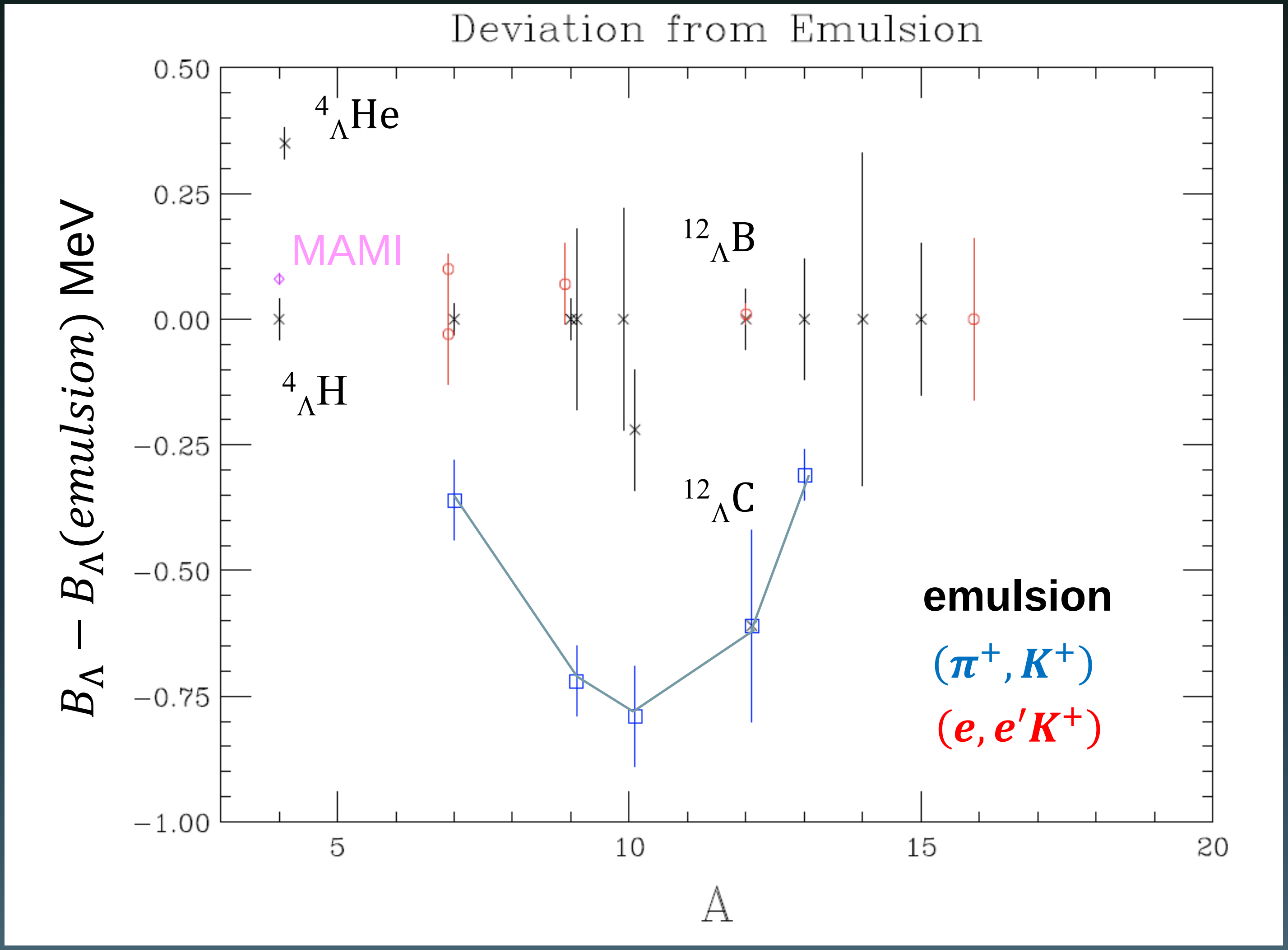




Mass dependence of B_Λ



Remove apparent A dependence



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

0.5 MeV (FWHM)

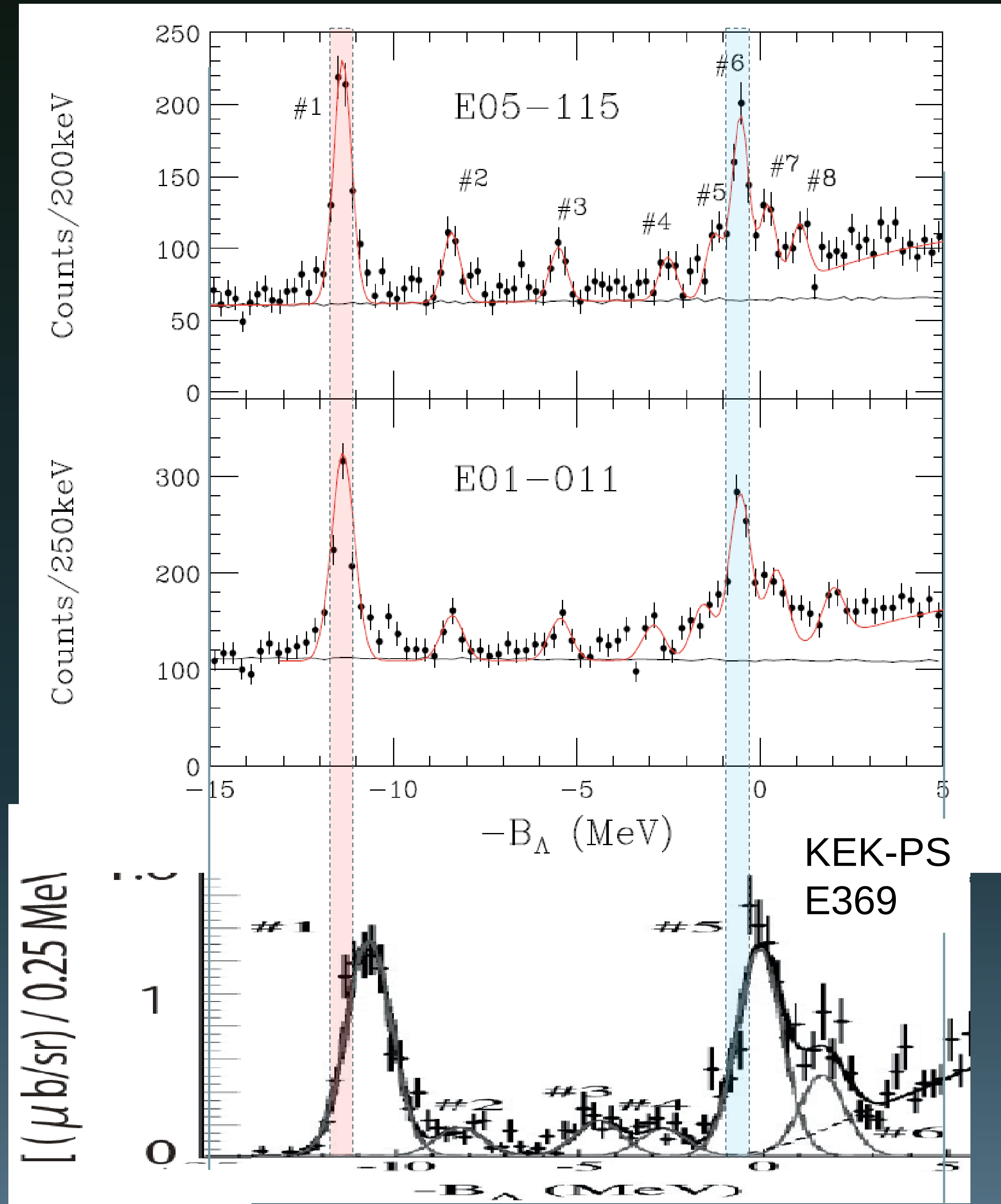
Absolute MM calibration

0.7 MeV (FWHM)

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

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.	$^{12}_{\Lambda}C \rightarrow \pi^- + p + {}^4He + {}^7Be$	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 $^{12}_{\Lambda}C$: ($\pi^- {}^{12}N$), ($\pi^- p {}^{11}C$), ($\pi^- p {}^3He {}^4He {}^4He$) and ($\pi^- p {}^4He {}^7Be$). 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 ($^{12}{}_{\Lambda}C$g.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 ($A \leq 15$)

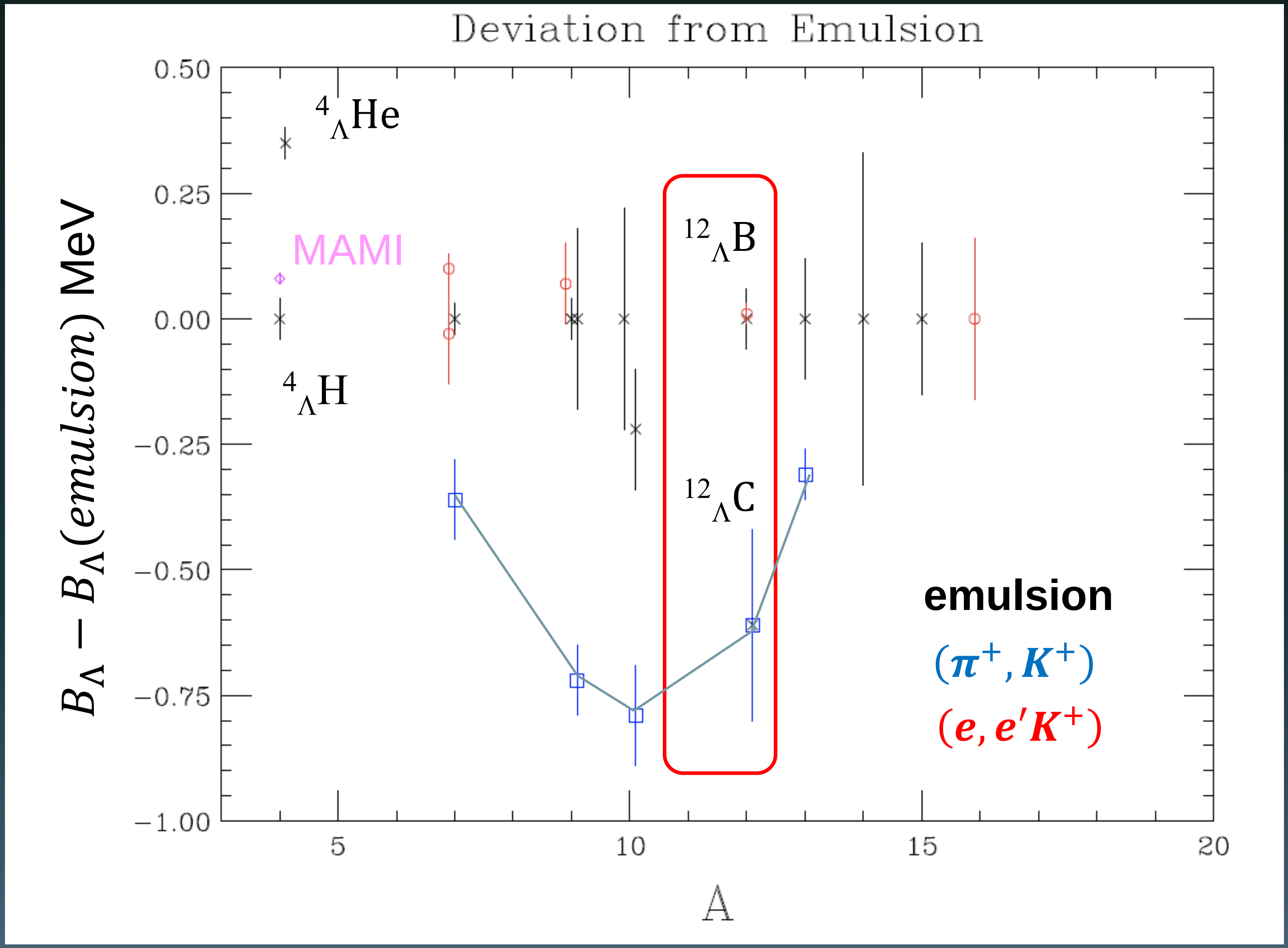
		(# of events)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

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

B_{Λ} ($^{12}{}_{\Lambda}B$g.s.) = 11.38 +- 0.02 (stat) MeV (JLab E05-115)

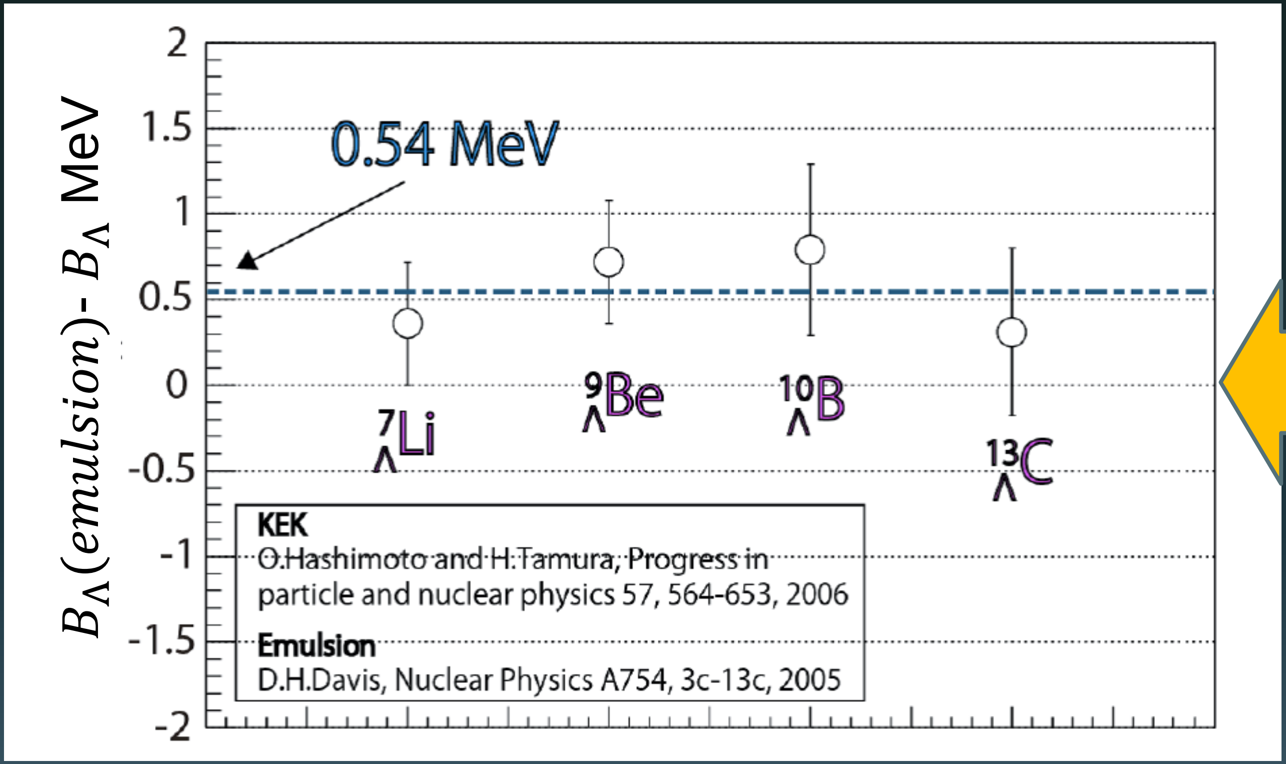
Totally independent measurement

Remove apparent A dependence



Possible shift of $^{12}{}_{\Lambda}C_{gs}$ B_{Λ}

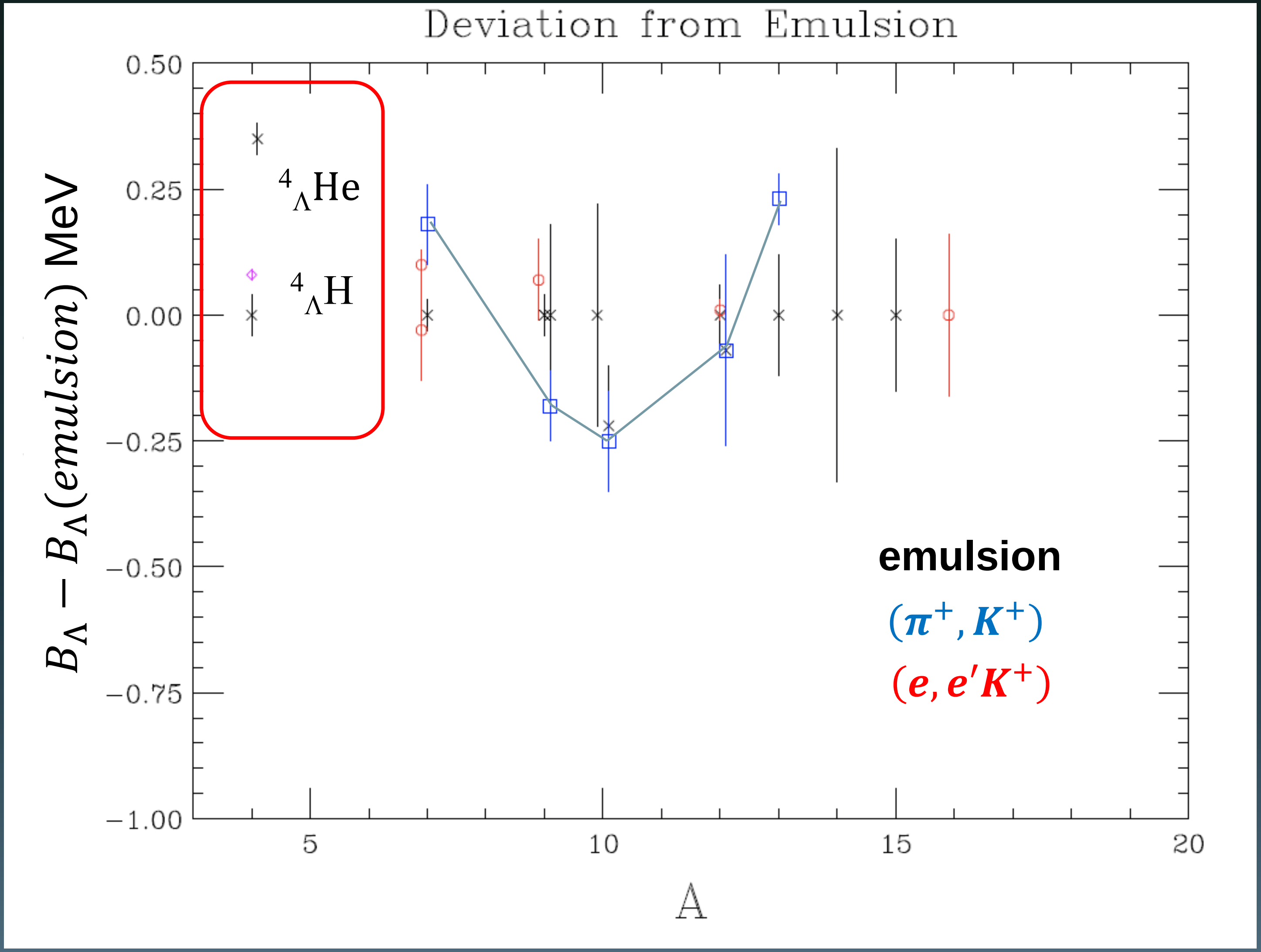
$^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$	-0.57 ± 0.19 $-0.62 \pm 0.19 \pm 0.11$	$^{12}_{\Lambda}\mathrm{C}$: 6 events, $^{12}_{\Lambda}\mathrm{B}$: 87 events present data for $^{12}_{\Lambda}\mathrm{B}$



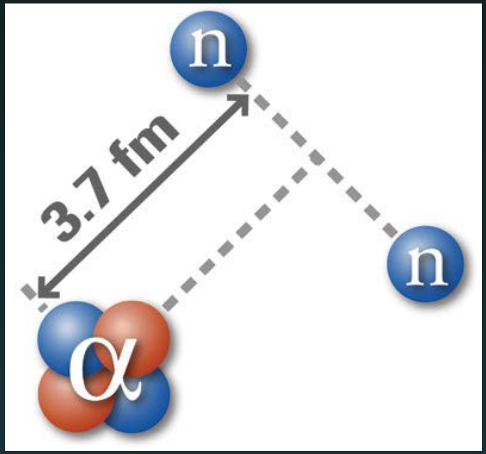
Should be 0

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

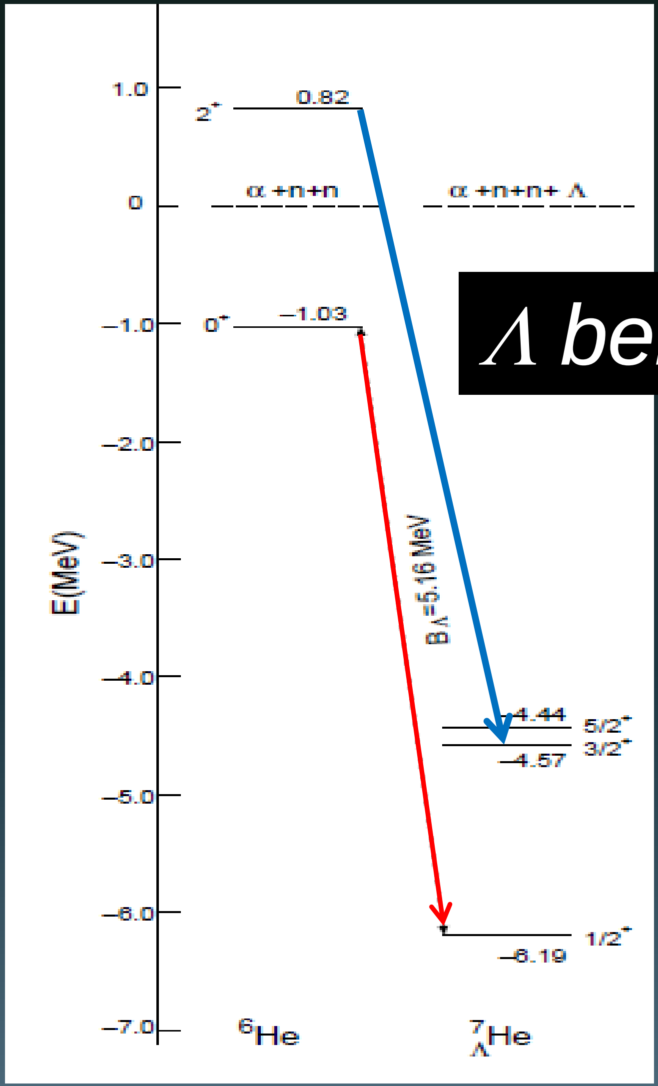
Shift $^{12}_{\Lambda}C_{gs}$ B_{Λ} by 0.54 MeV



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



${}^{6}He$: 2n halo

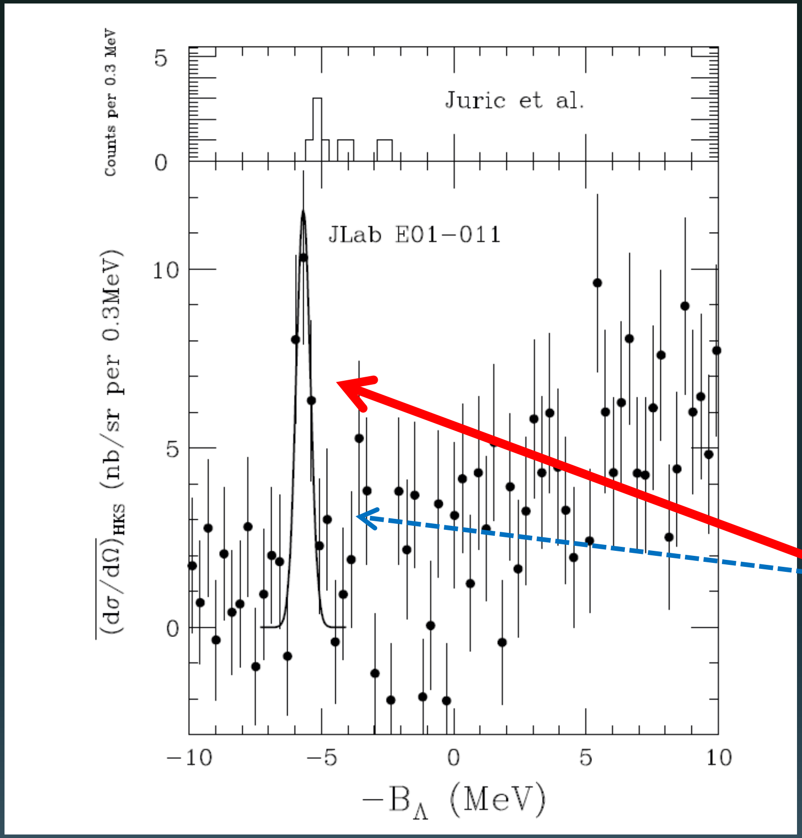


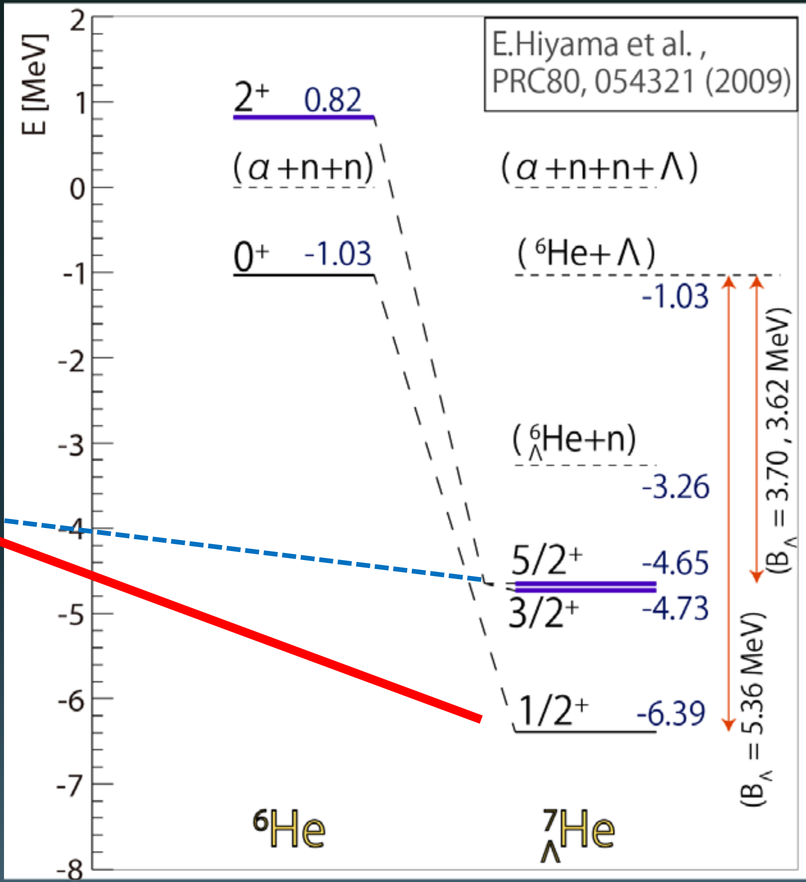
Λ behaves like glue

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

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

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





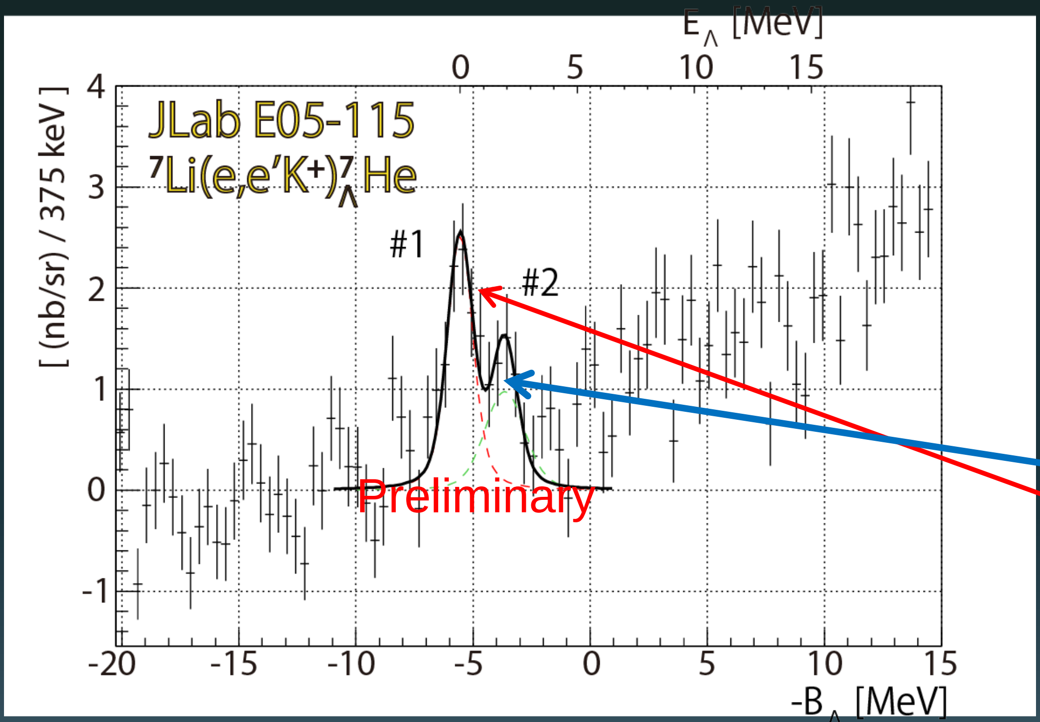
E01-011(HKS) 90 counts

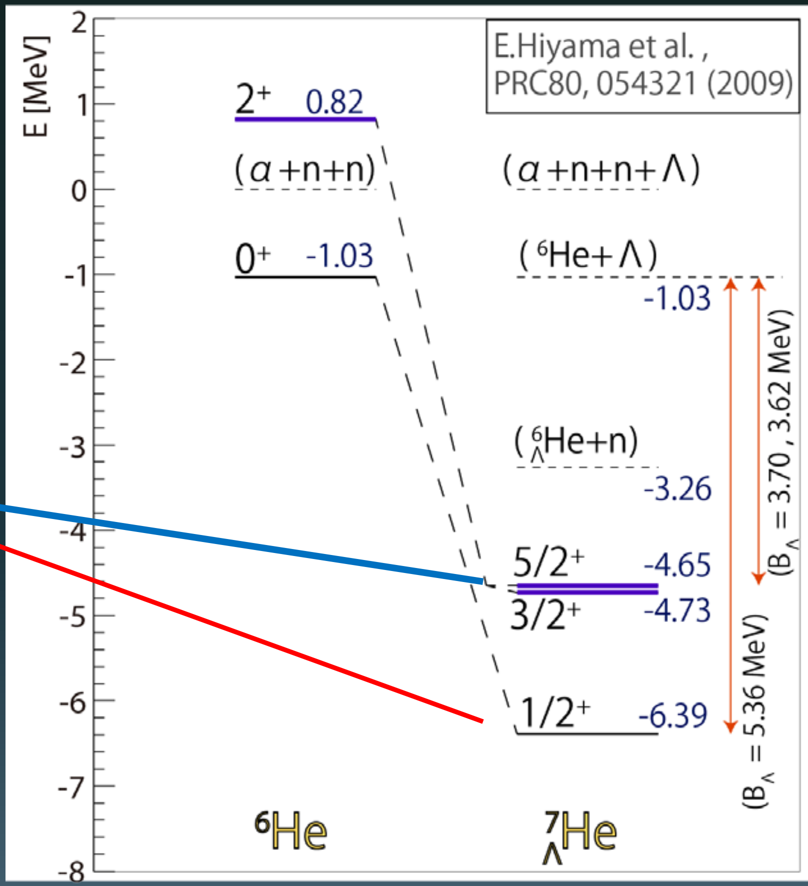
E05-115(HKS-HES) >500 counts

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.





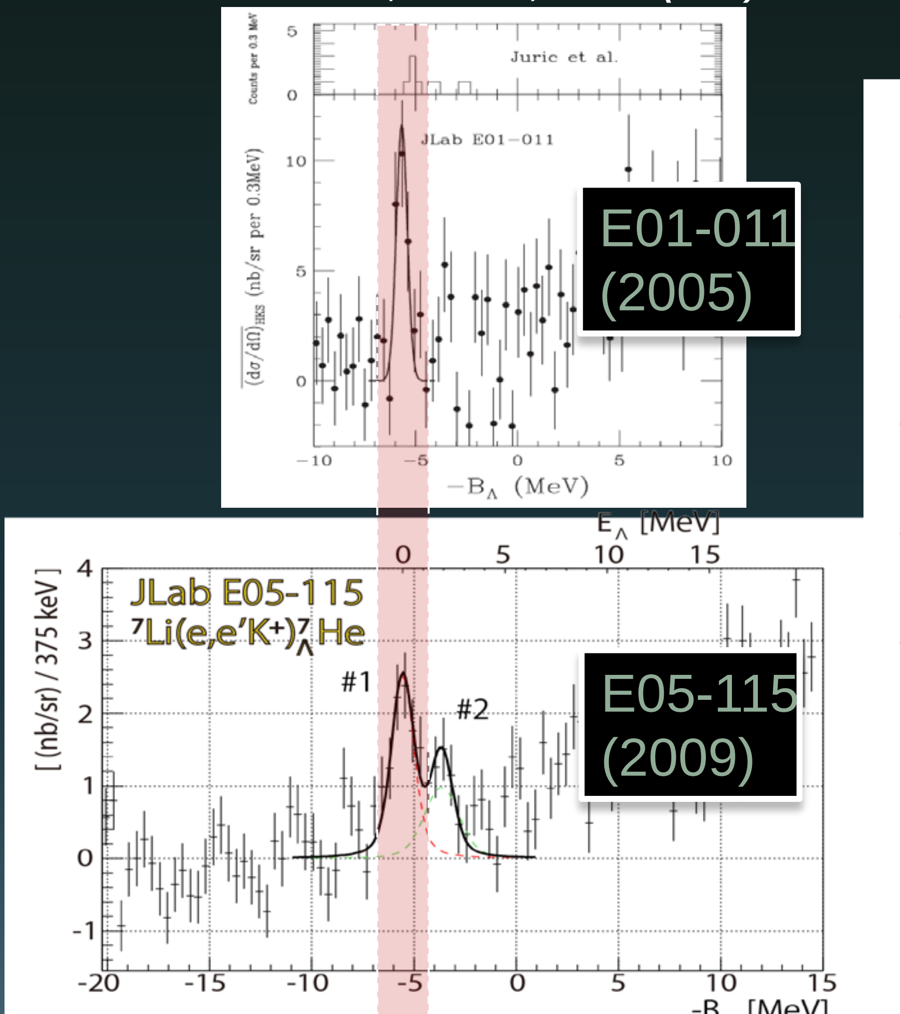
E01-011(HKS) 90 counts

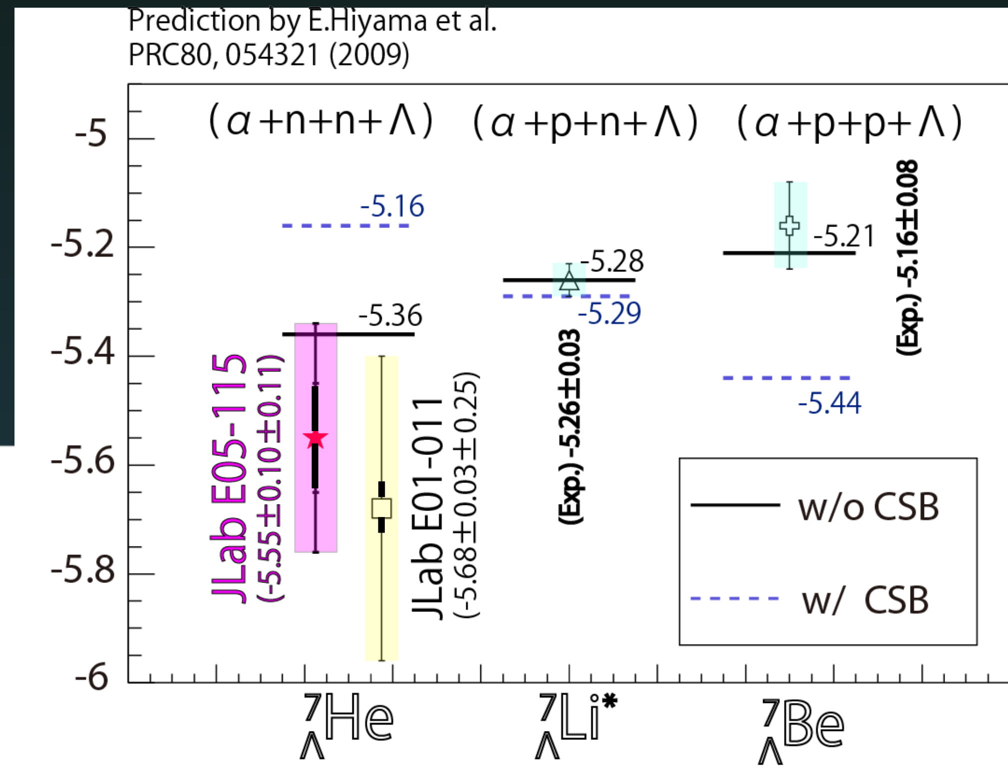
E05-115(HKS-HES) >500 counts

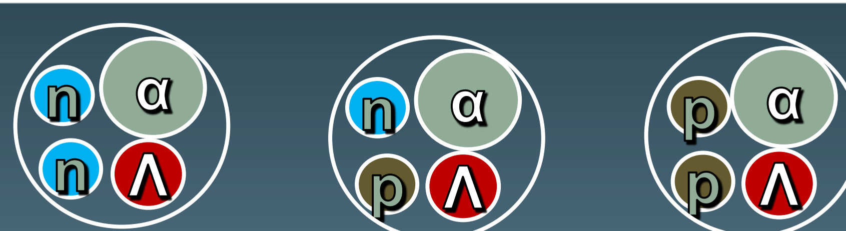
unbound ^{6}He excited state + Λ = bound $^{7}_{\Lambda}$He excited state

CSB interaction test in A=7 iso-triplet comparison

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

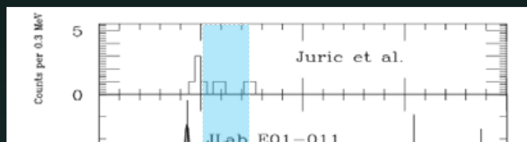




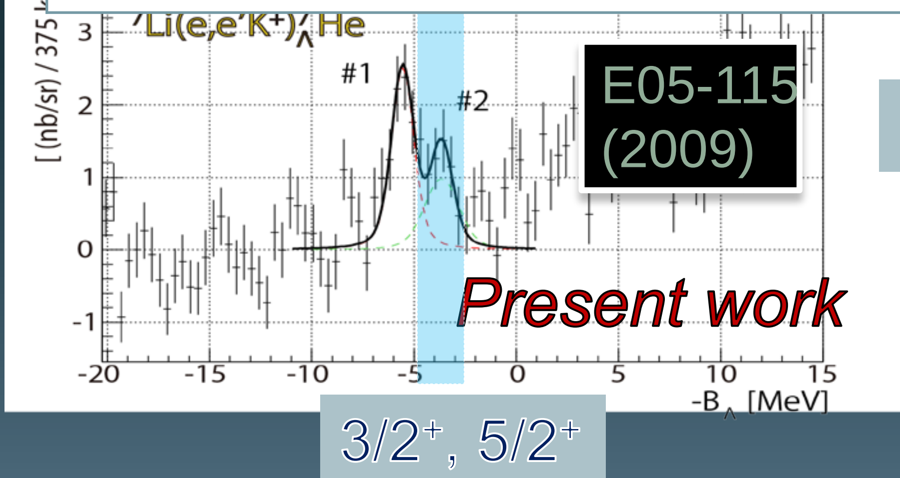


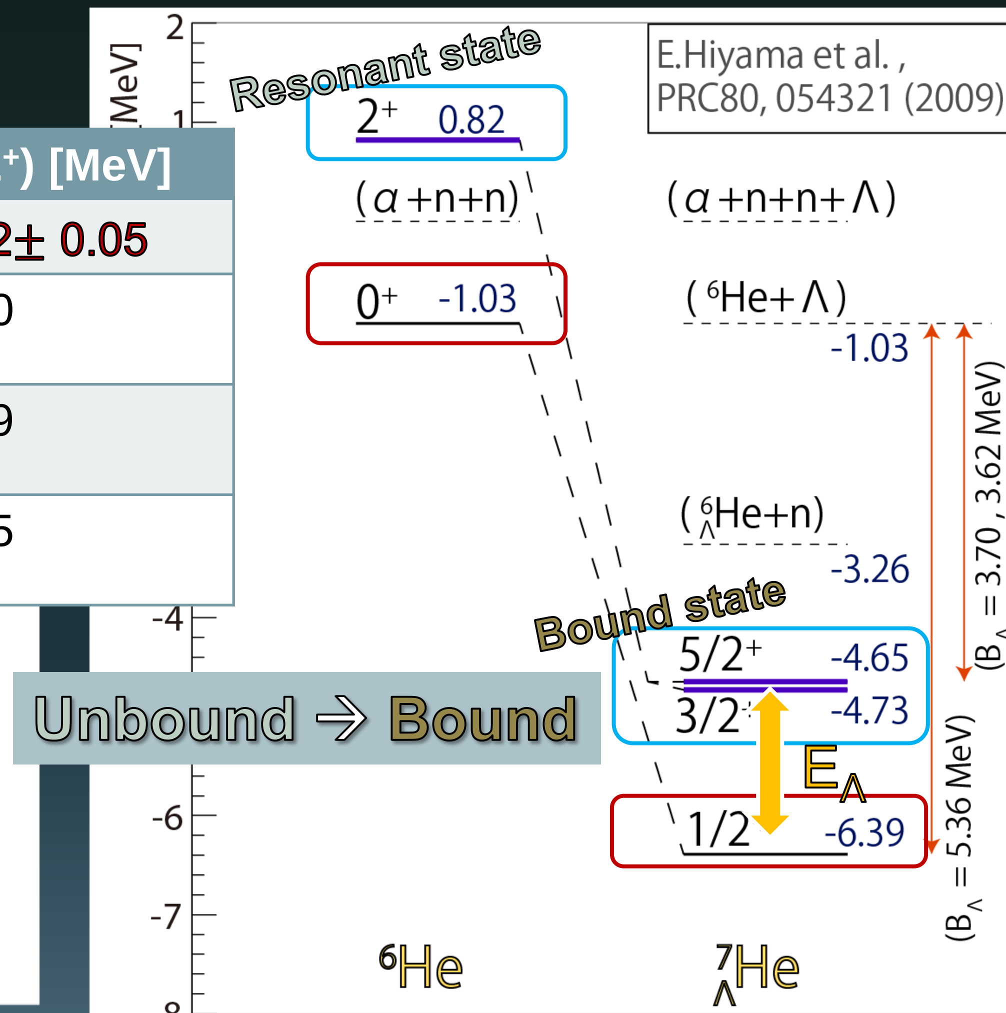
T.Gogami, Doctor Thesis (2014) Tohoku Univ.

CSB interaction test in A=7 iso-triplet comparison



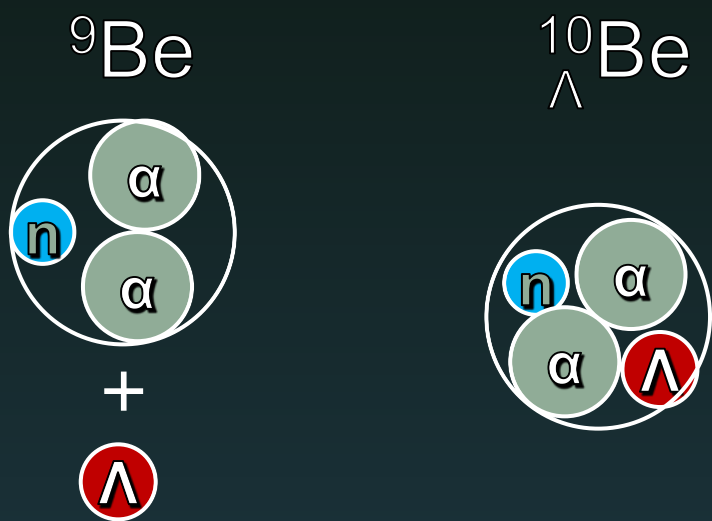
	E_Λ ($3/2^+$,$5/2^+$) [MeV]
JLab E05-115	**1.90±0.22± 0.05**
E.Hiyama et al., PRC 80, 054321 (2009)	1.70
M.Sotona et al., PTP 117 (1994)	1.79
D.J.Millener Private communication	1.75

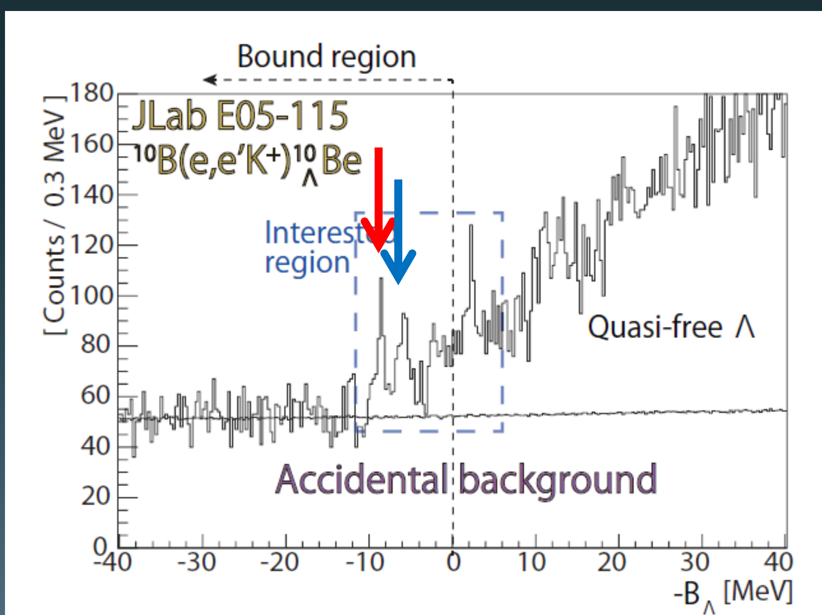


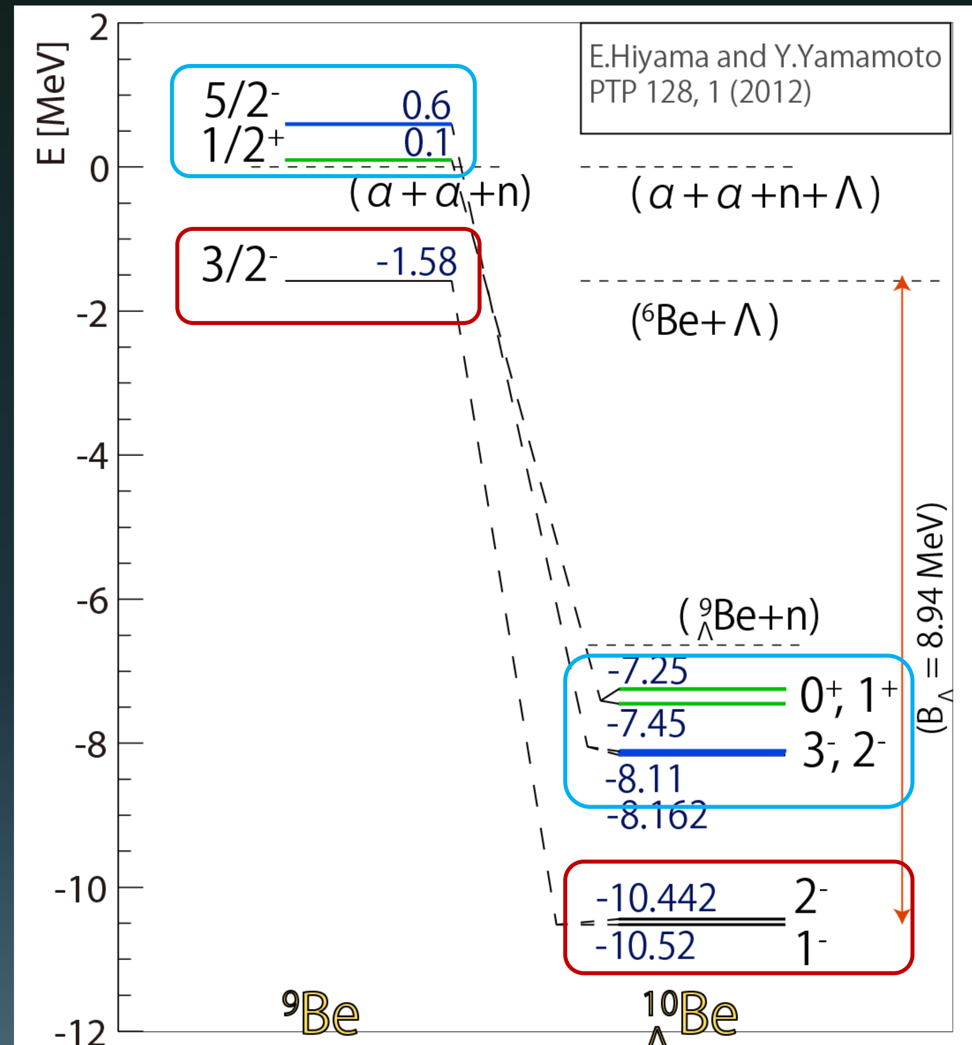


T.Gogami, Doctor Thesis (2014) Tohoku Univ.

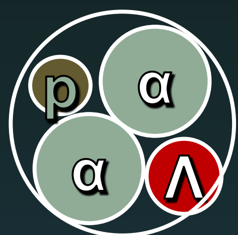
$^{10}B(e,e'K^+)^{10}_{\Lambda}Be$



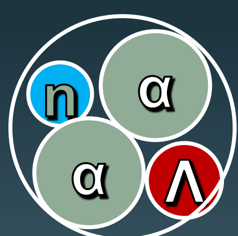




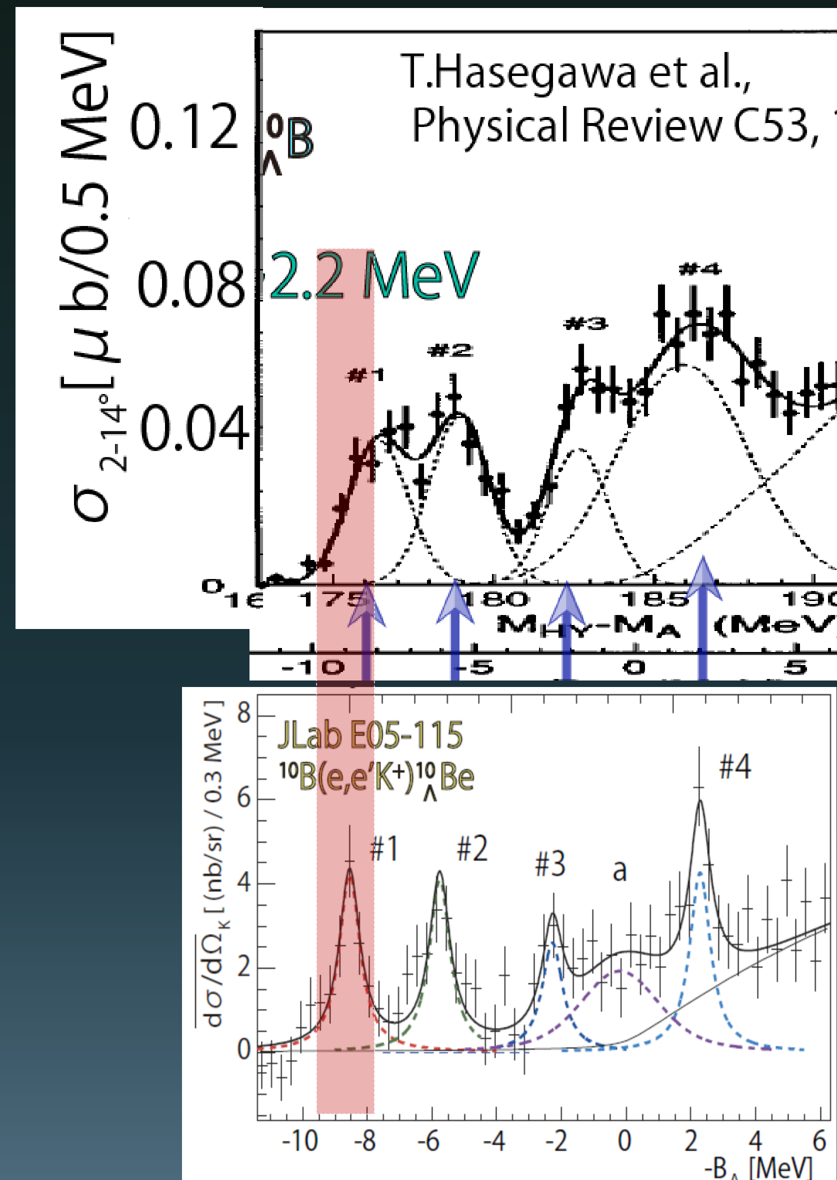
$^{10}{}_{\Lambda}$B and $^{10}{}_{\Lambda}$Be



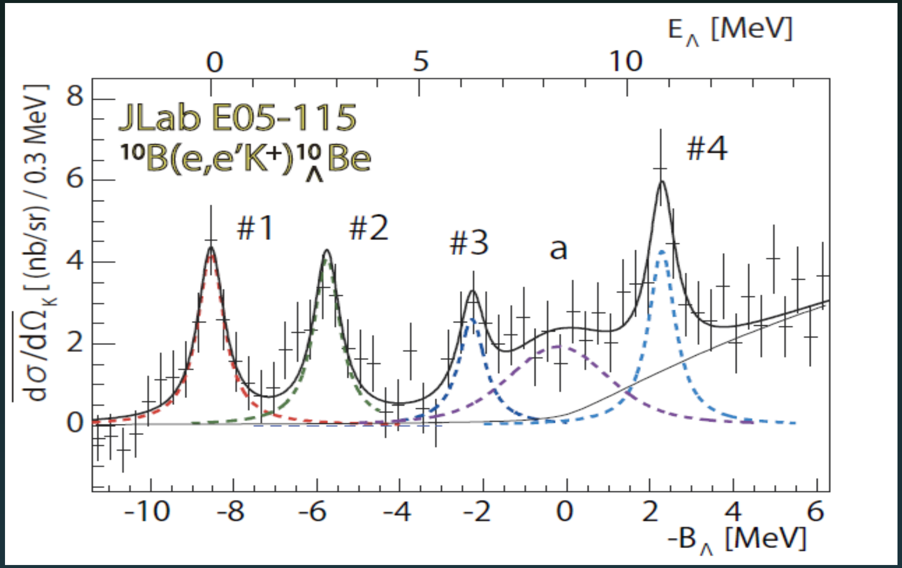
$^{10}_{\Lambda}$B

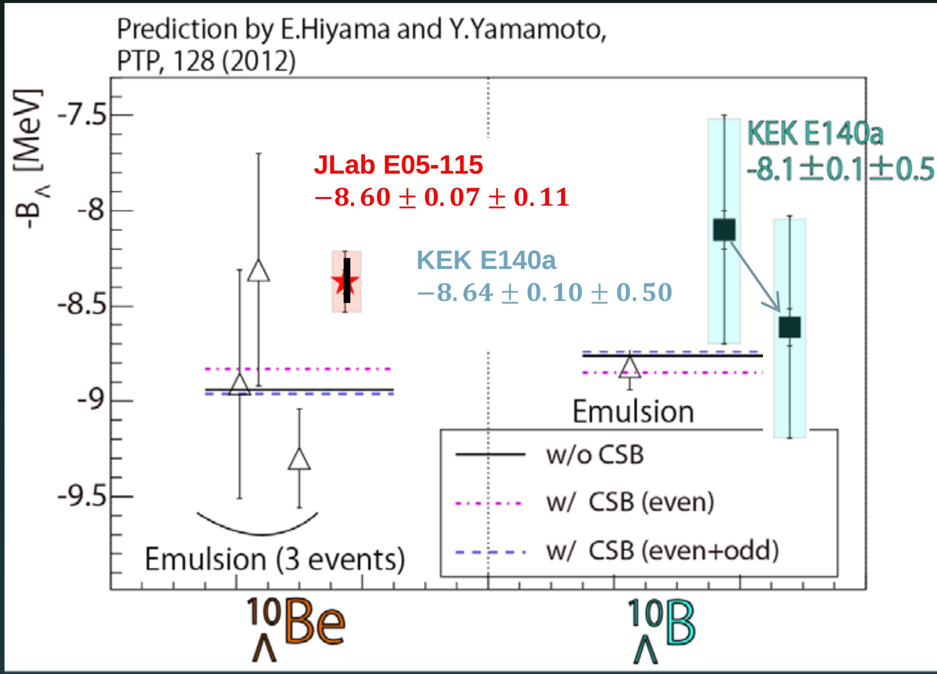


$^{10}_{\Lambda}$Be



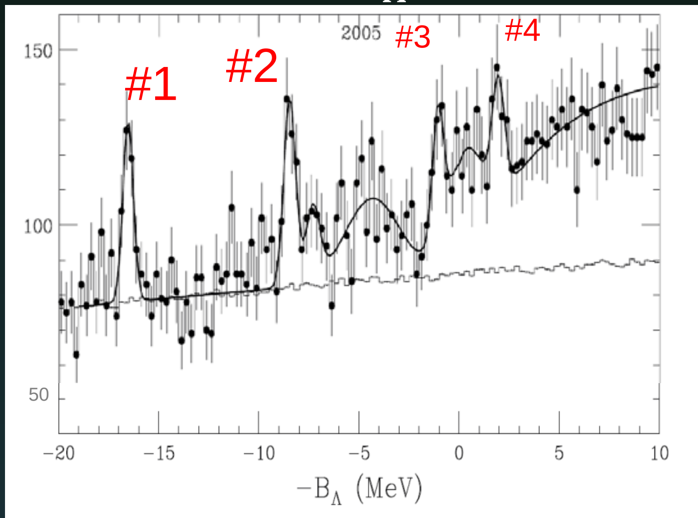
Comparison of the ground states (A=10)

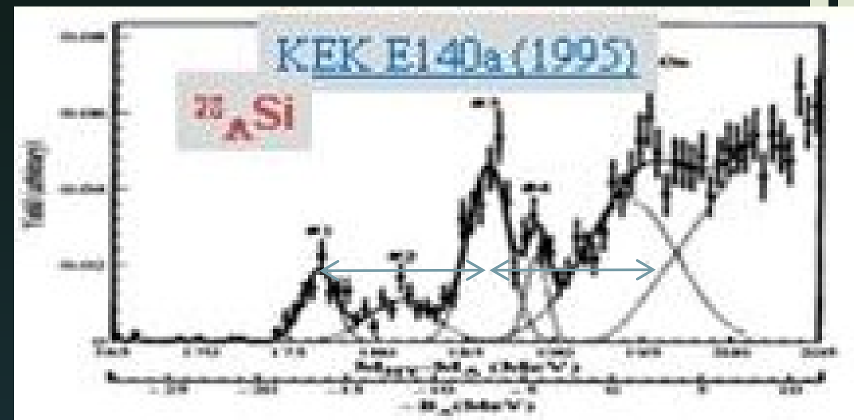


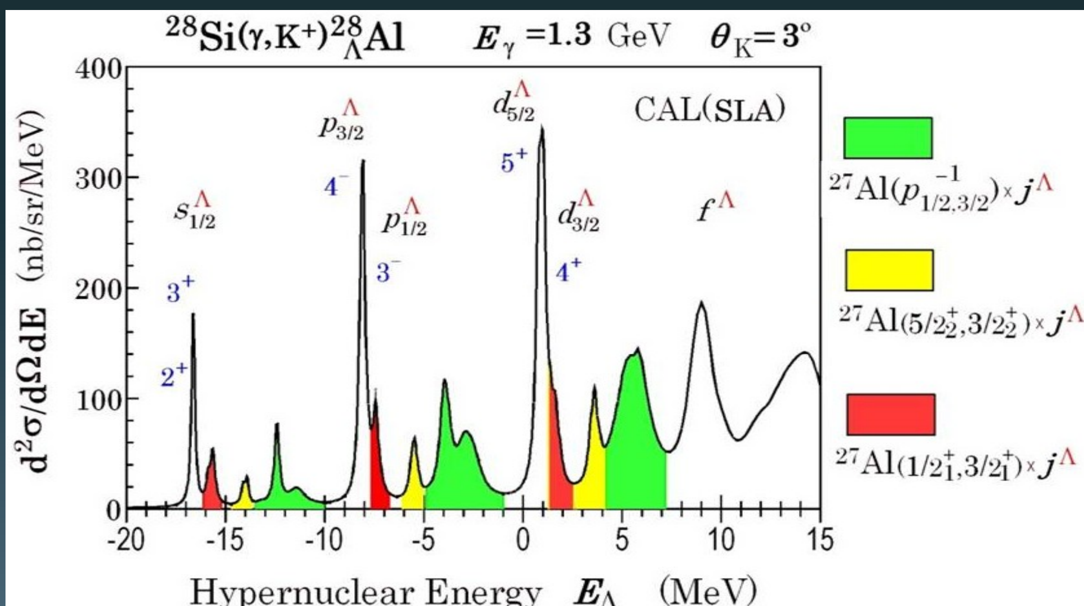


$^{28}_{\Lambda}Al$, first beyond p-shell hypernucleus by (e,eK)

$^{28}\mathrm{Si}(e,e'K^+)^{28}_{\Lambda}\mathrm{Al}$



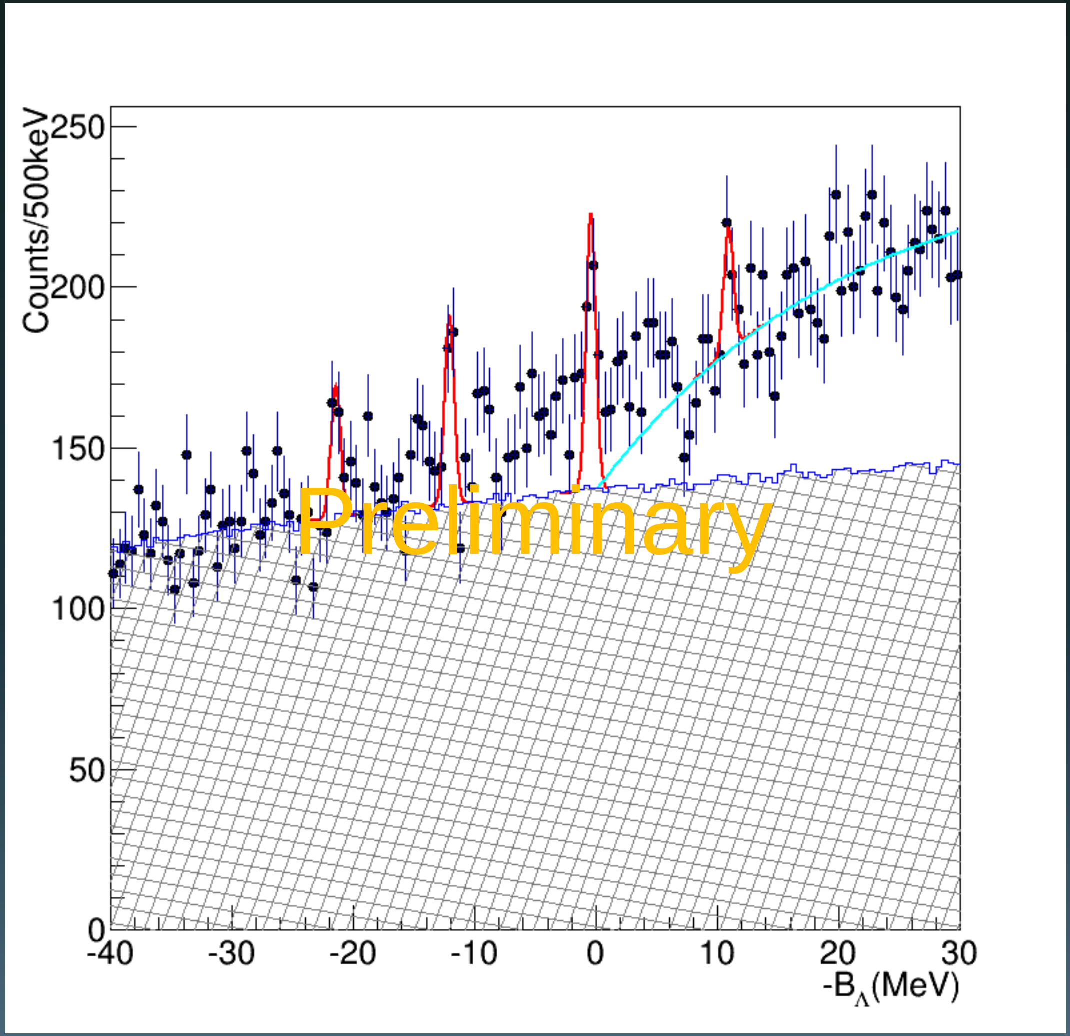




T.Motoba, JLab Hypernuclear WS (2014)

peak	B_Λ (MeV)
#1	-16.5
#2	-8.5
#3	-1.1
#4	+1.9

$$^{52}\mathrm{Cr}(e,e'K^+)^{52}_{\Lambda}\mathrm{V}$$



peak	B_{Λ} (MeV)
#1	-21.4
#2	-12.1
#3	-0.4
#4	+10.9

Summary

- We have been developing large magnetic spectrometers and new techniques in the last decade at JLab.

  The (e,e'K) HY spectroscopy **is *now established*.**
- ***Absolute binding energy calibration*** is one of great advantage of the (e,e'K) HY spectroscopy .
- 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 $^{10}_{\Lambda}Be$ was obtained.
- $^{28}_{\Lambda}Al$, $^{52}_{\Lambda}V$ spectra are getting finalized.
- **New experiment is now designed and proposed to JLab (C12-15-008).**

Hypernuclear study with electrons (JLab, Mainz) and with mesons (J-PARC) should progress complimentary in timely manner.