15 March 2016

THE 2ND JLAB HYPERNUCLEAR WORKSHOP

Introduction and Highlights of hypernuclear study at JLab

Satoshi N. Nakamura
Tohoku University

1^{st} JLab Hypernuclear WS

May 27-29, 2014 , We discussed :

1. What is necessary to understand of the elementary process of electro-production of strangeness
2. Experimental study of light hypernuclei and YN interaction including Charge Symmetry Breaking (CSB) effect and ΛN- ΣN-coupling.
3. What can be learned from precise determination of Λ binding energies
4. Deformation of core-nucleus and energy levels of Λ hypernuclei
5. Detailed spectroscopy of heavy hypernuclei and potential impacts of measurement to mean-field theory, shell-models and single particle nature of Λ in deep inside of nuclei.
6. Uniqueness of JLab hypernuclear program in contrast to other facilities such as J-PARC, Mainz, future FAIR

Summary of 1st JLab Hyp. WS summary by H.Tamura

What can JLab answer?

My personal idea

Motivation ... physics

Elementary H(e,e'K+)Λ

BB interactions

Charge Symmetry Breaking

$^{4}_{\Lambda}$H pi decay, $^{4}_{\Lambda}$H* production,..

Impurity effect in nuclear structure

New means to clearly probe the exotic nuclear structure (e.g. triaxial deformation)

$^{27}_{\Lambda}$Mg

nadrons and nuclei from quarks

Properties and behavior of baryons in nuclei

μ_{Λ}

Study of high-density (strange) nuclear matter from s.p.e. of heavy Λ hypernuclei

e.g. $^{208}_{\Lambda}$Pb, A=50~100, $^{27}_{\Lambda}$Mg

Needs more theoretical studies

51 days (1224h) option for high priority targets

Target	Purpose	High Priority (hours)
Engineering	Beam, target, spectrometers, detectors DAQ	1 calendar month
Calibrations Various targets	Optics, kinematics, absolute energy scale	**167**
Physics I : Few-body	**Direct ΛN int. study (CSB,FSI)**	
^{4}He ($^{4}_{\Lambda}$H)	CSB for A=4 system	**177**
H_2 (Λ, Σ^0)	Elementary, calibration	35
D_2 and ^{3}He ($^{2}_{\Lambda}$n, $^{3}_{\Lambda}$H)	ΛN int. study through FSI	140
~~^{3}T ($^{3}_{\Lambda}$n)~~	~~Exotic bound state search~~	
Subtotal		352
Physics II : Mid-Heavy	**3B force study – EoS w/ Y**	
^{40}Ca ($^{40}_{\Lambda}$K)	High prec. exp. Reliable Calc.	**103**
~~^{48}Ca ($^{48}_{\Lambda}$K)~~	~~Iso-spin dep.~~	
^{89}Y ($^{89}_{\Lambda}$Sr)	Heavy HY	**124**
^{208}Pb ($^{208}_{\Lambda}$Tl)	Heaviest HY	**478**
Subtotal		705
Total	Fit in 51 PAC days (1224h)	**1224**

Proposal submitted to PAC43

A study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

C12-15-008 : Conditionally approved (C2)

Issues: The PAC views the most compelling science presented as the measurements of binding energy of the medium mass nuclei $^{48}\Lambda K$ and $^{40}\Lambda K$. It is these measurements, along with the calibration measurements, that are conditionally approved. The PAC believes there should be a strong connection between understanding the ΛNN force and the 2 solar mass neutron star observations. However, the science case even for these measurements still needs refinement, and the connection has not been well articulated. Theoretical calculations are possible in the 40,48 nuclei, as well as in neutron matter. While AFDMC (Pederiva et al, arXiv:1506.04042) calculations have been performed with simplified interactions (AV4' + one term in UIX, and a ΛN and ΛNN interaction), a more complete picture may be feasibly obtained. Even using the simplified interaction in AFDMC, the calculations indicate that the tensor parameter could be well constrained by a measurement of BΛ in an asymmetric nucleus. This argument should be strengthened and explored, possibly by a workshop. The PAC believes the collaboration would benefit from a more integrated theoretical effort in this area.

Summary:
The collaboration should submit an updated proposal to study $^{48}\Lambda K$ and $^{40}\Lambda K$ along with a stronger theoretical connection to neutron star physics.
The PAC is not convinced that measurements of the A dependence of BΛ will provide meaningful input to theoretical calculations of the equation of state for neutron stars. Therefore the ^{208}Pb measurements and other parts of this proposed work, including CSB efforts, are deferred. Completely new proposals would need to be submitted to the PAC in order to address these additional physics topics.

Goal of this workshop

To fullfill PAC43 requrements:

- Stronger *theoretical* connection between iso-spin dependence (eg. $^{40}{}_{\Lambda}K$, $^{48}{}_{\Lambda}K$) and NS.

  Other possibilities of targets?
  How to deduce NS information from HY experiments.

- PAC43 was not convinced that A dependence measurements give meaningful inputs to NS EoS. *Do we agree about this?*
  Any other meaning of heavy HY study?

- Do recent progresses about A=4 CSB from MAMI and J-PARC affect our strategy for a few body programs?

Discussion about strategy for future hypernuclear programs at JLab.

The 2nd JLab Hypernuclear Workshop

8:00am - 8:30am	Opening and Highlights of Hypernuclear Study at JLab	Nakamura (Tohoku)
8:30am - 9:00am	AMD Calculations of **Medium**/**Heavy** Hypernuclei with the ΛNN Three-Body Force in the Nijmegen Potential	Isaka (RIKEN)
9:00am - 9:30am	Perspectives of ab Initio Computations of **Medium**/**Heavy** Hypernuclei	Pederiva (Trento)
9:30am - 10:00am	AFDMC Calculations on **Medium-Heavy** Hypernuclei	Lonardoni (ANL)
10:00am - 10:20am	*Coffee Break*	
10:20am - 10:50am	Proposal of Spectroscopic Study of **Medium Heavy** Hypernuclei	Nakamura (Tohoku)
10:50am - 11:20am	Significance of Studies on **Light** Hypernuclei	Hiyama (RIKEN)
11:20am - 11:50am	Determining the Unknown Λ-n Interaction Through Study of Λnn Resonance	Gibson (LANL)
11:50am - 12:20pm	Recent Achievements at J-PARC and Future Prospects of Hypernuclear Study	Tamura (Tohoku)
12:20pm - 2:00pm	*Lunch Break - on your own*	
2:00pm - 2:30pm	Significance of Detailed Structure Study of **Hypernuclei**	Motoba (Osaka E-C Univ.)
2:30pm - 3:00pm	Extracting Hypernuclear Properties from the (e,e'K) **Cross Section**	Benhar (INFN Rome)
3:00pm - 3:30pm	Spectroscopic Study of **Light** Hypernuclei	Markowitz (FIU)
3:30pm - 4:00pm	Consideration of Experiments on ΛN Interactions and **Light** Hypernuclei at JLab	Tang (Hampton/JLab)
4:00pm - 4:30pm	Spectroscopic Study of **Heavy** Hypernuclei	Garibaldi (INFN Rome) and Silviu Covrig Dusa (JLab)
4:30pm - 4:50pm	*Coffee Break*	
4:50pm – 6:00pm	Open Discussions	

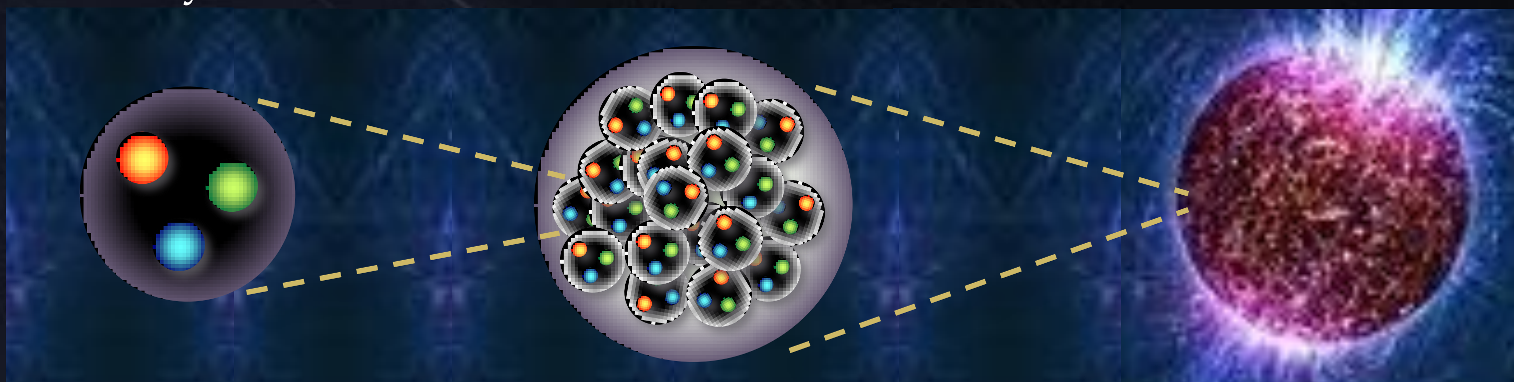
Highlights of hypernuclear study at JLab

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.

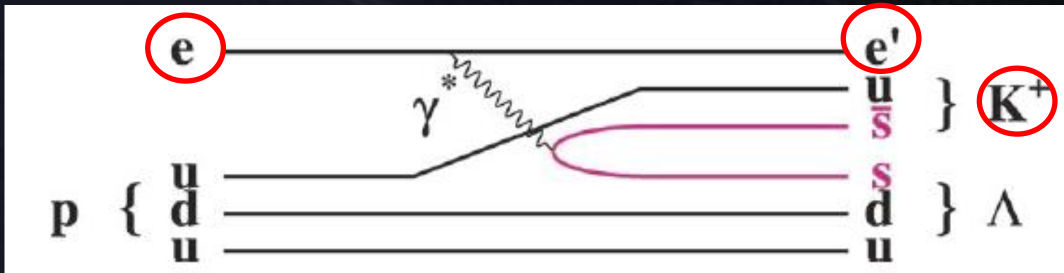
Obs. 2 $M_{\odot}$

Hyperon Puzzle

Baryon Interaction

LQCD

$(e,e'K^+)$ vs. others



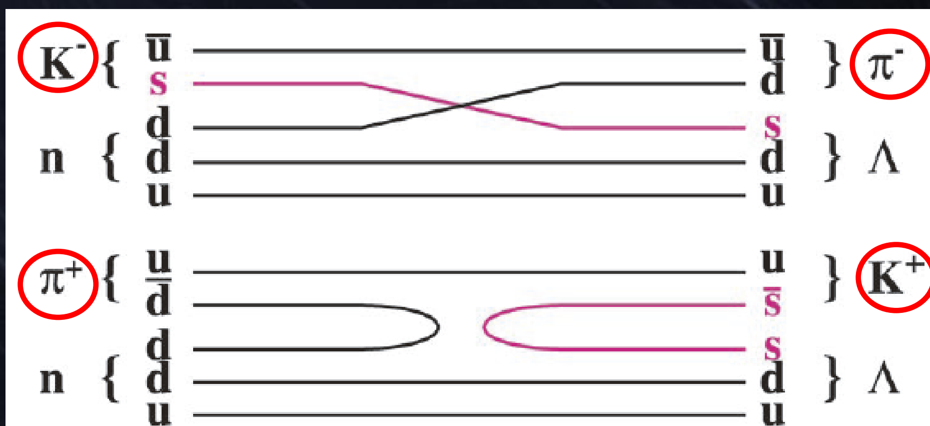
$(e,e'K^+)$

Excellent mass resolution

(~ 0.5 MeV)

Absolute energy calibration

$p(e,e'K^+)\ \Lambda, \Sigma^0$



(K^-, π^-)

(π^+, K^+)

1-2 MeV resolution
Normalized to $^{12}{}_{\Lambda}C$ mass

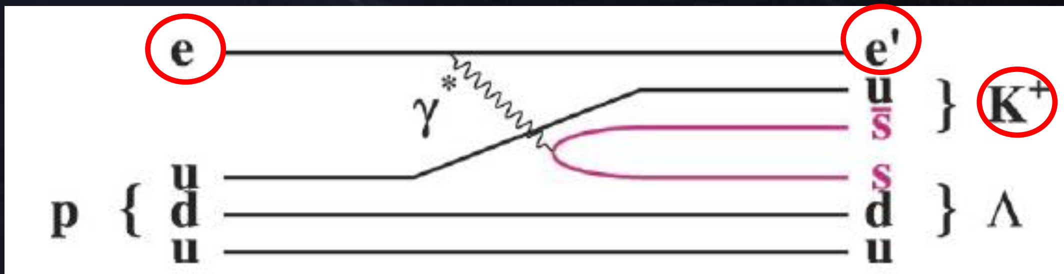
γ-ray spectroscopy

Super high resolution (a few keV)
But **ONLY level spacing** measurable

decay π

Excellent mass resolution (~0.1 MeV)
But **ONLY mass of ground state of light HY**

(e,e'K+) vs. others



(e,e'K+)

Excellent mass resolution

(~ 0.5 MeV)

Absolute energy calibration

p(e,e'K+) Λ, Σ^0

Currently only possible at JLab

E_e > 1.5 GeV high quality e beam

$\Delta p/p \sim 10^{-4}$, >1GeV/c spectrometers

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

All techniques are complementary.

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

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

Publications from JLab HY study

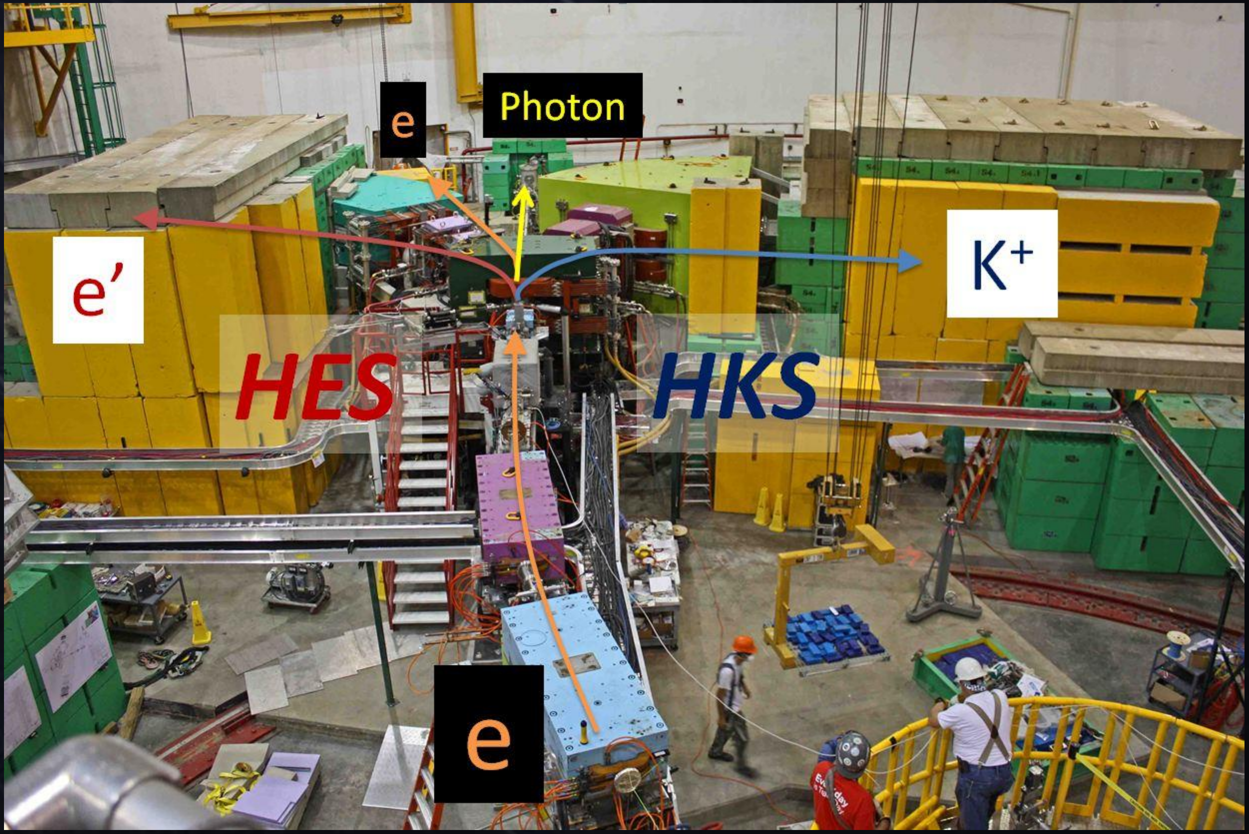
T. Miyoshi et al. PRL 90, 232502 (2003)
L.Yuan et al. PRC 73, 044607 (2006)
M.Iodice et al. PRL 99, 052501 (2007)
F.Cussano et al. PRL 103, 202501 (2009)
S.N.Nakamura et al. PRL 110, 012502 (2013)
L.Tang et al. PRC 90, 034320 (2014)
G.M.Urciuoli et al. PRC 91, 034308 (2014)
T.Gogami et al. PRC 93, 034314 (2016)

PhD : T.Miyoshi, L.Yuan, M.Sarsour, X.Zhu, Y.Okayasu, A.Matsumura,
T.Seva, V.M.Rodriguez, P.Baturin, Y.Song, X.Qiu,
D.Kawama, C.Chen, T.Gogami,
F.Cussano

15 PhD

Hypernuclear study with the (e,e'K+) reaction

Initiated and established at **JLab**



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

0.5 MeV (FWHM)

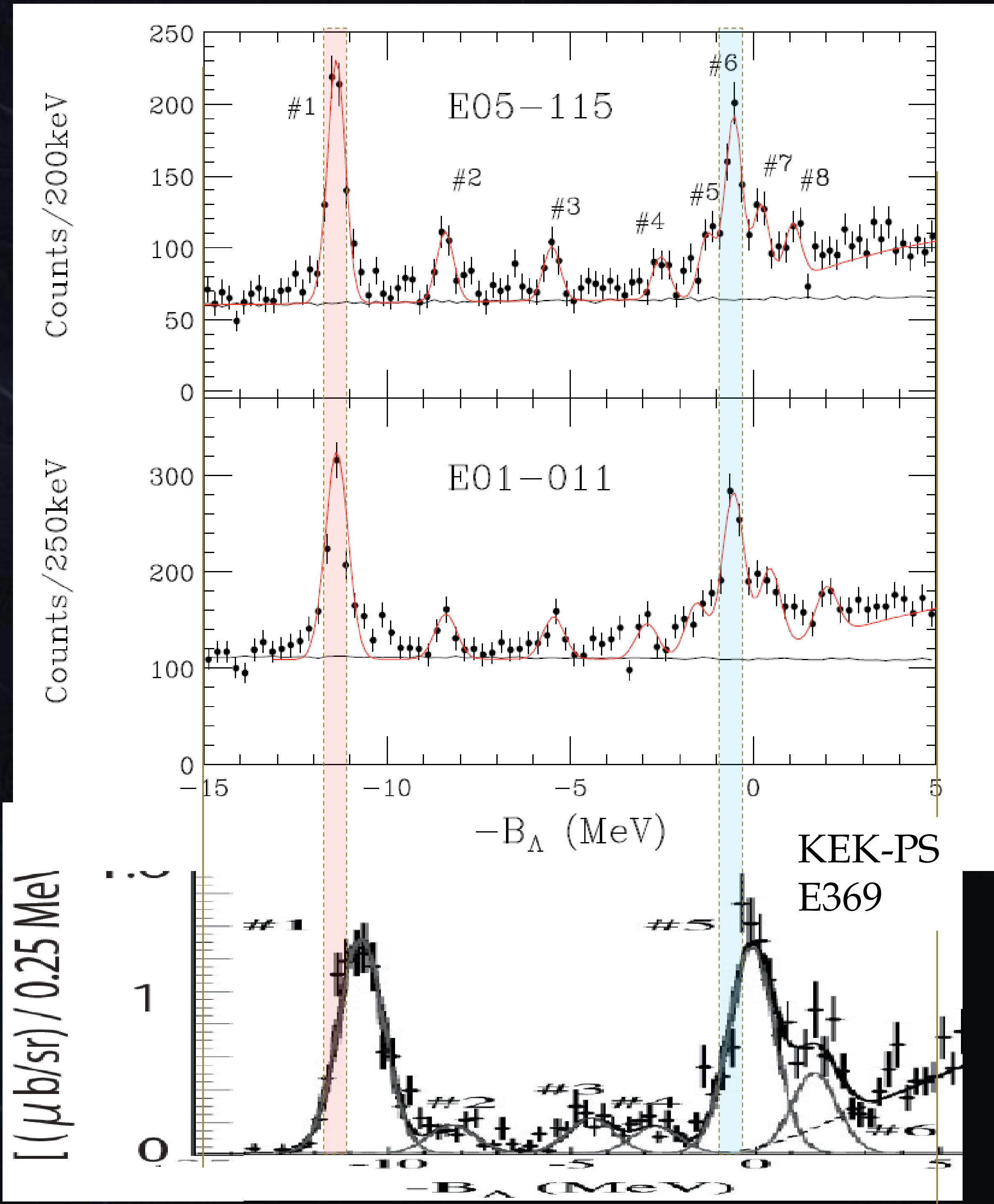
Absolute MM calibration

0.7 MeV (FWHM)

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

1.45 MeV (FWHM)

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



$^{12}{}_{\Lambda}B$ emulsion data

Nuclear Physics B52 (1973) 1–30.

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

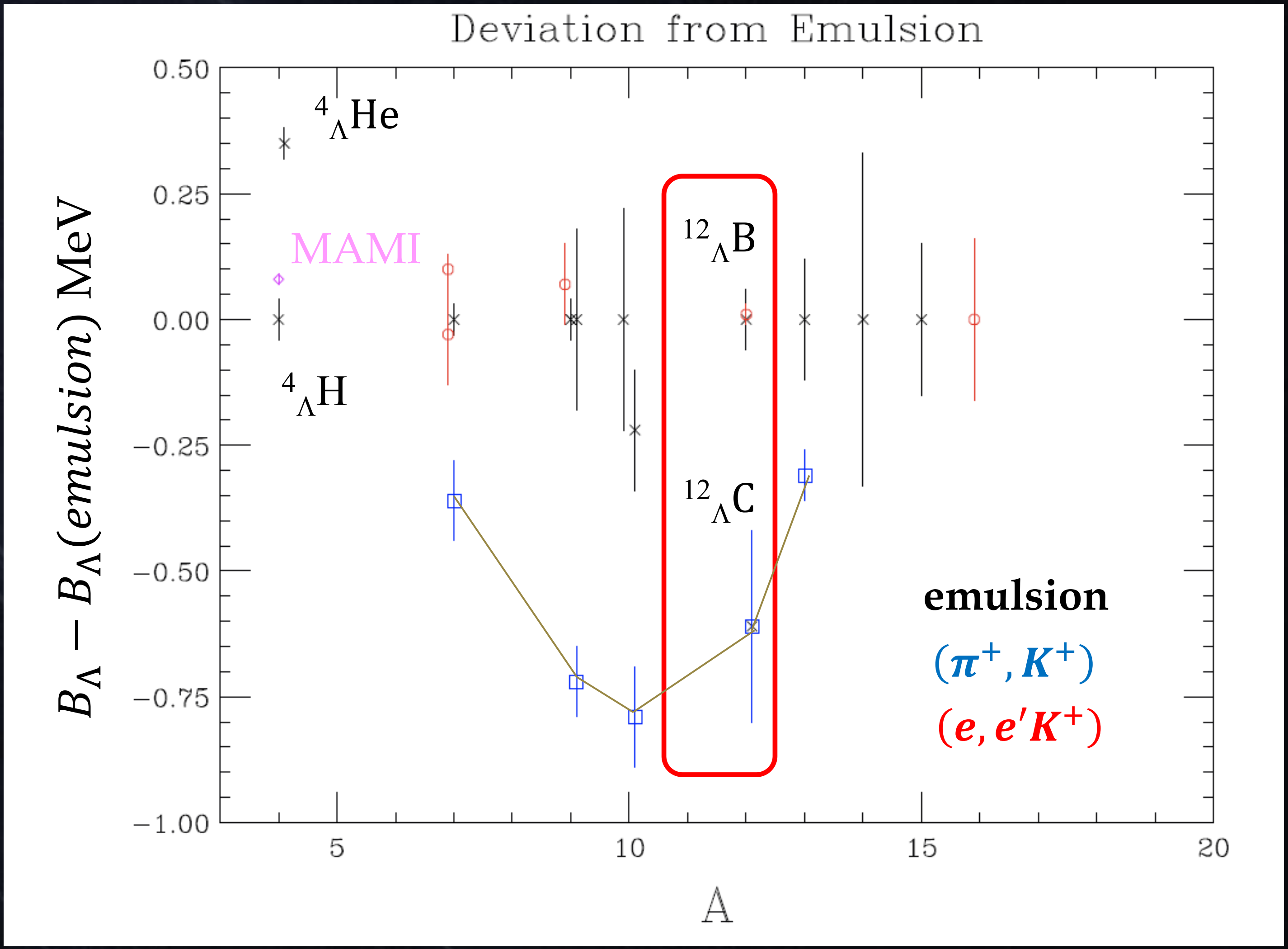
		(# of events)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

B_Λ ($^{12}{}_{\Lambda}$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

Remove apparent A dependence



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

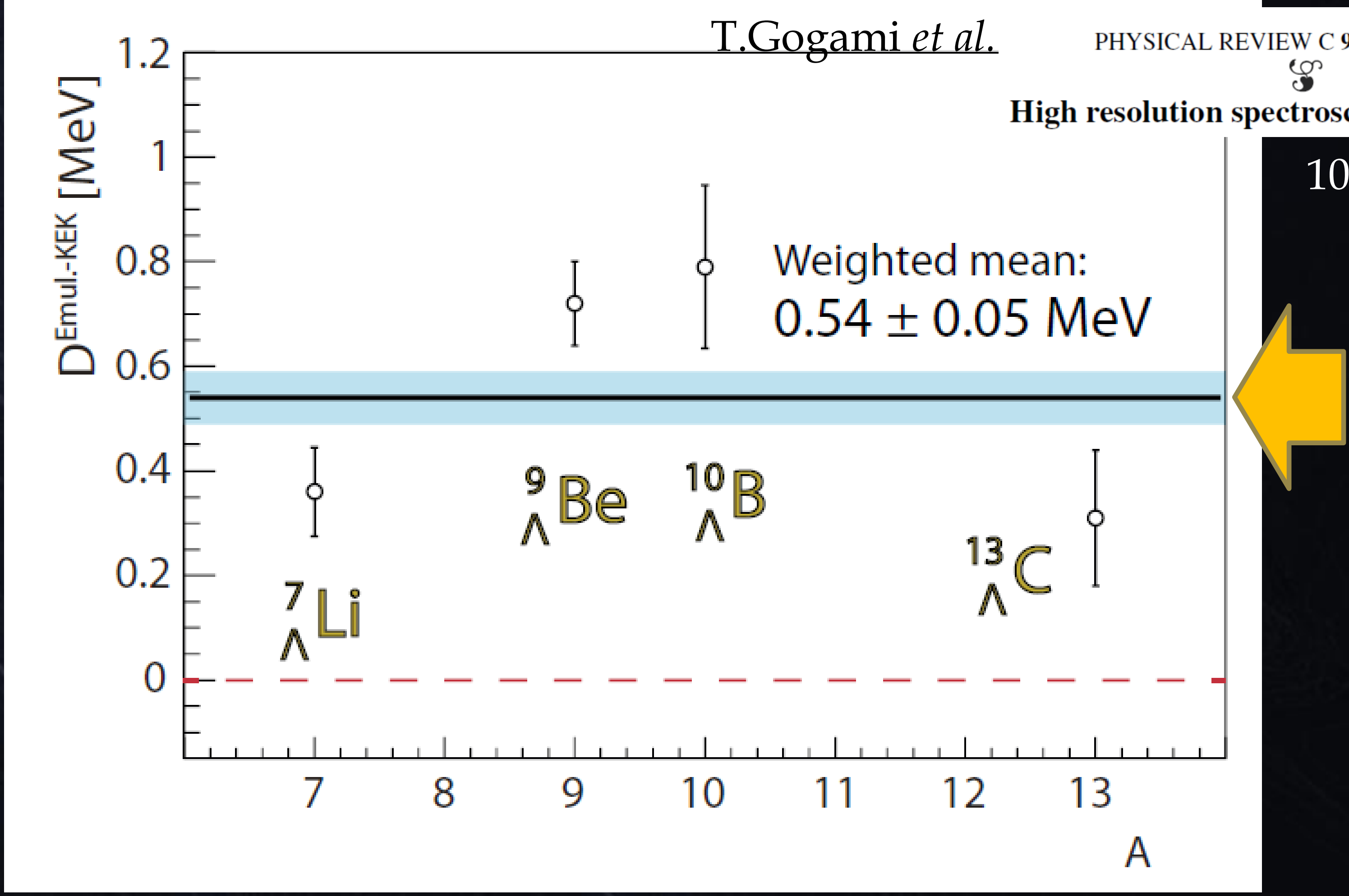
$^{12}_{\Lambda}C - ^{12}_{\Lambda}B$	-0.57 ± 0.19 $-0.62 \pm 0.19 \pm 0.11$	$^{12}_{\Lambda}C$: 6 events, $^{12}_{\Lambda}B$: 87 events present data for $^{12}_{\Lambda}B$

T.Gogami *et al.*

PHYSICAL REVIEW C **93**, 034314 (2016)

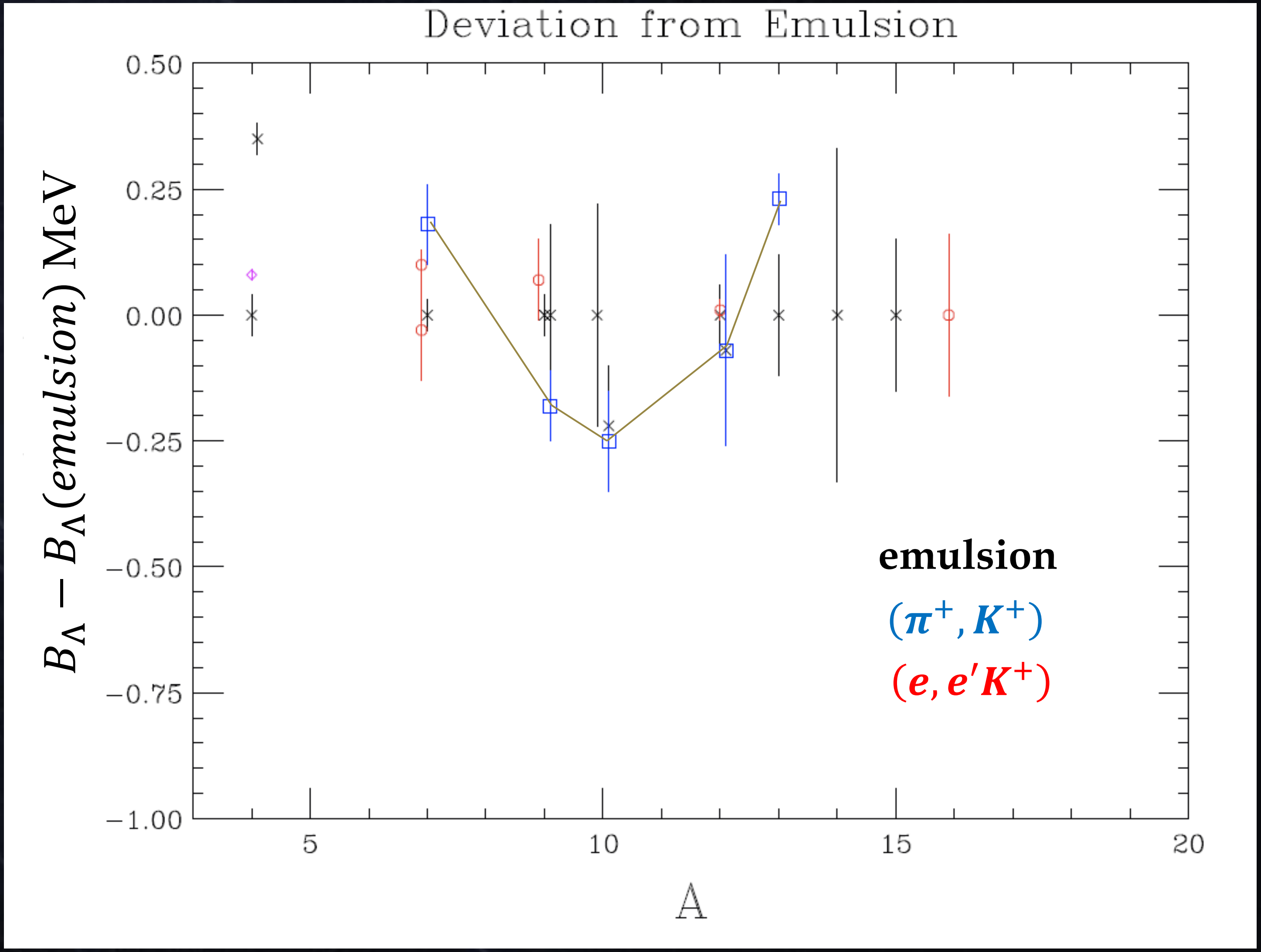
High resolution spectroscopic study of $^{10}_{\Lambda}Be$

10 March (2016)



Should be 0

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



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

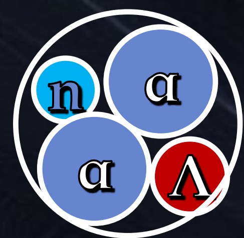
T.Gogami *et al.*

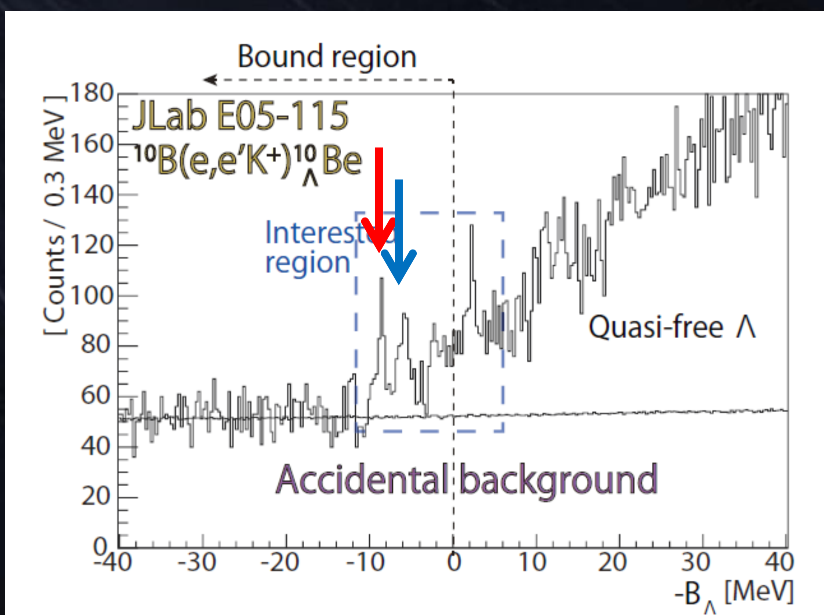
PHYSICAL REVIEW C **93**, 034314 (2016)

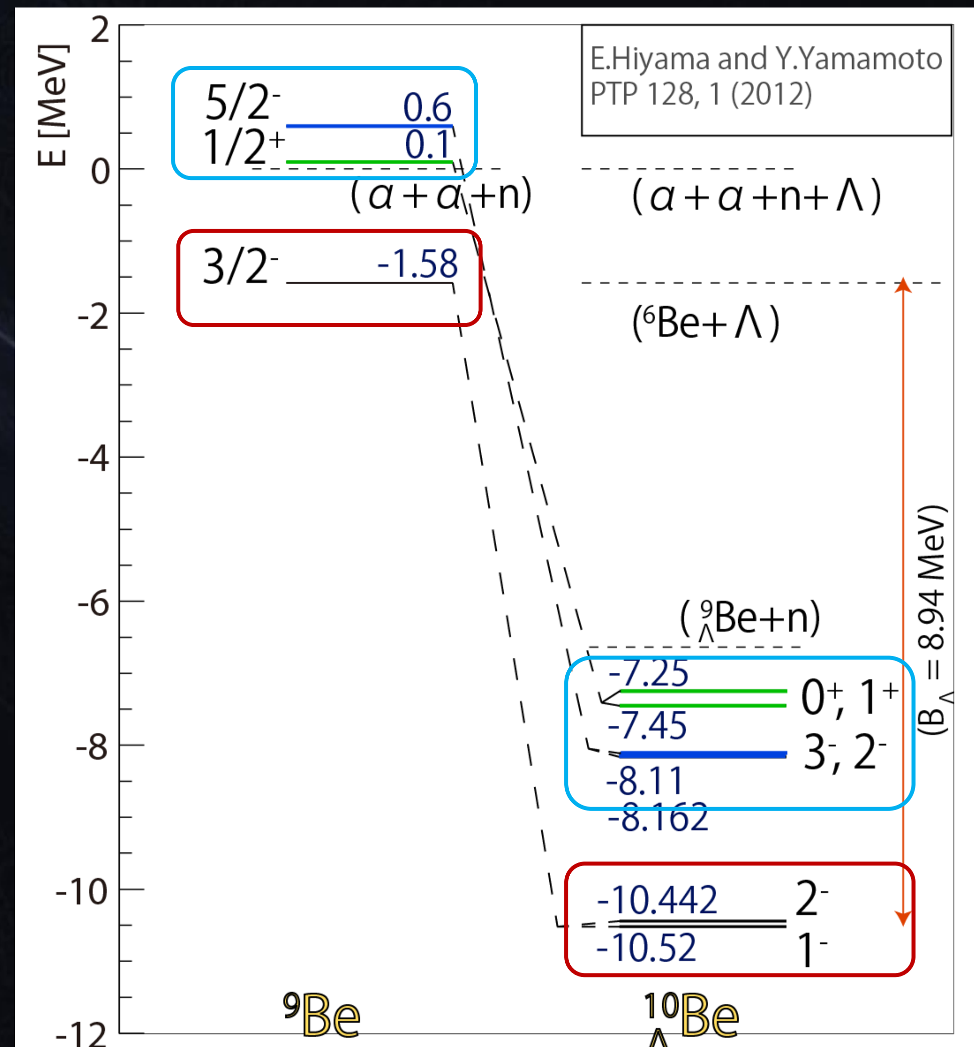
High resolution spectroscopic study of $^{10}_{\Lambda}Be$

^{9}Be

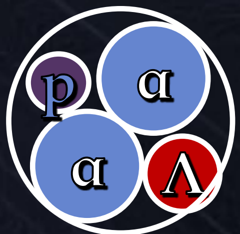
$^{10}_{\Lambda}Be$



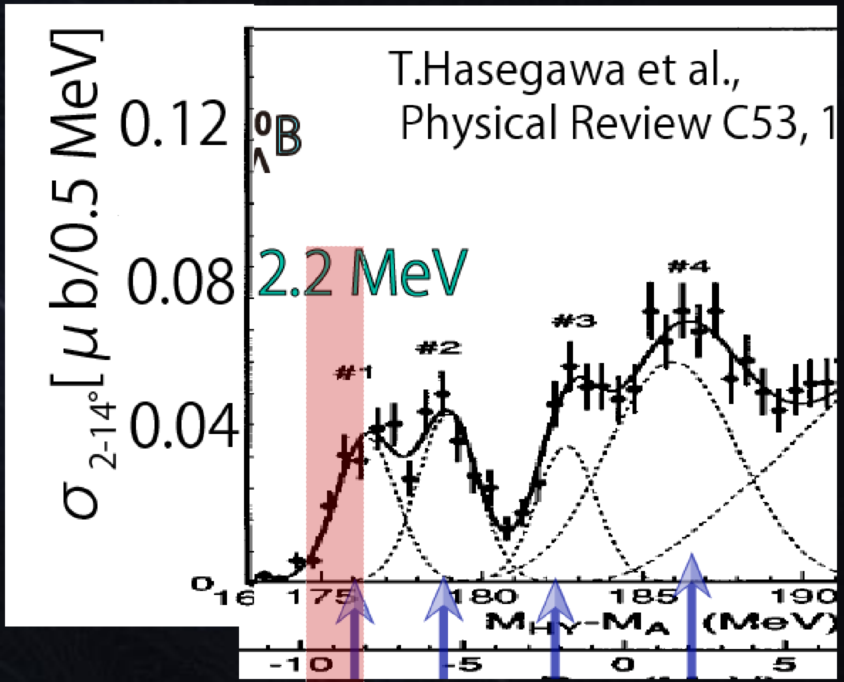


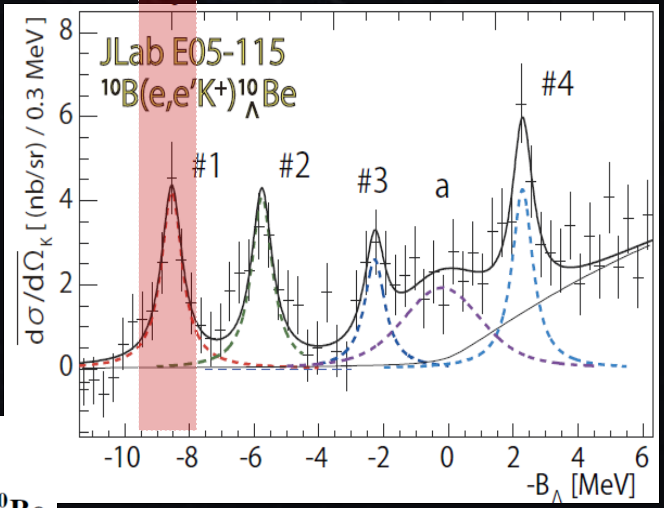


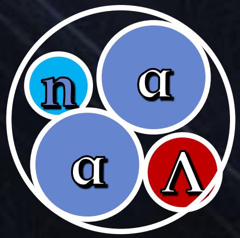
$^{10}_{\Lambda}B$ and $^{10}_{\Lambda}Be$



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







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

T.Gogami *et al.*

PHYSICAL REVIEW C **93**, 034314 (2016)

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

Hall A E94-107, Excellent S/N spectra

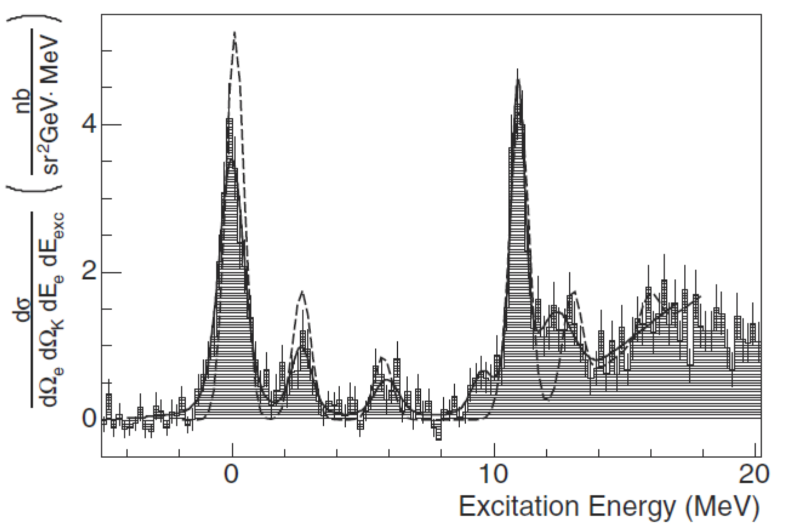


FIG. 3. The $^{12}_{\Lambda}$B excitation-energy … curve) and a theoretical prediction … imposed on the data. See text for de…

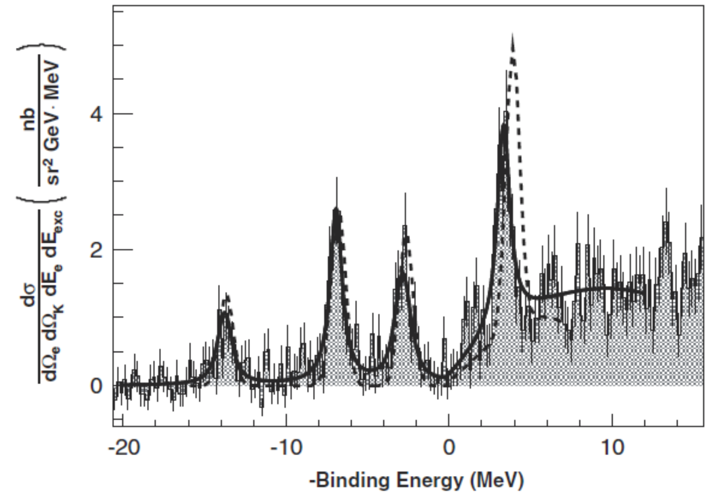


FIG. 3. The $^{16}_{\Lambda}$N binding-energy spectrum. The best fit using Voigt functions (solid curve) and a theoretical prediction (dashed … imposed on the data. See text for details.

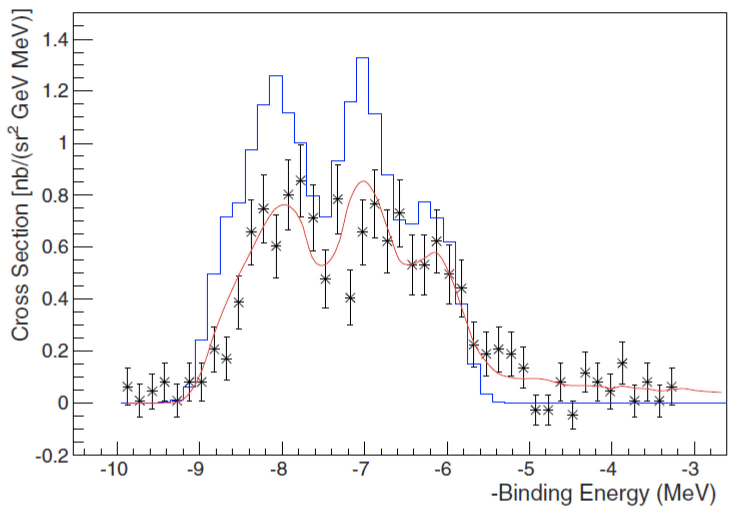


FIG. 3. (Color online) The $^{9}_{\Lambda}$Li differential cross section as a function of the binding energy. Experimental points vs Monte Carlo results (red curve) and vs Monte Carlo results with radiative effects turned off (blue histogram).

Charge Symmetry Breaking of the ΛN interaction

Charge Symmetry Breaking for NN system

EM Corrections

$(a_{pp}) = -7.8$ fm → $[a_{pp}]_{SI} = -17.3 \pm 0.4$ fm

$a_{nn} = -18.8 \pm 0.3$ fm

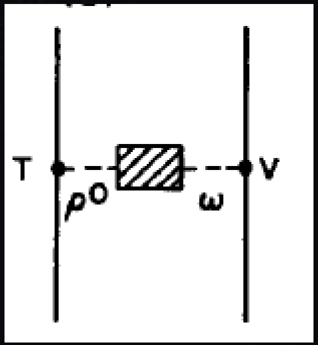
$B(^3H) - B(^3He) = 764$ keV → $[B(^3H) - B(^3He)]_{SI} = 71$ keV

$\Delta m = m(d) - m(u) \cong 3$MeV

$P_{CS}|u\rangle = |d\rangle$

$P_{CS}|d\rangle = -|u\rangle$

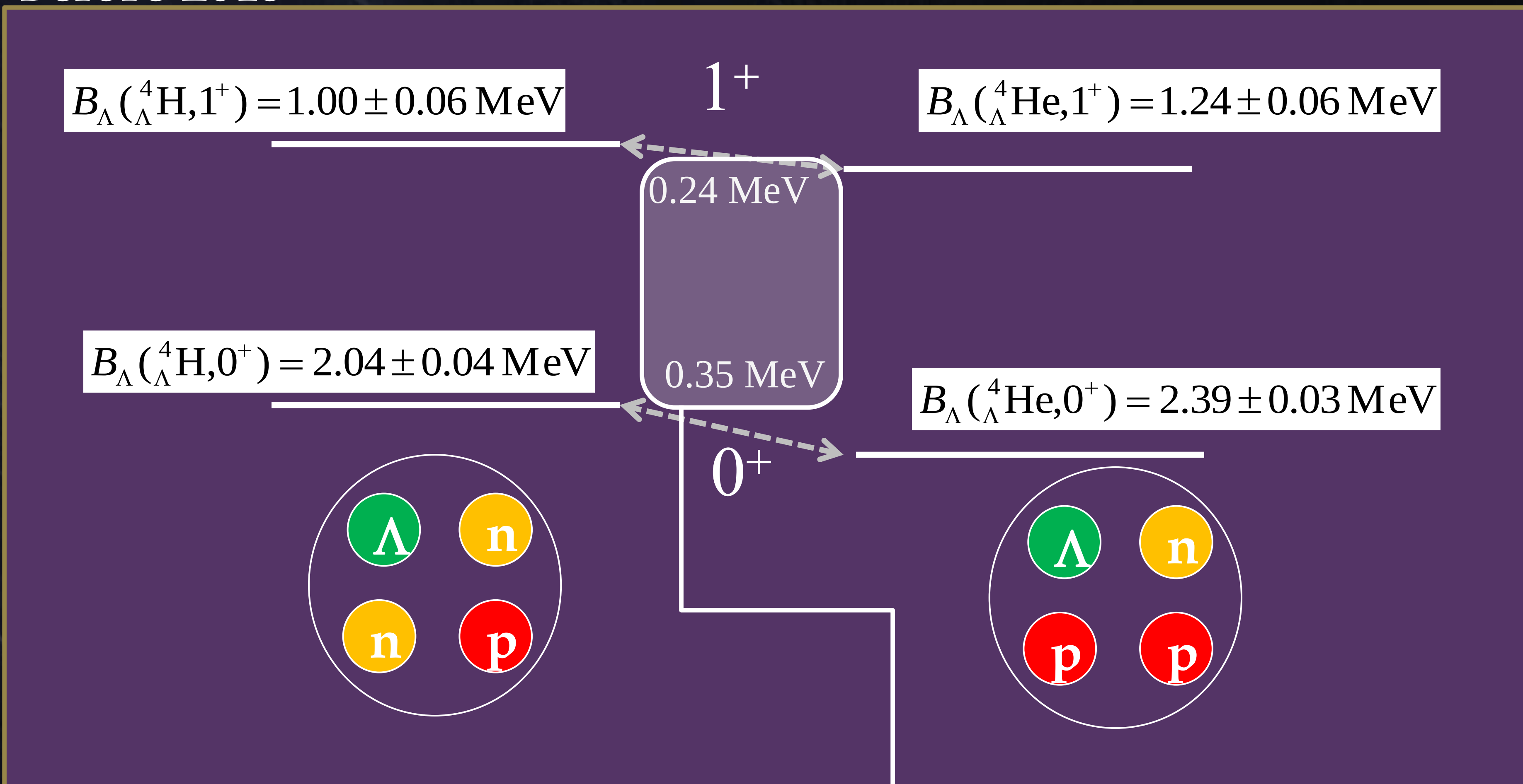
$\rho^0 - \omega$ mixing



A=4 system
CSB ΛN potential

Data from
Emulsion
NaI γ-ray

Before 2015



Coulomb effect is very small.

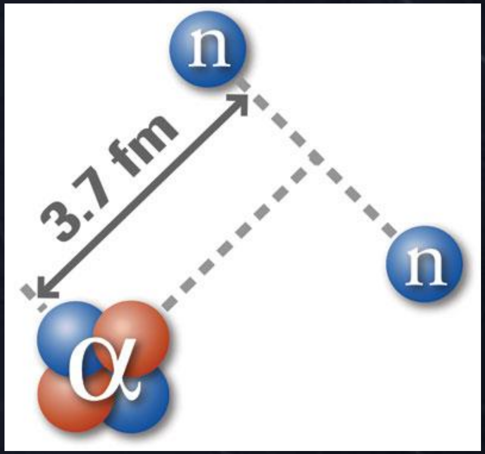
$-\Delta B_c = 0.050 \pm 0.02\ \mathrm{MeV}$,

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

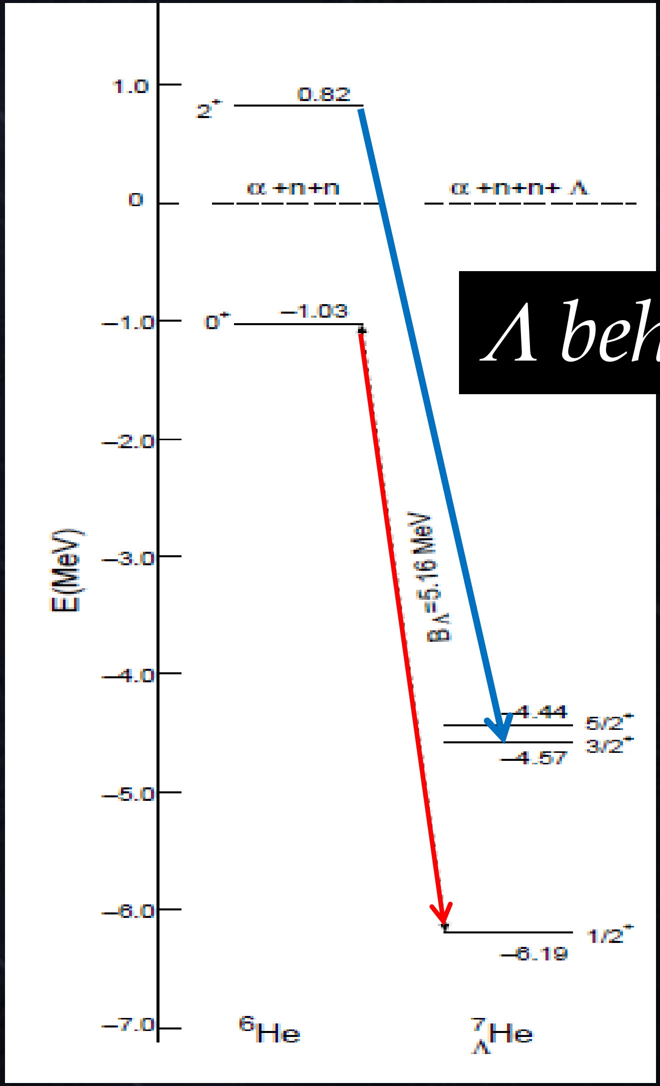
Charge Symmetry Breaking

cf) $B({}^3\mathrm{H}) - B({}^3\mathrm{He}) - \Delta B_c \sim 70$ keV

$^{7}_{\Lambda}He$ = ^{6}He + Λ



^{6}He : 2n halo

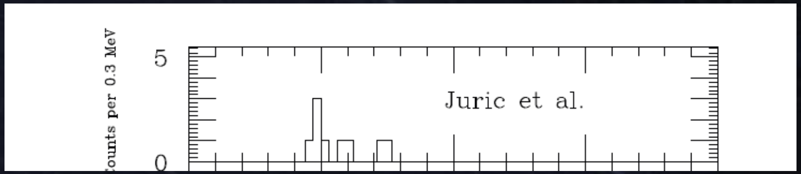


Λ behaves like glue

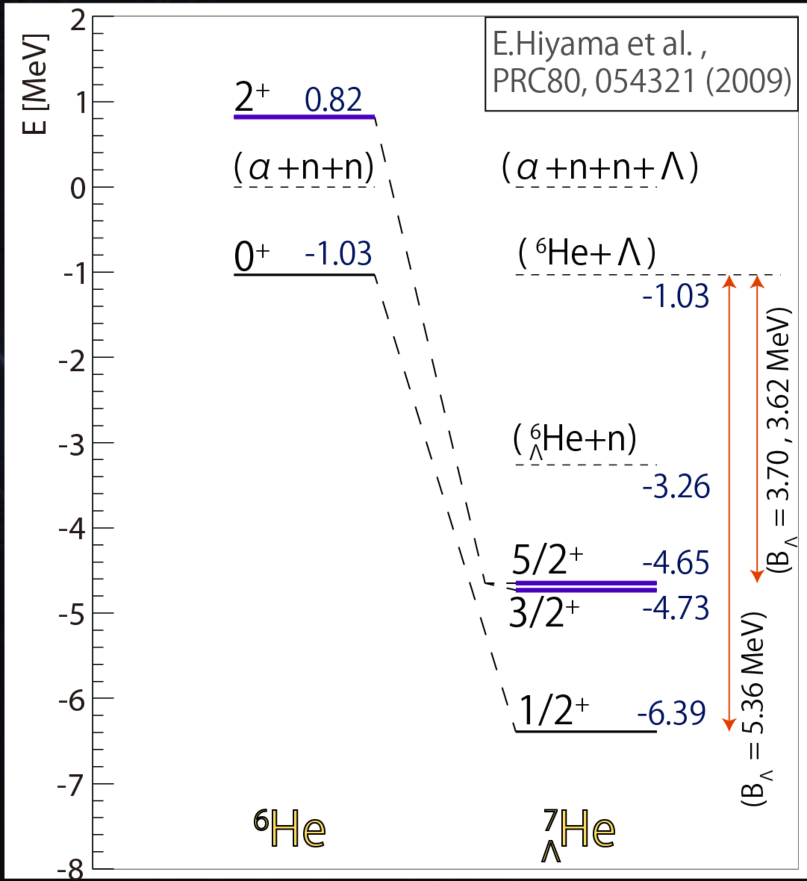
E.Hiyama et al. PRC 80, 054321 (2009)

$^{7}_{\Lambda}$He spectrum

Juric et al., Nucl. Phys. A484 (1988) 520

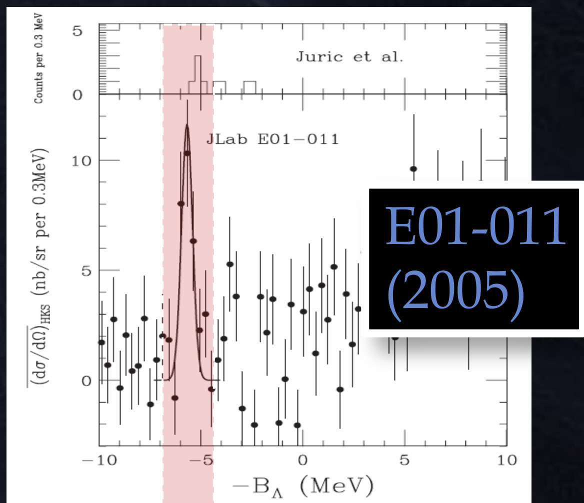


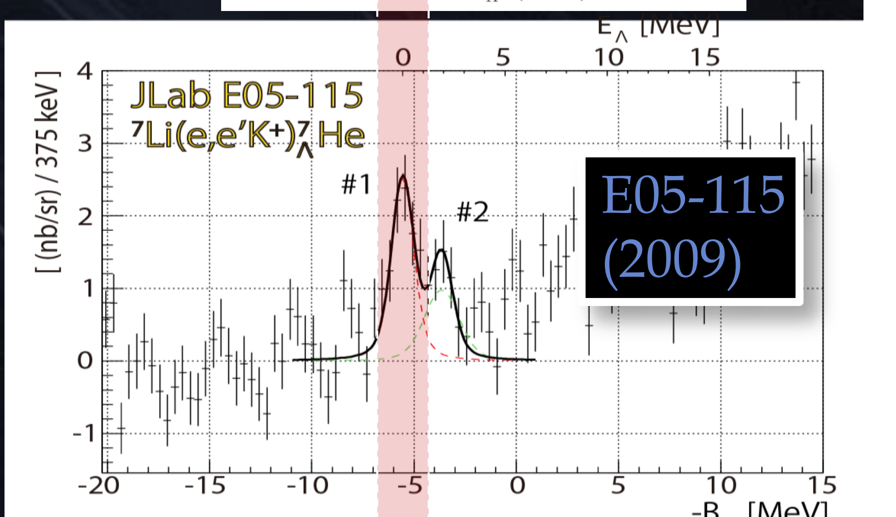
No B_{Λ} was obtained.



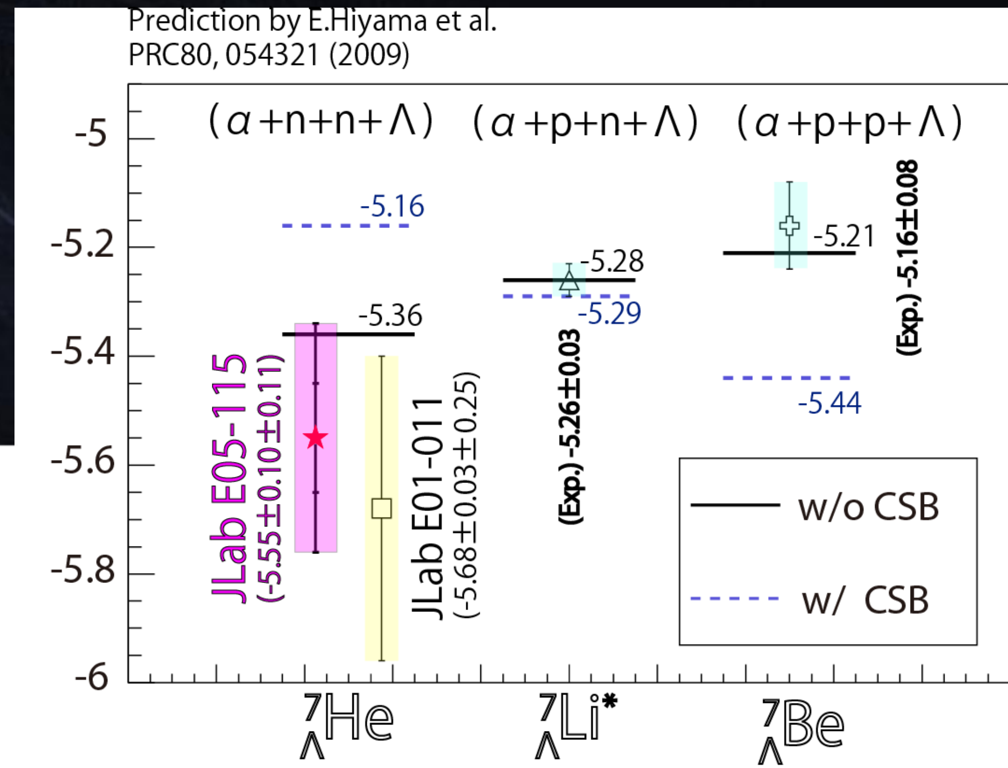
CSB interaction test in A=7 iso-triplet comparison

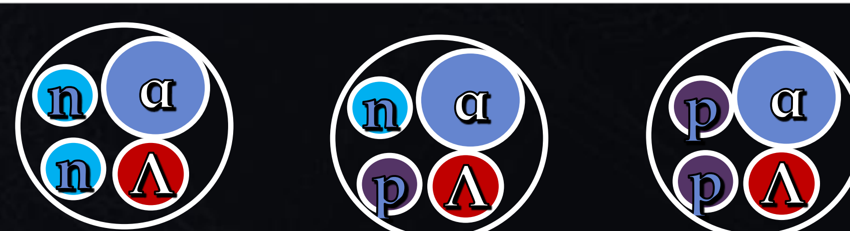
SNN et al., PRL 110, 012502 (2013)





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



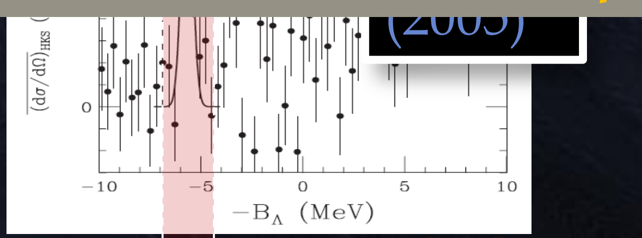


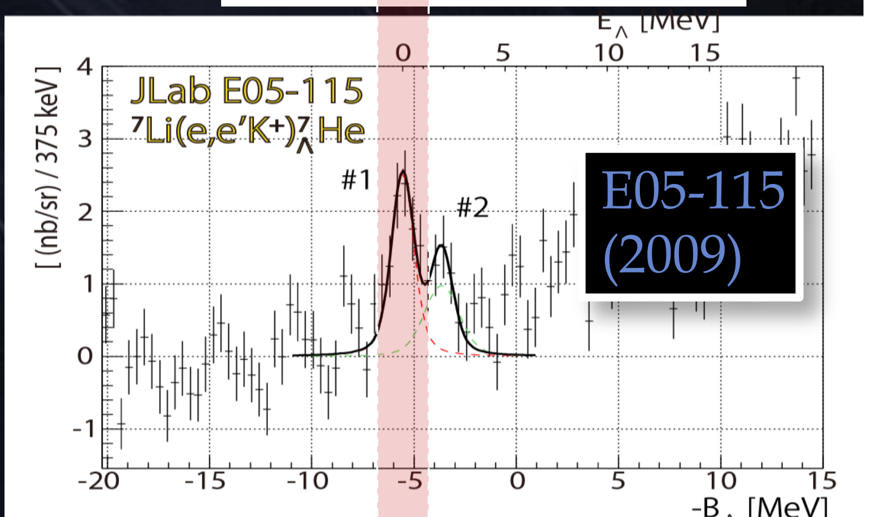
CSB interaction test in A=7

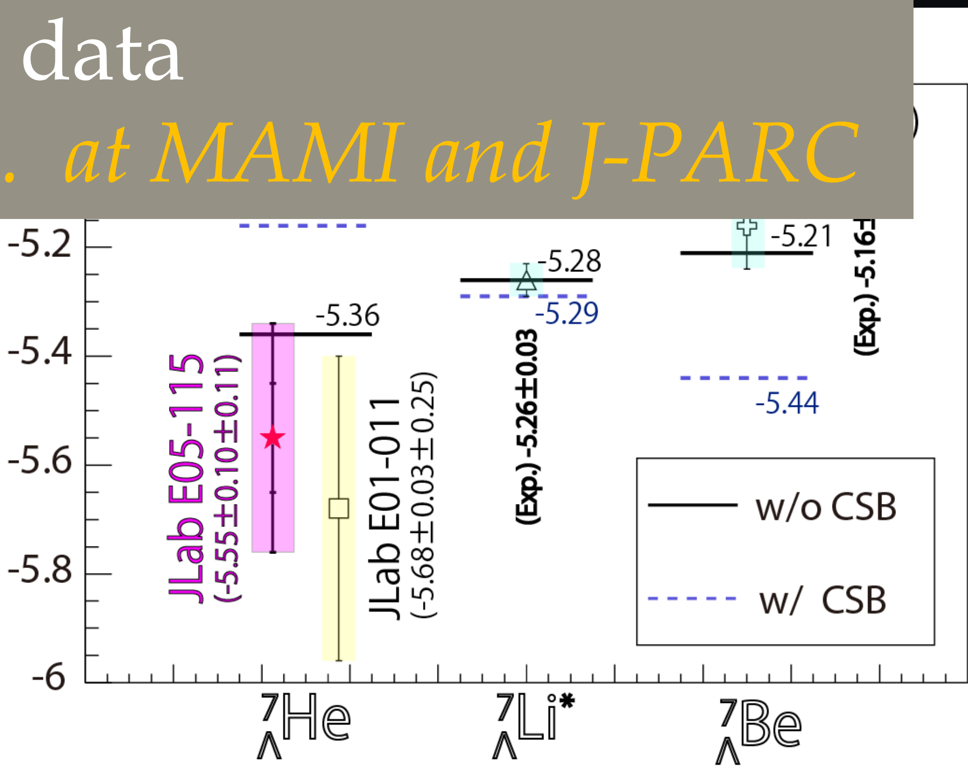
CSB potential is not necessary for A=7

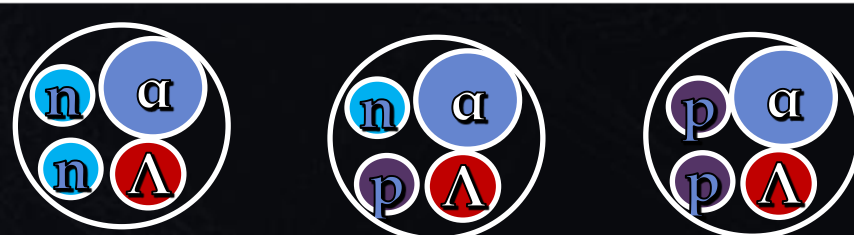
Assumed CSB potential is too naïve or problem for A=4 data

→*New exps. at MAMI and J-PARC*



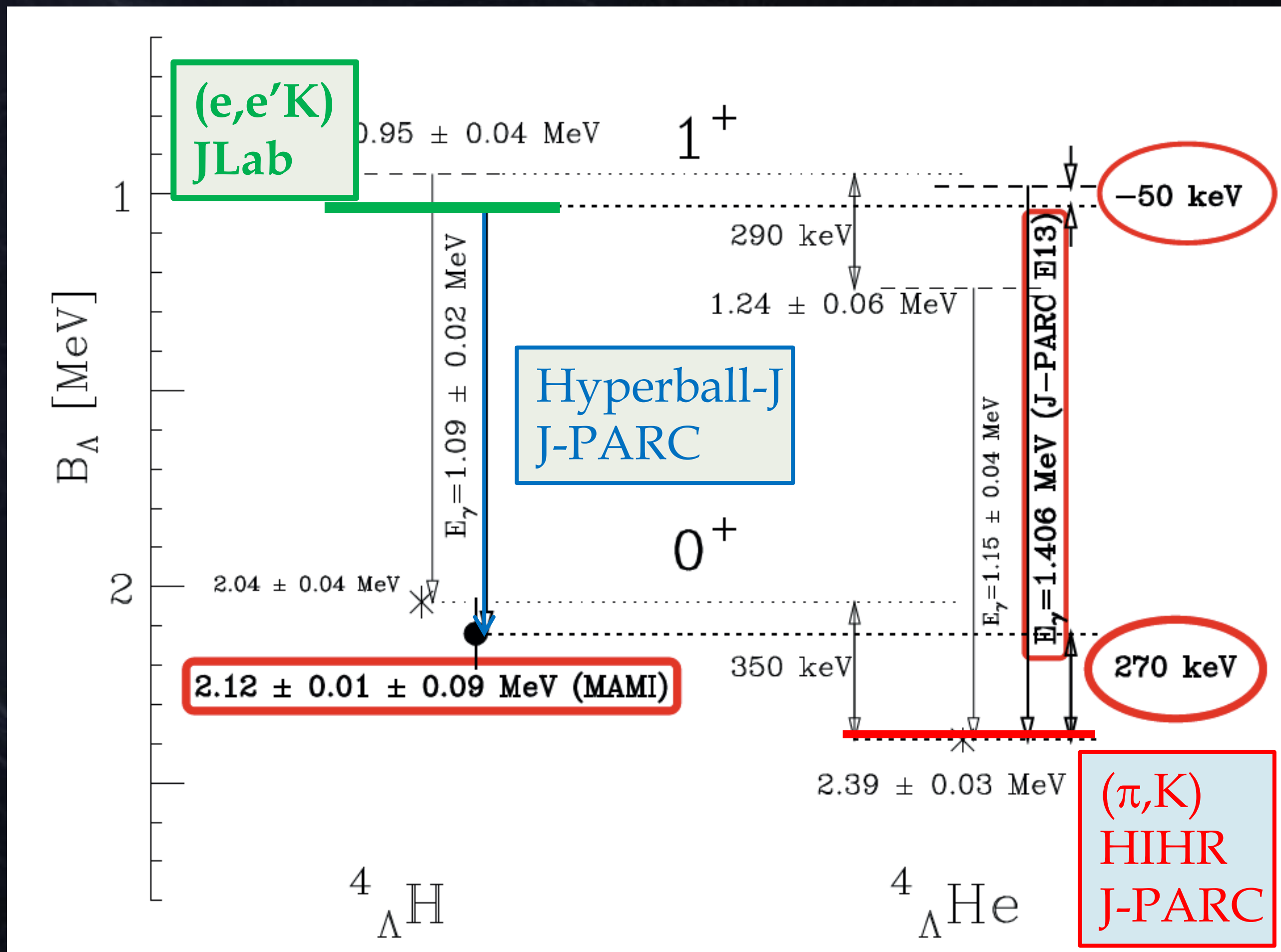






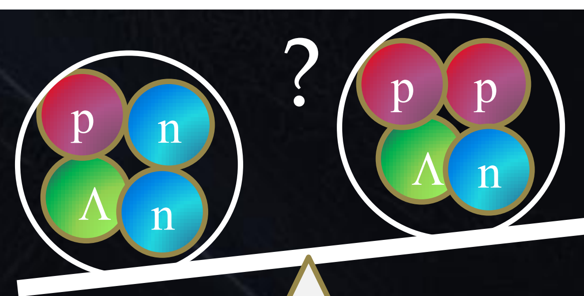
T.Gogami, Doctor Thesis (2014) Tohoku Univ.

CSB for A=4 hypernuclei : *Future* Measurements



Small CSB

Large CSB



ΛN-ΣN coupling
is a key

Summary

Spectroscopy of Lambda hypernuclei with electron beams

⇨ Established at JLab ⇨ Decay π at MAMI

$^{9}_{\Lambda}$Li $^{10}_{\Lambda}$Be $^{12}_{\Lambda}$B $^{16}_{\Lambda}$N ⇨ Abs. B_{Λ} determination sugg. 0.54MeV shift for all (π,K)

Observation of $^{7}_{\Lambda}$He excited state :

New possibility to bridge physics of hypernuclei and unstable nuclei.

Determination of $B_{\Lambda}(^{7}_{\Lambda}He_{gs})$ triggered intensive study for A=4 iso-doublet hypernuclei ($^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He)

⇨ Mainz : Decay π spectroscopy

J-PARC E13 : γ–ray spectroscopy

Hypernuclear studies recently made great progresses at other facilities.
JLab should lead spectroscopy of Lambda HY in timely manner.