东北大学

7^{th} Sep. 2011

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International Conference on Exotic Atoms and Related Topics EXA2011

Strangeness Physics at JLab

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

Put "exotic"s !

Exotic particles (μ, π, K) + Atom (nucleus + electrons)

Exotic Atom

Impurity

size or shape changes

probe to detailed structure of the system

study interaction under extreme conditions

Hypernucleus

Introduction of **strangeness**

hyperon (s quark) + nucleus (u, d quarks)

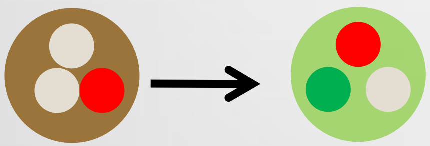
EM Production of hypernuclei

$$E_e, \vec{P}_K, \vec{P}_{e'} \Rightarrow m(HY)$$

Should be noted :

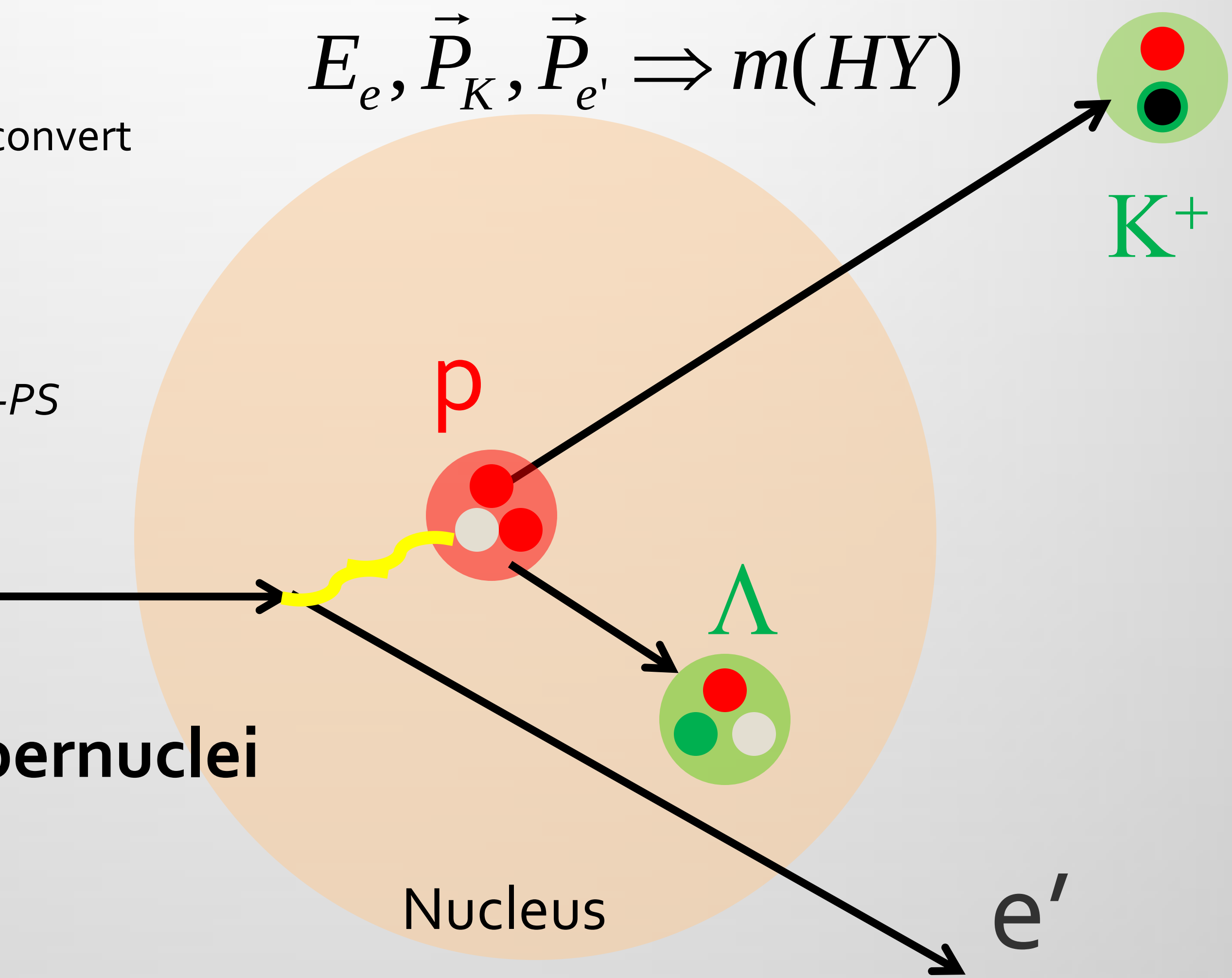
(K^-,π^-), (π^+, K^+) reactions convert

neutron to Λ



70's~90's BNL-AGS, KEK-PS

e^-



Produce new hypernuclei

Z(e,e'K$^+$)$_\Lambda$(Z−1) reaction

Characteristics of (e,e'K) HY study

Electromagnetic production

Convert Proton to Lambda :

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

Absolute mass calibration with Λ and Σ^0

Both spin flip and non-spin flip amplitudes in forward angles

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

High Quality Electron Beam is Essential !

[illegible] Hypernuclear Cross Section

Coincidence Measurement (e', K^+)

Limited Statistics

DC beam is necessary

Necessary e⁻ beam for hypernuclear study

Continuou

Electron be

High curre

Beam stab

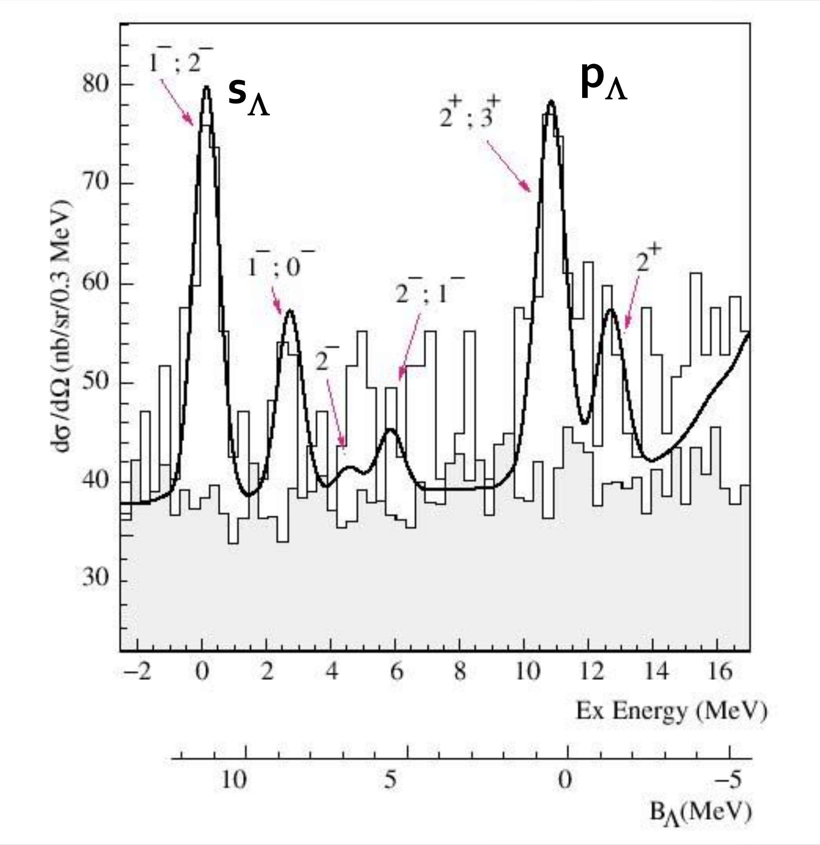
- Momentu
- Good emi

So far, only JLab CEBAF had been providing such a beam.
Now upgraded MAMI-C can also!

The first (e,e'K$^+$) hypernuclear experiment (E89-009, HNSS)

Demonstrated that :

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



the **(e,e'K)** hypernuclear spectroscopy is **possible!**

Sub-MeV energy resolution
<800 keV (FWHM)

PRL 90 (2003) 232502, PRC 73 (2006) 044607

Improvement of the 1st Generation experiment

Energy resolution as well as acceptance are limited by the kaon spectrometer (SOS)

- ***High Resolution Spectrometers (HRS x 2) in Hall A***
  (Long orbit -> Higher momentum)
  Septum + Large e'-K opening angle (Hall A)

- ***New short orbit spectrometer in Hall C***
  High resolution Kaon Spectrometer (HKS)

Zero degree tagging method to maximize virtual photon flux

1st Gen. Severe background from electrons associated with Bremsstrahlung (200 MHz for e′ arm)

Splitter + Tilt Method (Hall C)

The 2nd Generation Experiments :

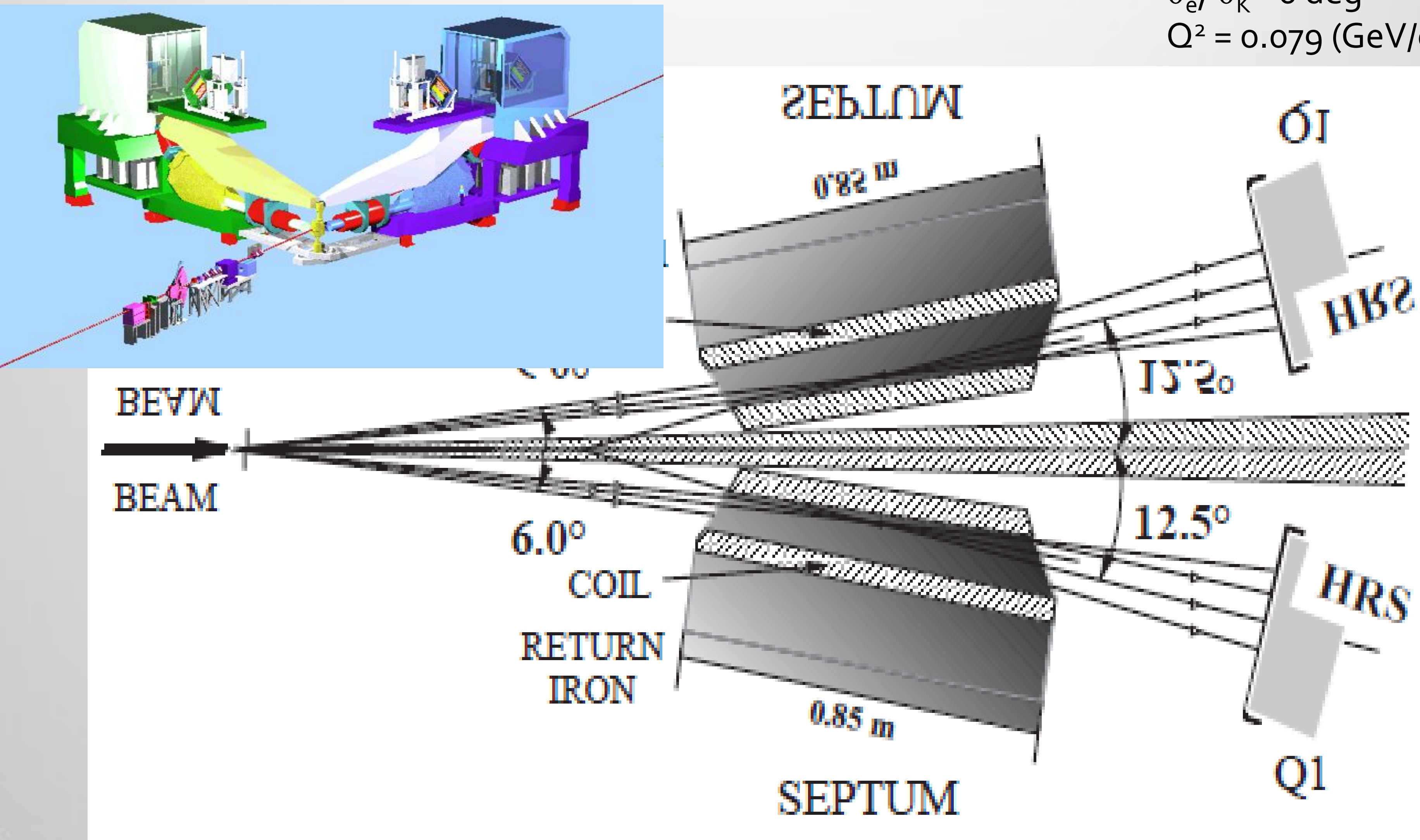
E94-107 (Spokespersons: Frullani, Garibaldi, LeRose, Markowitz, Saito)

E01-011 (Spokespersons: Hashimoto, Tang, Reinhold, Nakamura)

Hall-A Hypernuclear Program

E94-107

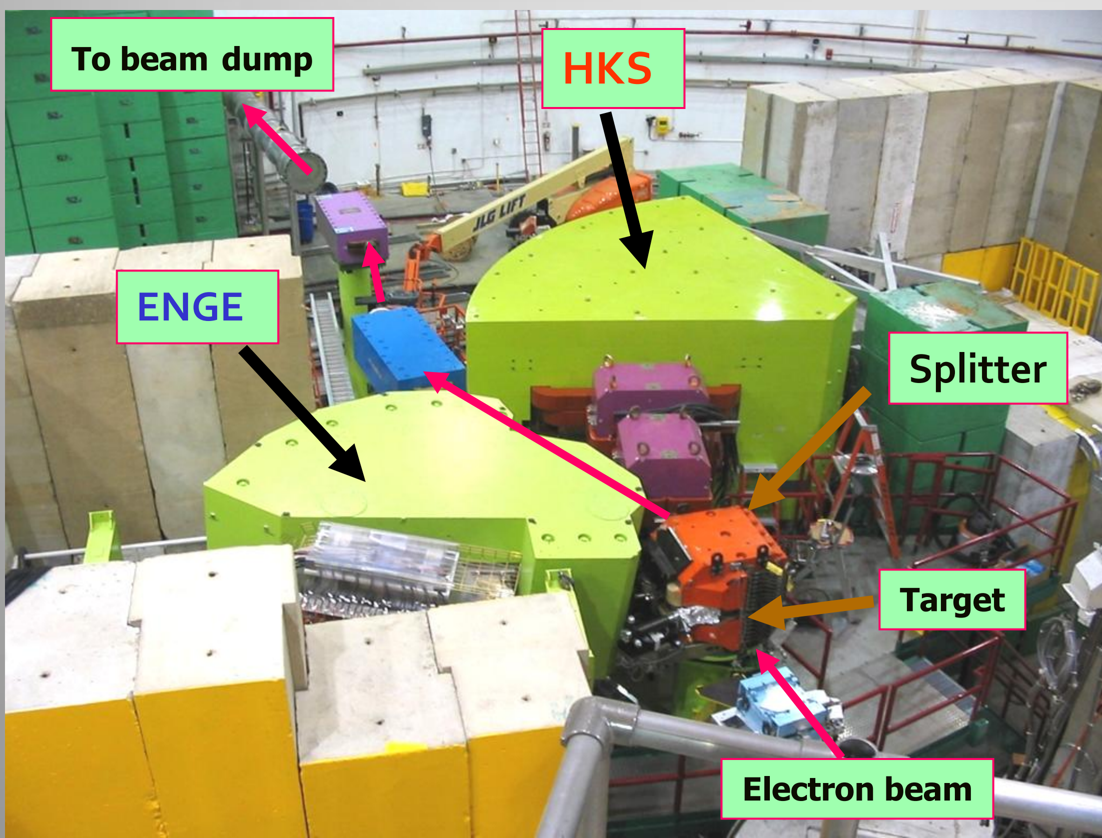
$E_e = 4$ GeV,
$P_{e'} = 1.8$ GeV/c
$\nu = 2.2$ GeV
$P_K = 2.0$ GeV/c
θ_e, $\theta_K \sim 6$ deg
$Q^2 = 0.079$ $(\mathrm{GeV/c})^2$



Second Generation Exp. at JLab

2005 E01-011 (Hall C)

First step to midium heavy hypernuclei (^{28}Si, ^{12}C, ^{7}Li)



Two Major Improvements

New HKS

Tilt Method

Beam: 30 μA , 1.8GeV
HKS: $\Delta p/p = 2 \times 10^{-4}$ [FWHM]
Solid angle 16msr(w/ splitter)

Hypernuclei in wide mass range

A 1 E89-009 ^{12}C 20 50 200 10^{57}

E94-107 & E01-011

^{7}Li ^{9}Be ^{12}C ^{16}O ^{28}Si

Elementary Process

Strangeness electro-production

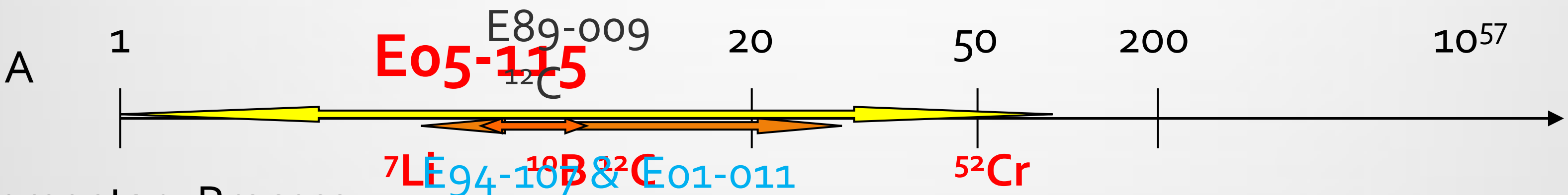
Light Hypernuclei (s,p shell)

Fine structure
Baryon-baryon interaction in SU(3)
$\Lambda\Sigma$ coupling in large isospin hypernuclei
Cluster structure

Neutron/Hyperon star,
Strangeness matter
Hyperonization →
Softening of EOS ?

Medium - Heavy hypernuclei
Single-particle potential
Distinguishability of a Λ hyperon
$U_0(r)$, $m_\Lambda^*(r)$, $V_{\Lambda NN}$, ...

Hypernuclei in wide mass range



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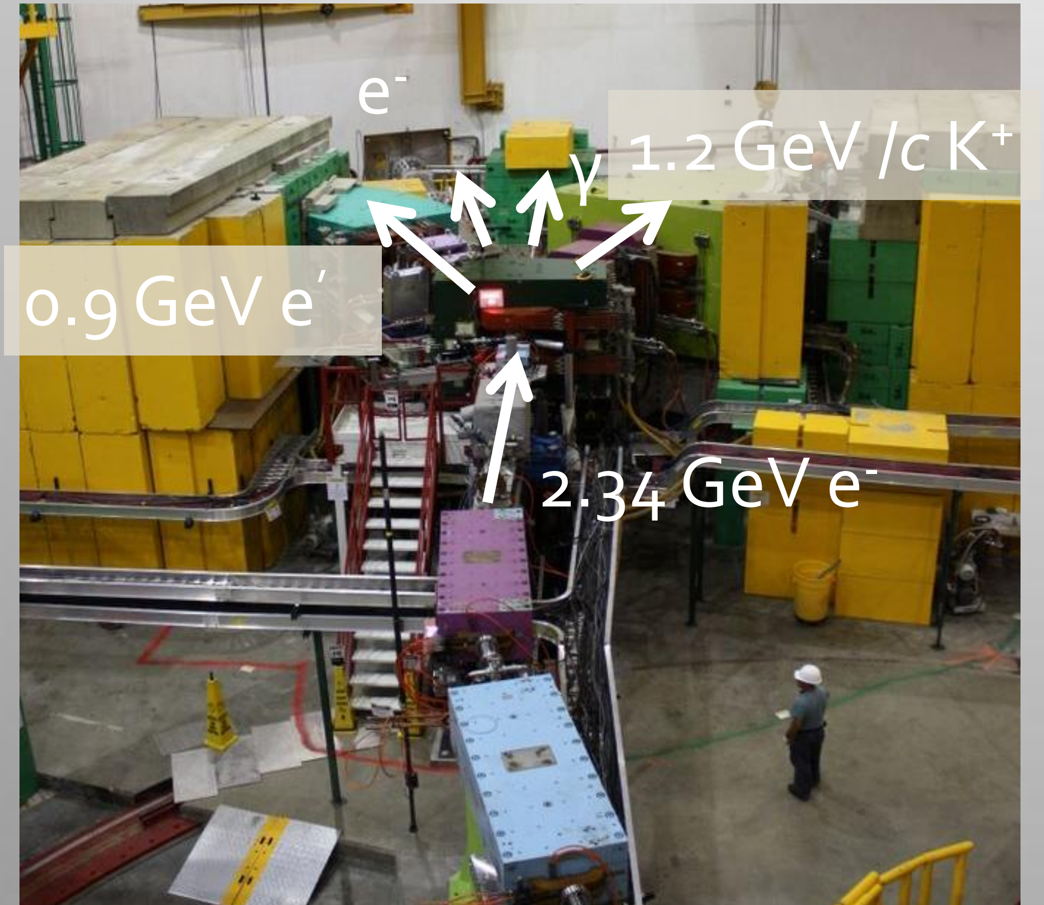
3^{rd} Generation Experiment

Third Generation Exp. at JLab

2009 E05-115 (Hall C)

Wide mass range hypernuclear spectroscopy ($^{52}{}_{\Lambda}V$, $^{12}{}_{\Lambda}B$, $^{10}{}_{\Lambda}Be$, $^{9}{}_{\Lambda}Li$, $^{7}{}_{\Lambda}He$)



Major Improvements

(10 times more VP tagging)

New HES+SPL
best match to HKS

New pre-chicane
beamline

New Calibrations
H2O cell target
Beam energy scan

Highlights of JLab hypernuclear study

$^{12}{}_{\Lambda}$B : Absolute binding energy, Reference

$^{9}{}_{\Lambda}$Li : p-shell hypernuclei

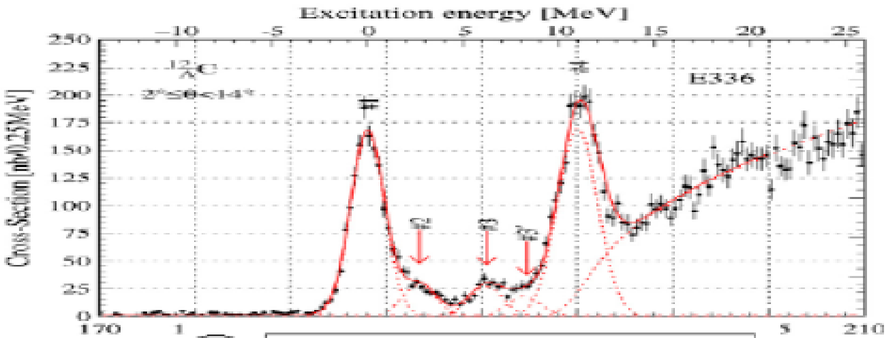
$^{16}{}_{\Lambda}$N : $p_N^{-1}\, s_{\Lambda}$ state, Water fall target

$^{28}{}_{\Lambda}$Al : First beyond-p shell HY. by (e,e'K)

$^{7}{}_{\Lambda}$He : First reliable data, CSB effect

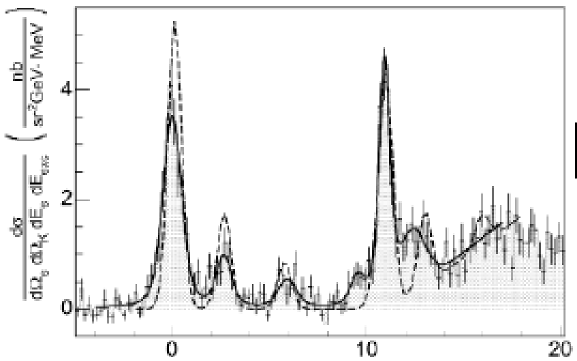
$^{52}{}_{\Lambda}$V, $^{10}{}_{\Lambda}$Be analyses are in progress

$^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$ @ KEK-PS
$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$ @ JLab Hall A & C

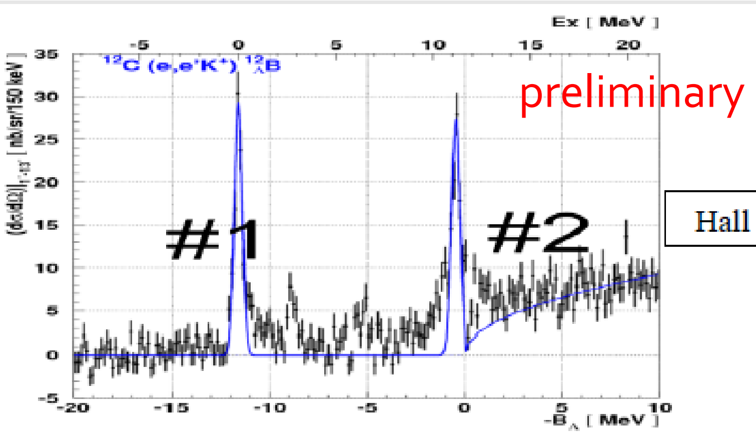


Resolution ~ 2MeV

Excitation energy
(gs energy from emulsion)



Resolution ~ 0.65MeV



Resolution ~ 0.5MeV

Absolute binding energy

Experiment	s_Λ $Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	s_Λ Width [MeV] $\pm$ (stat.)	p_Λ $Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	p_Λ Width [MeV] $\pm$ (stat.)
E01-011	0 ($-11.40 \pm 0.01 \pm 0.14$)	0.61 ± 0.05	$11.05 \pm 0.01 \pm 0.19$ ($-0.41 \pm 0.01 \pm 0.13$)	0.87 ± 0.13
E89-009 [25, 26, 66]	0 (-11.52 ± 0.35)	0.75	(-0.49 ± 0.16)	N/A
E94-107 [64]	0	1.15 ± 0.18	10.93 ± 0.03	0.67 ± 0.15

$^{12}{}_{\Lambda}C$ 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. ${}^{12}_{\Lambda}C \to \pi^- + {}^{12}N$(g.s.)	—	11.14±0.57	[4]
2. ${}^{12}_{\Lambda}C \to \pi^- + p + {}^{4}He + {}^{7}Be$	3.0±0.8	10.45±0.33	[3]
3. ${}^{12}_{\Lambda}C \to \pi^- + p + {}^{11}C$	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 ($^{12}{}_{\Lambda}$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)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	$\boxed{11.45 \pm 0.07}$

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

B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.40 +- 0.01 +- 0.14 MeV (E01-011 Preliminary)

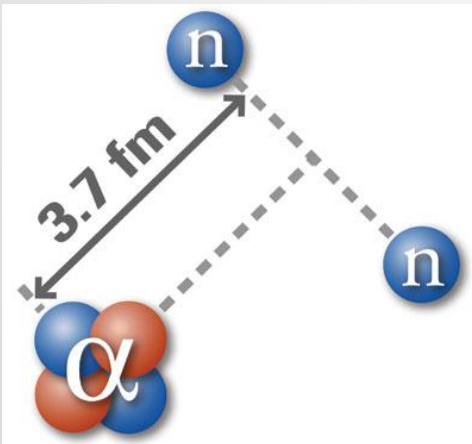
Totally independent measurement

Ref) A=4 System

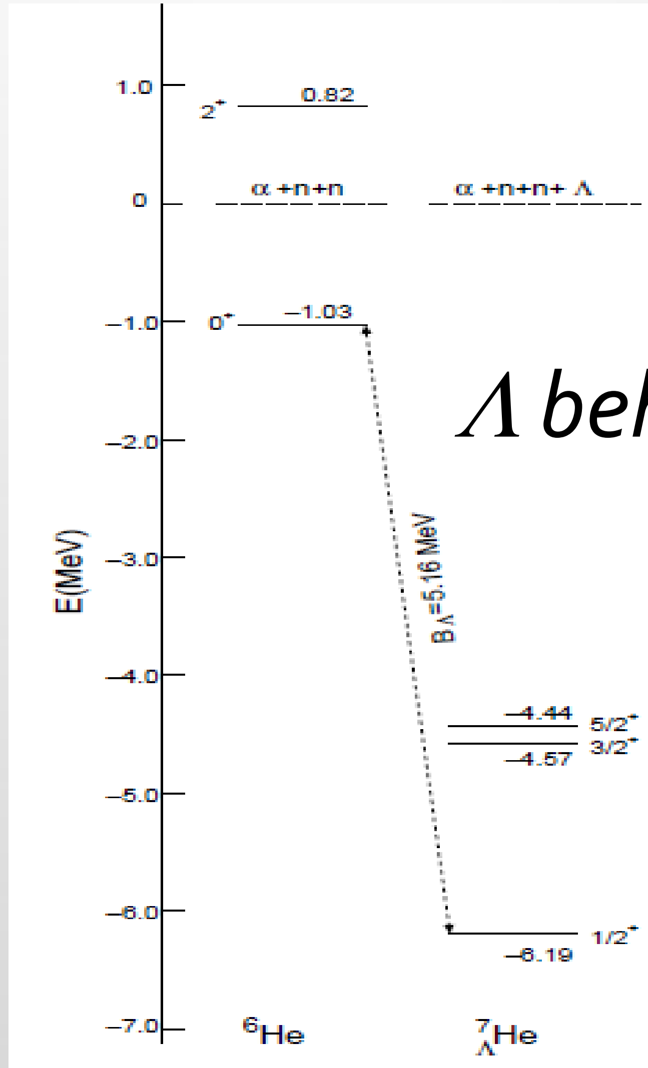
$^4_{\Lambda}H$	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
$^4_{\Lambda}He$	$\pi^- + {}^1H + {}^3He$	83	2.42 ± 0.05
	$\pi^- + {}^1H + {}^1H + {}^2H$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04

0.22 MeV difference

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



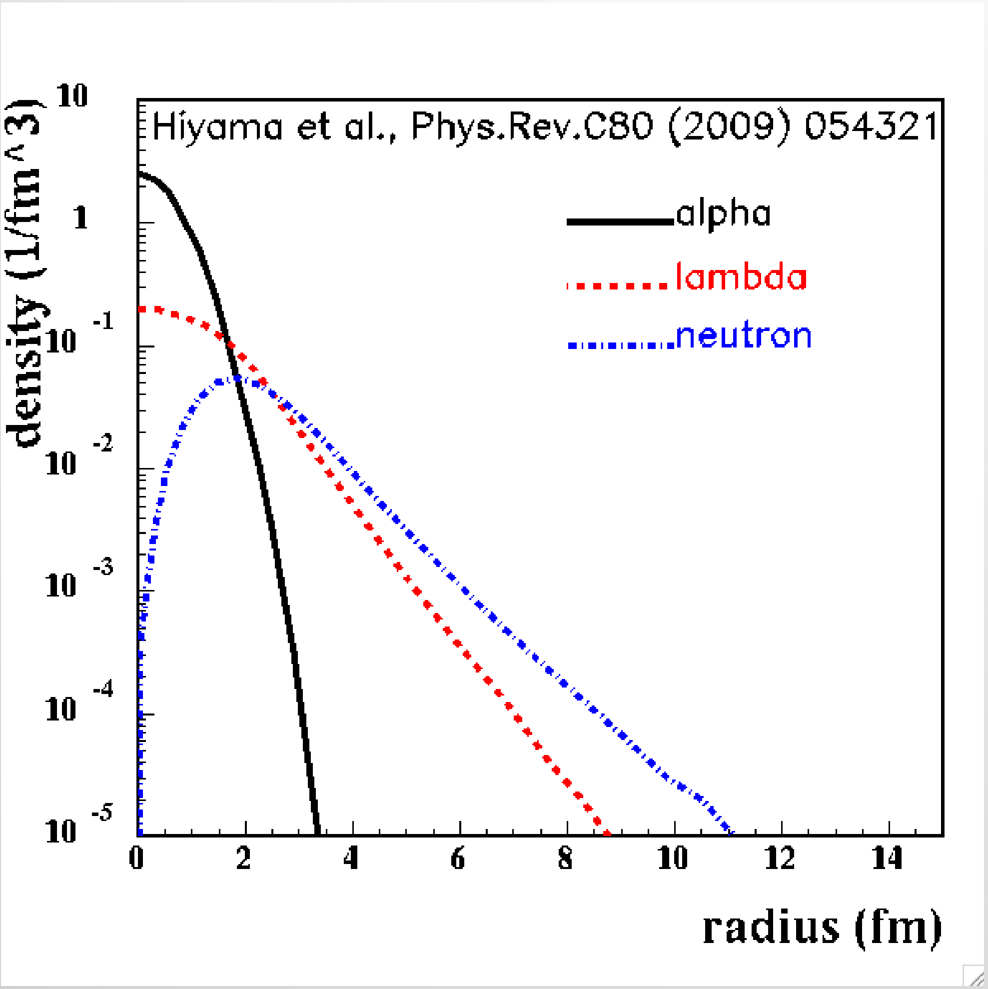
${}^{6}He$: 2n halo

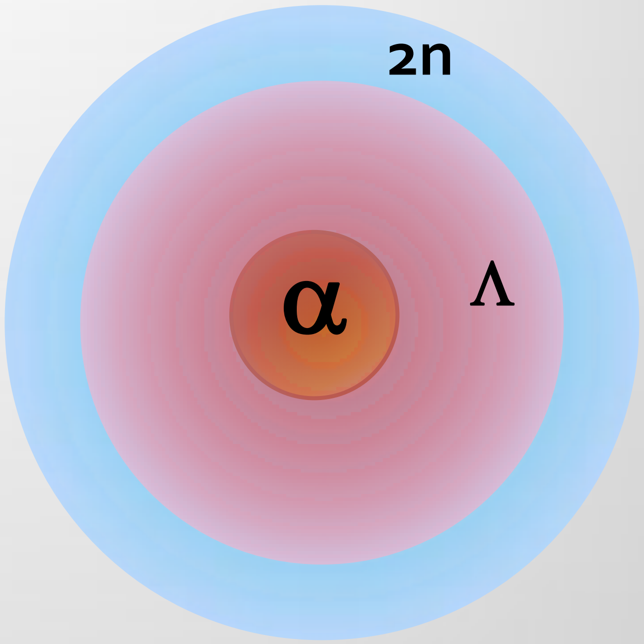


Λ behaves like glue

E.Hiyama et al. PRC (2009)

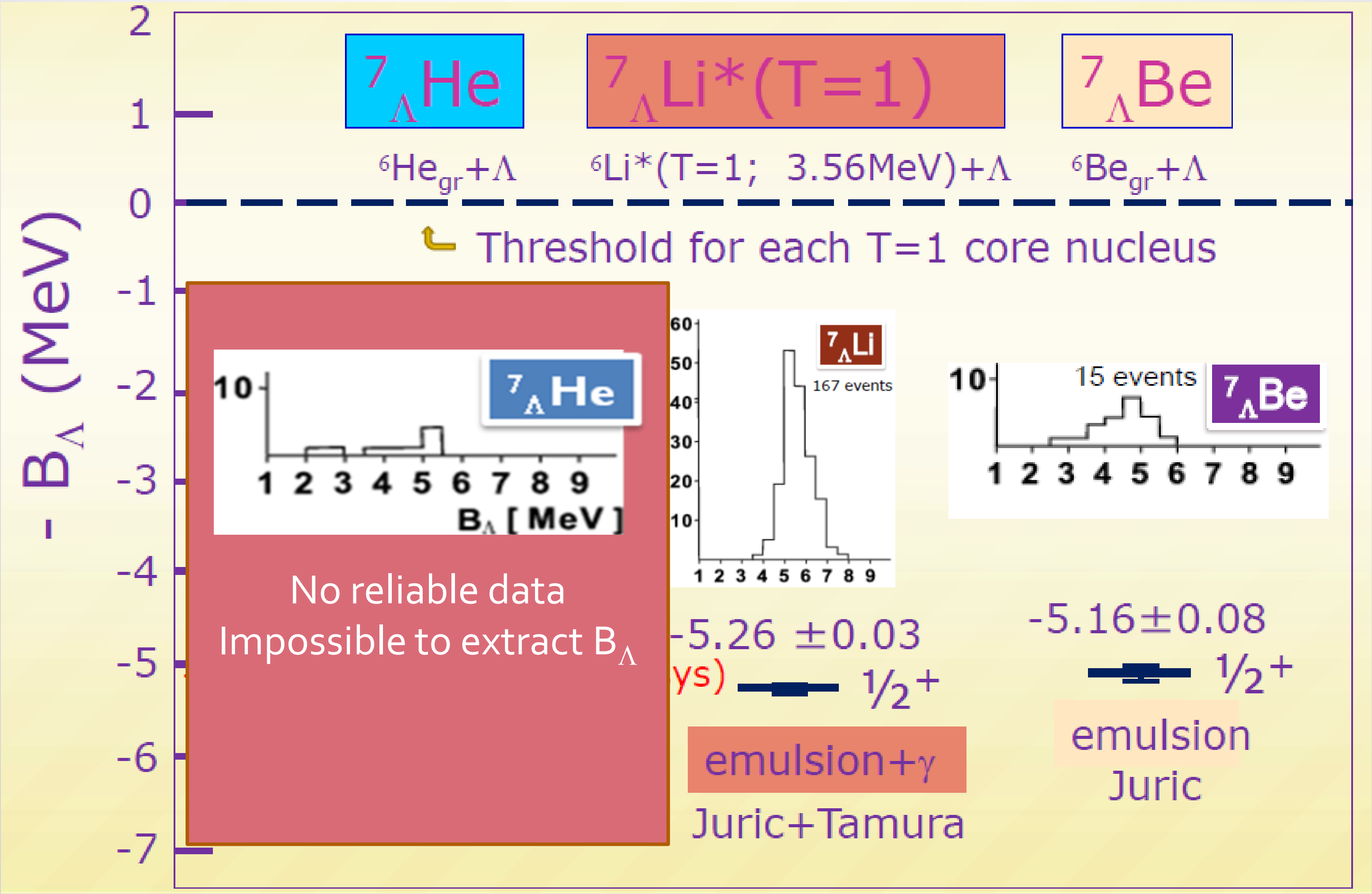
$^{7}_{\Lambda}$He Density Distributions





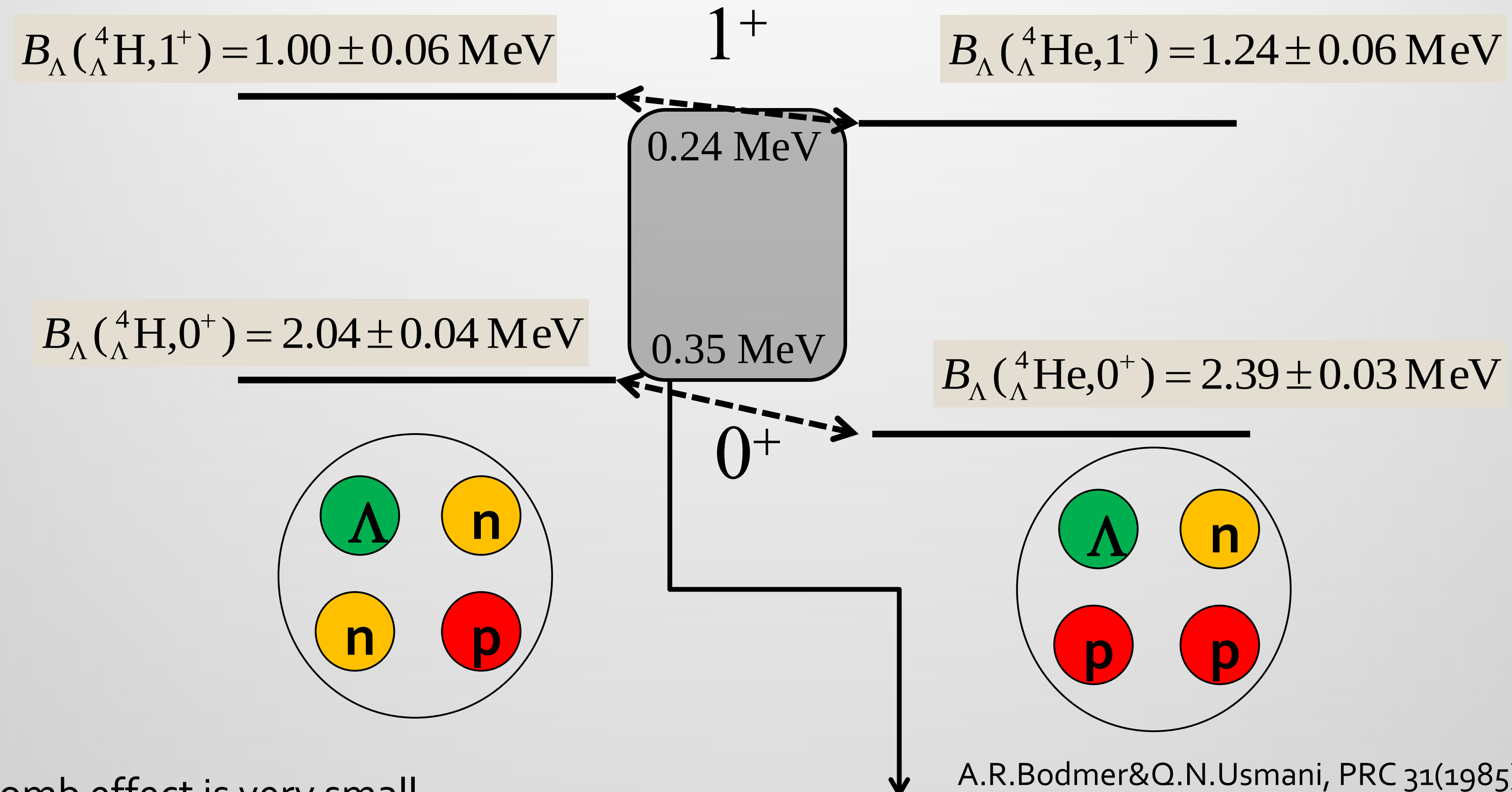
$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

First reliable observation of $^{7}_{\Lambda}He$ w/ good statistics



M.Juric et al. NP B52 (1973) 1

A=4 system
CSB ΛN interaction



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

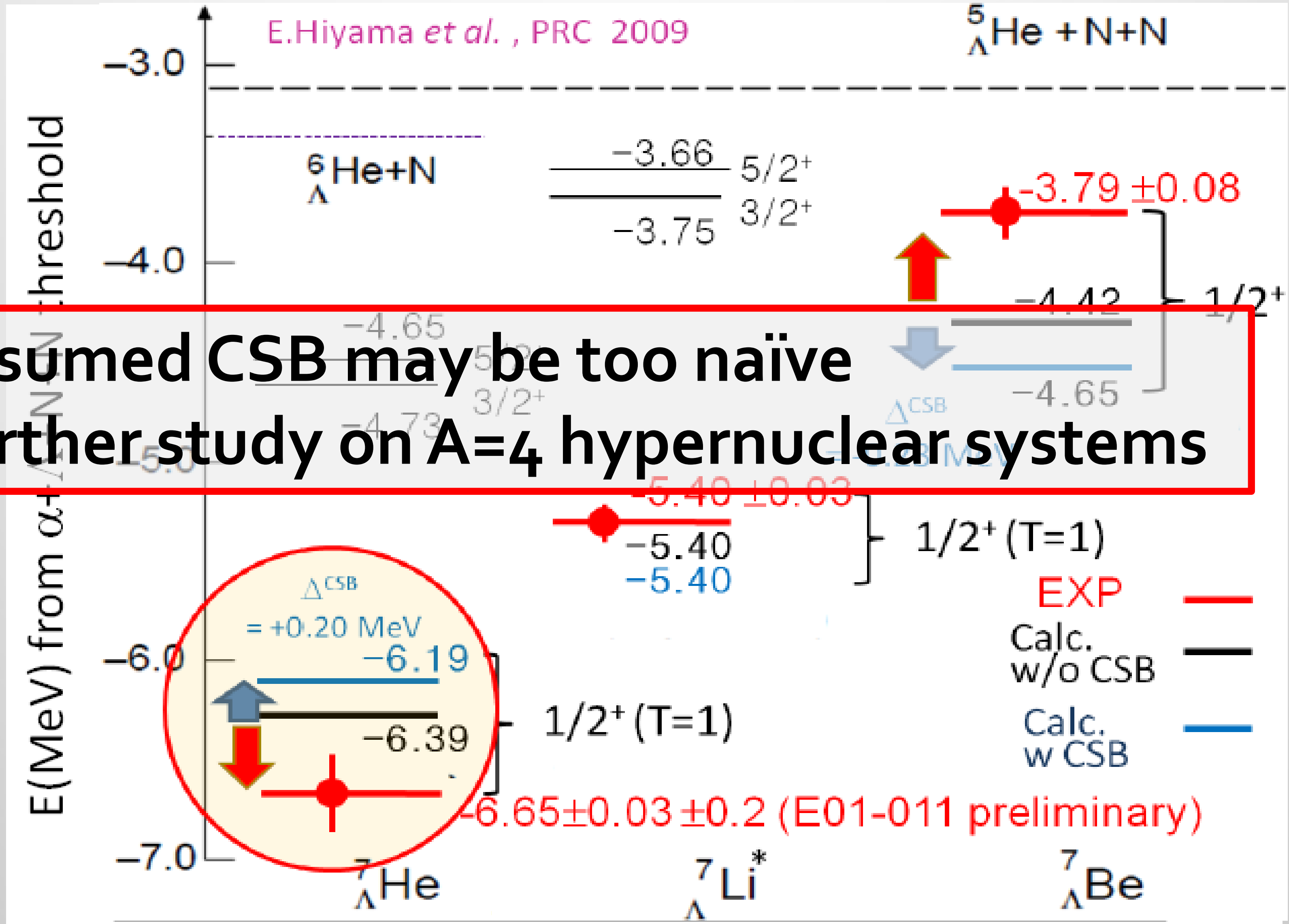
Coulomb effect is very small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV} ,$$
$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

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

CSB effect by cluster model

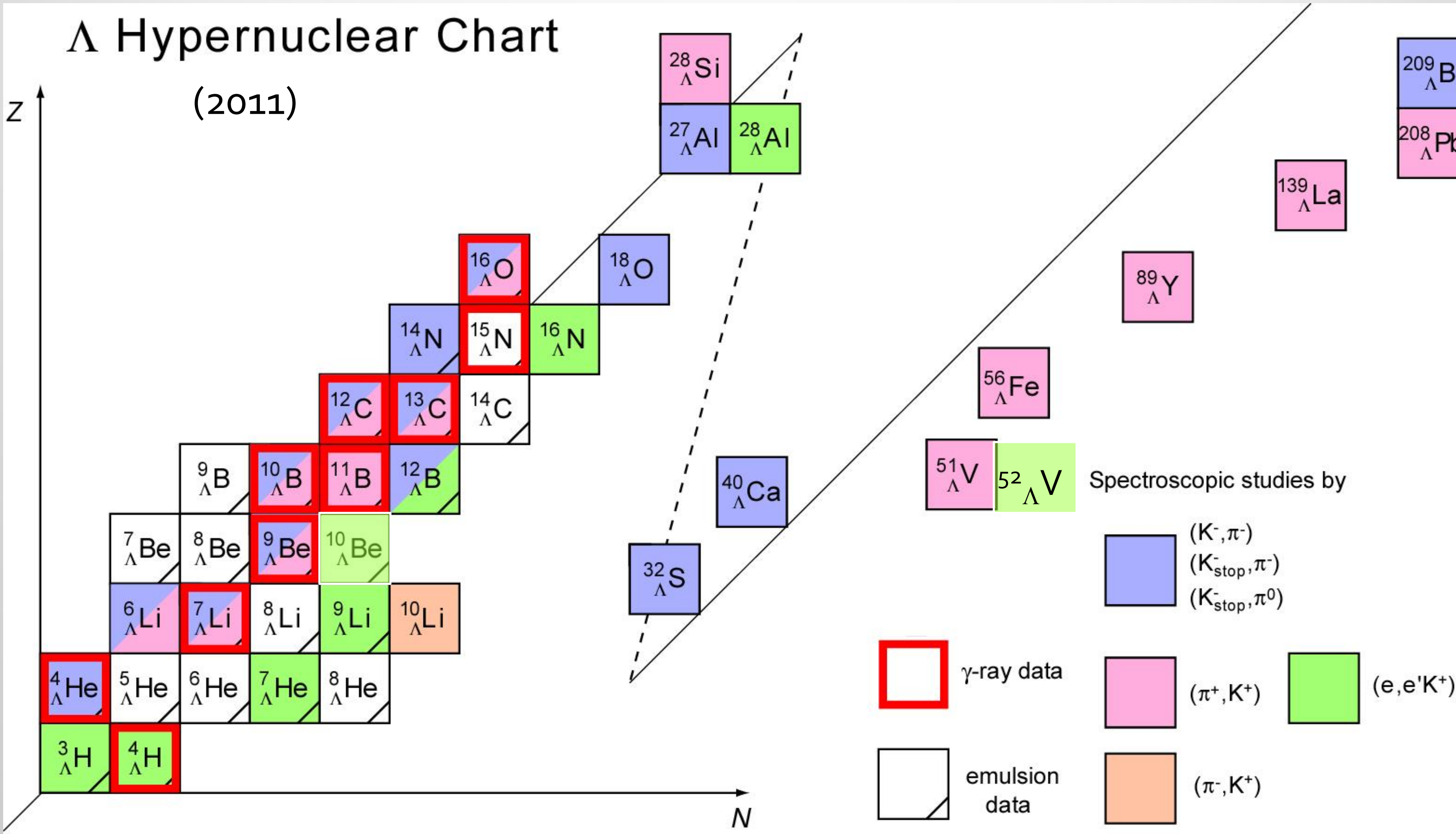
A=7, T=1 iso-triplet E.Hiyama *et al.* PRC80,054321(2009)



Assumed CSB may be too naïve

Further study on A=4 hypernuclear systems

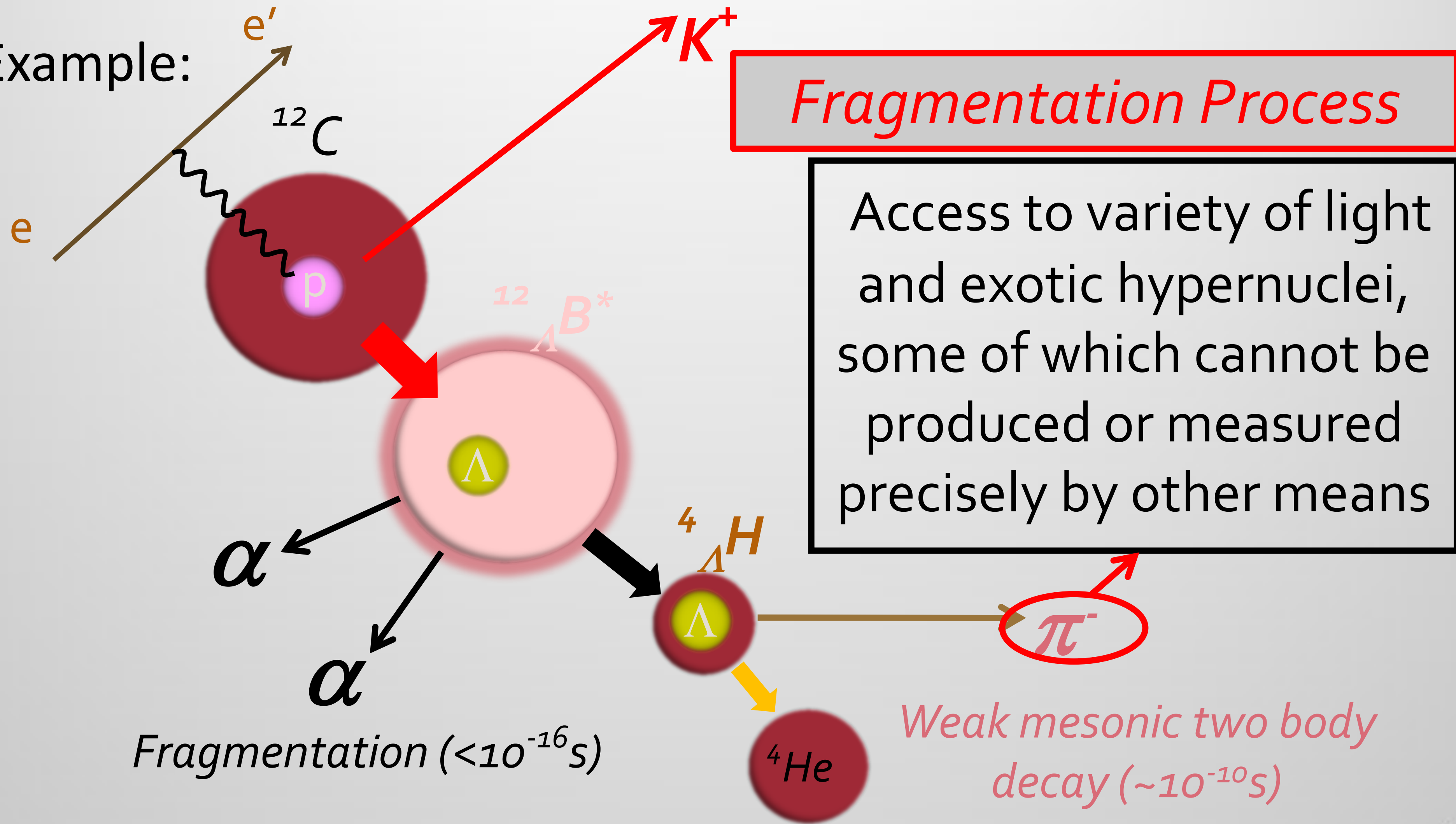
Present Status of Λ Hypernuclear Spectroscopy



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

Decay π Spectroscopy of electro-magnetically produced HY (JLab E10-001 and MAMI-C KaoS project)

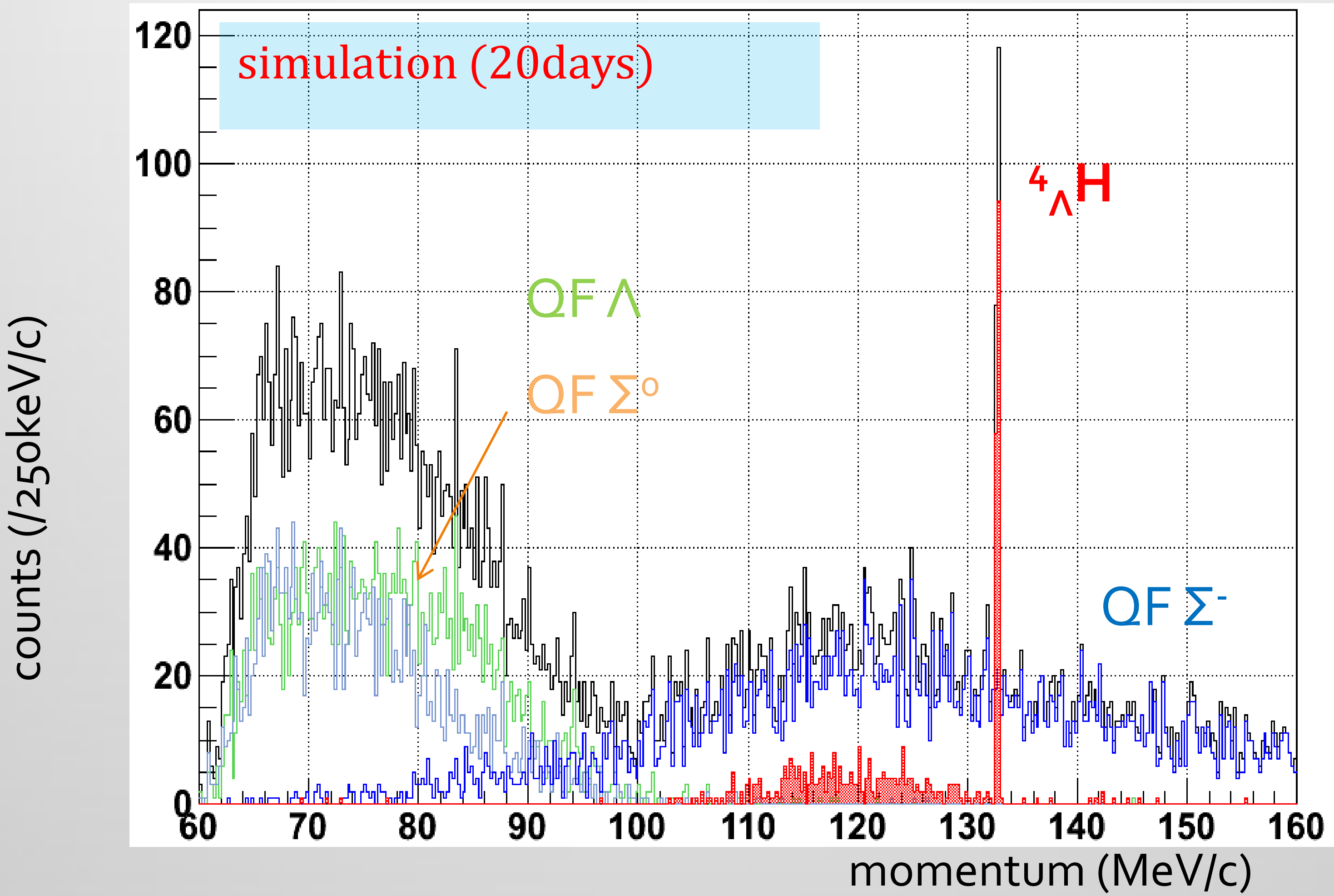
Example:



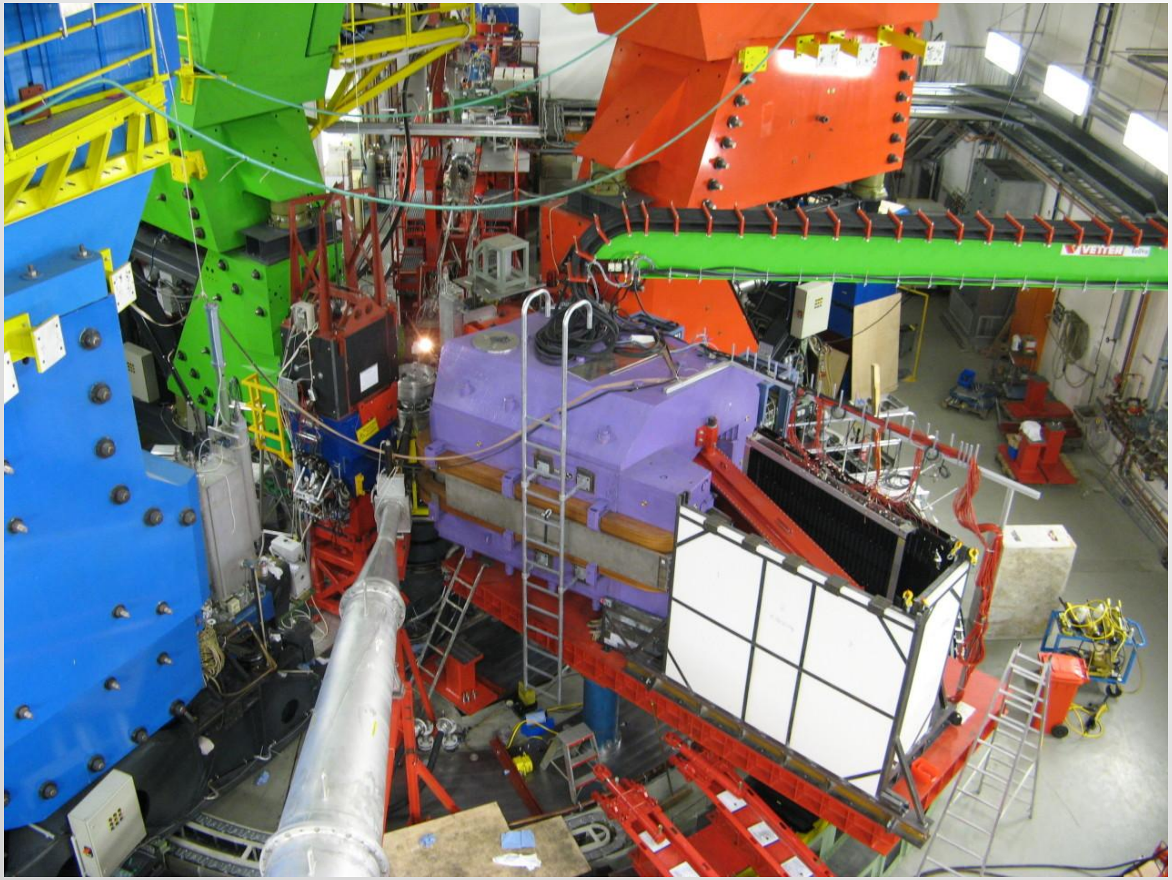
Expected Spectrum (simulation)

condition — beam current 50 uA, target **^{9}Be 30mg/cm^{2}**

$^{4}{}_{\Lambda}$H peak **140 counts/20days,** FWHM **110 keV/c**



KaOS at MAMI-C (Mainz Univ.)



Pilot runs have Started at MAMI-C

Summary

The (e,e'K$^+$) hypernuclear spectroscopy was ***initiated at JLab***.

We have been developing many tools (HKS, HES, SC-Septum) and techniques (Tilt-method, RICH, Water-fall target) in the last decade and **it is** ***now established***.

The (e,e'K) HY study at JLab/MAMI-C will play key role in the strangeness physics in collaborating with other facilities.