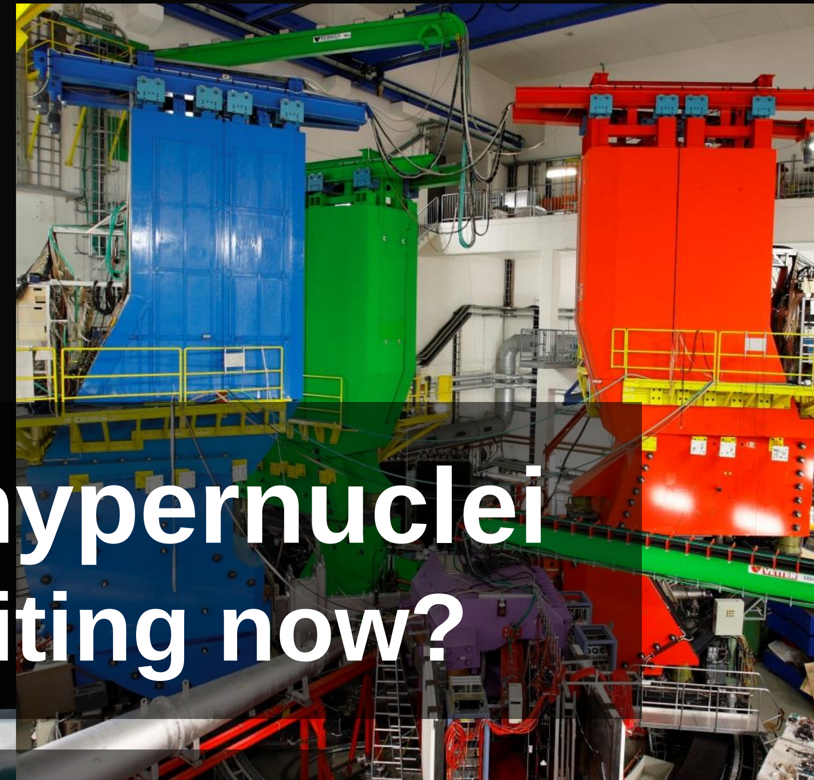


Overview of hypernuclei
What are exciting now?

Tohoku University
H. Tamura

Contents

1. Introduction
   Why we study hypernuclei?

2. ΛN interaction from light Λ hypernuclei
   A=4 charge symmetry breaking
   A very new result of $^{4}_{\Lambda}$He γ-ray

3. Toward strange nuclear matter in neutron stars
   Ξ / $\Lambda\Lambda$ hypernuclei and S=-2 BB interaction
   A new result of Ξ hypernuclei
   Heavy Λ Hypernuclei and ΛNN interaction

4. Summary

1. Introduction

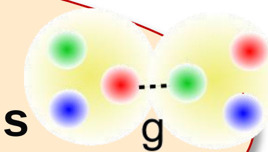
Why we study hypernuclei?

Motivations of hypernuclear physics

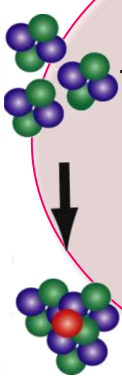
BB interactions

Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures

Test lattice QCD calculations



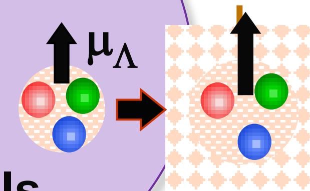
Impurity effect in nuclear structure



Changes of size,
deformation, clustering,
Appearing new symmetry,
…

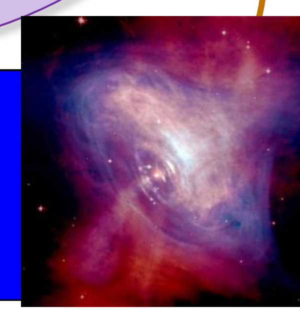
Properties and behavior of baryons in nuclei

μ_Λ in a nucleus,
Single particle levels
of heavy Λ hypernuclei
...



Clues to understand hadrons and nuclei from quarks

Cold and dense nuclear matter with strangeness



Importance of BB interactions

YN, YY interactions in free space

YN scattering

YY correlation in HIC

Light Hypernuclei (Few body systems)

YN, YY interactions in nuclear matter

= (YNN force / ρ dependence of YN, YN in neutron-rich matter)

Heavy hypernuclei

YN, YY interactions from high density matter in HIC ?

$\Rightarrow$ **Necessary to understand**
the baryonic matter EOS (=neutron star matter)
for $\rho \sim 0$ -- $5\rho_0$, with strangeness

Few-body Λ hypernuclei

Exact calculations possible

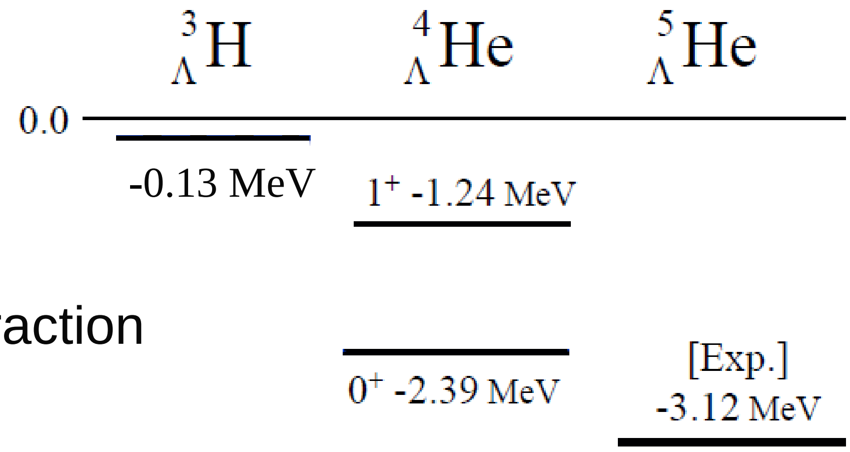
A=3 $^{3}_{\Lambda}H$ B_{Λ} =130 keV => stringent test for ΛN interaction

$\tau < 200$ ps (by HIC): why so short??

Weak decay branches not measured well

nnΛ bound ?

pnΛ(T=1) ?



A=4 $^{4}_{\Lambda}H$/ $^{4}_{\Lambda}He$

0+/1+ ΛN spin-spin, ΛN–ΣN interaction

Charge symmetry breaking ?

A=5 $^{5}_{\Lambda}He$

Overbinding problem

=> B_{Λ}(A=3,4,5) explained well with ΛN–ΣN interaction

2. ΛN interaction from Light Λ hypernuclei

Charge Symmetry Breaking in A=4

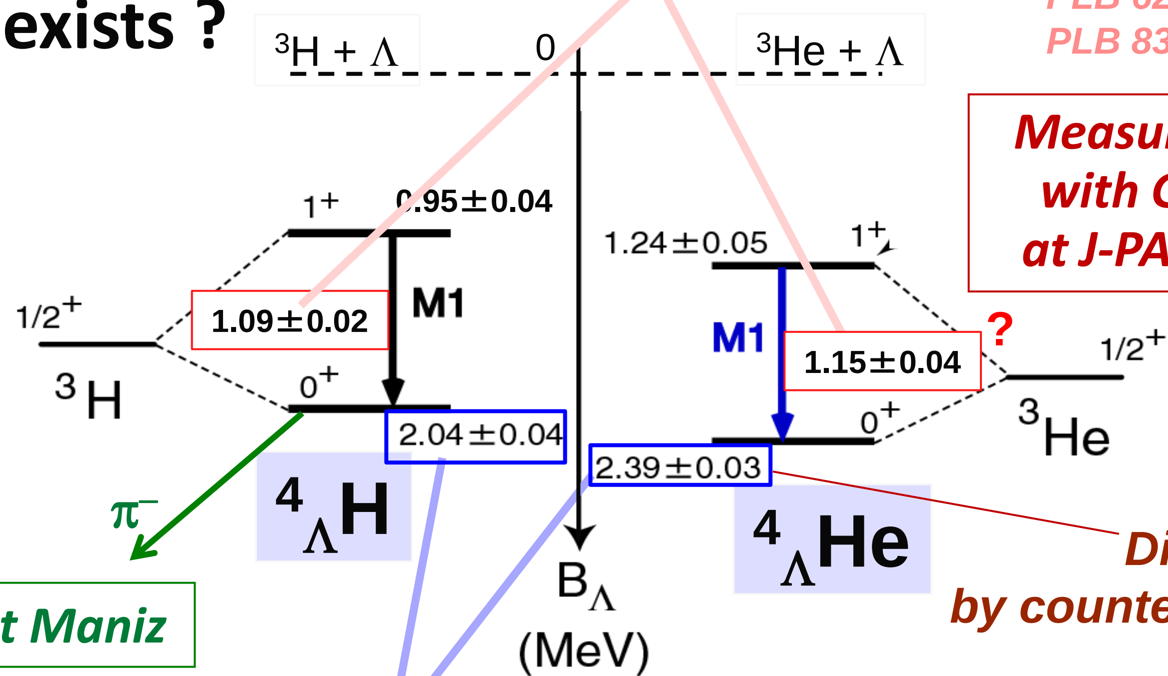
Charge Symmetry Breaking puzzle in A=4

$\Lambda n \neq \Lambda p$

a large CSB exists ?

Old NaI data

Bedjidian et al.
PLB 62 (1976) 467
PLB 83 (1979) 252



Measured with Ge at J-PARC

Difficult by counter experiments

Measured at Maniz

A. Esser et al., PRL 114 (2015) 12501

no systematic error

Old emulsion data

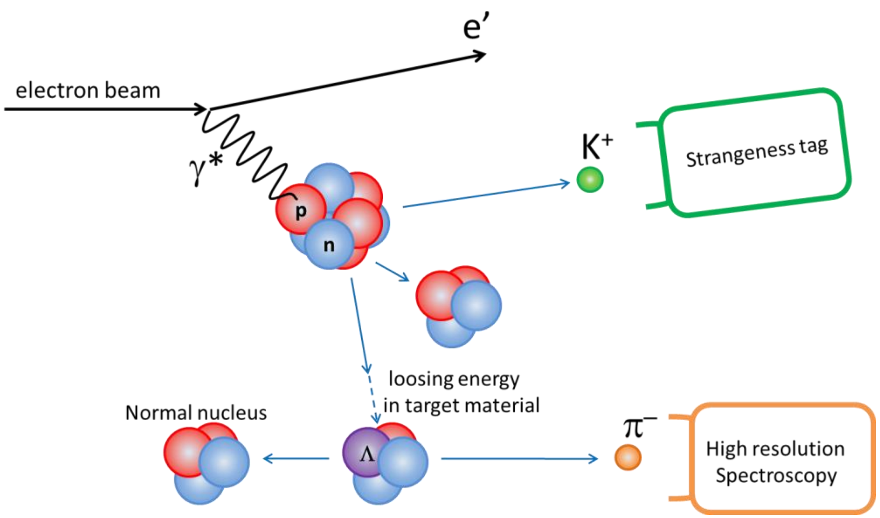
M. Juric et al. NPB 52 (1973) 1

Experimental confirmation of CSB also necessary

Origin is unkown.
ΛN-ΣN coupling? But 4-body calc's with Λ–Σ mixing using Nijmegen interactions give ΔB < 100keV
=> Long standing puzzle

Slide by Achenbach

Pion decay spectroscopy @Mainz



Primary Beam

Energy	1.5 GeV

Target

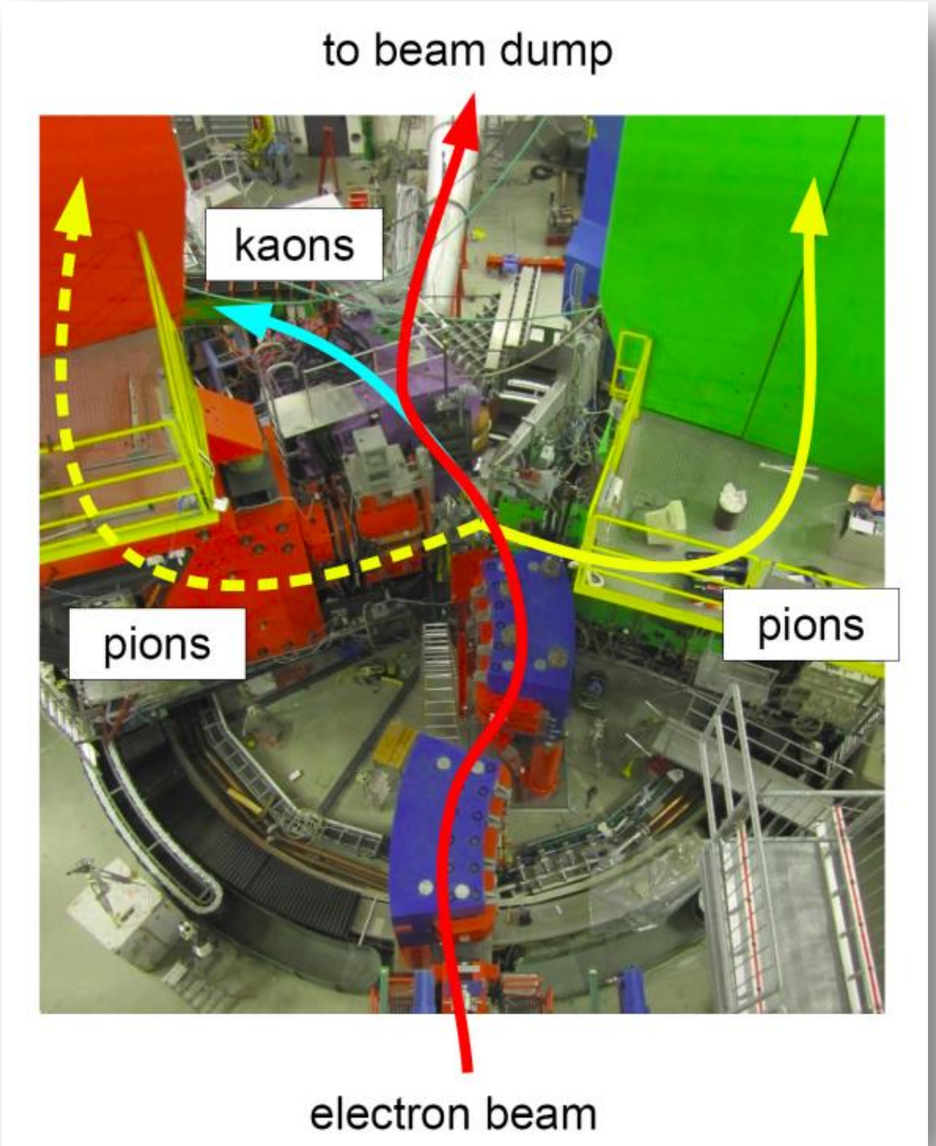
Material	^{9}Be
Thickness	125 μm
Tilt angle	54 deg

Kaos

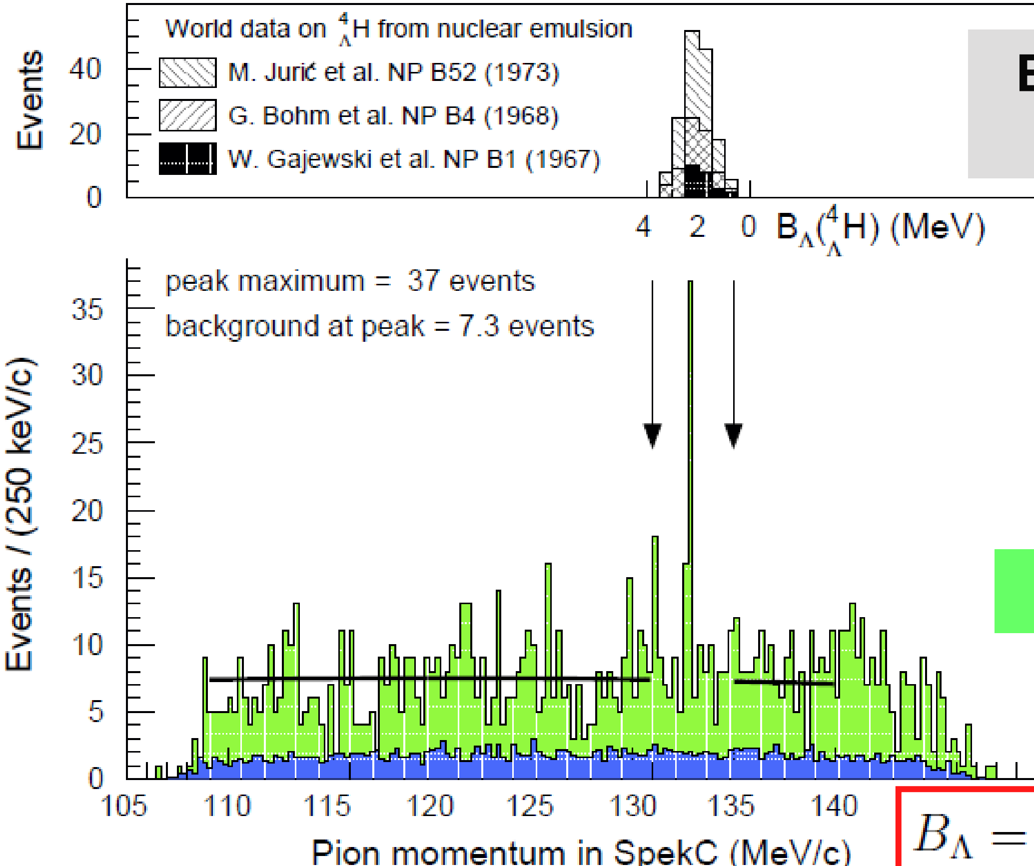
Cent. Mom	+900 MeV/c
Detector	MWPC, TOF, AC

Spek-A, C

Cent. Mom	- 115/ -125 MeV/c
Detector	DC, TOF, GC



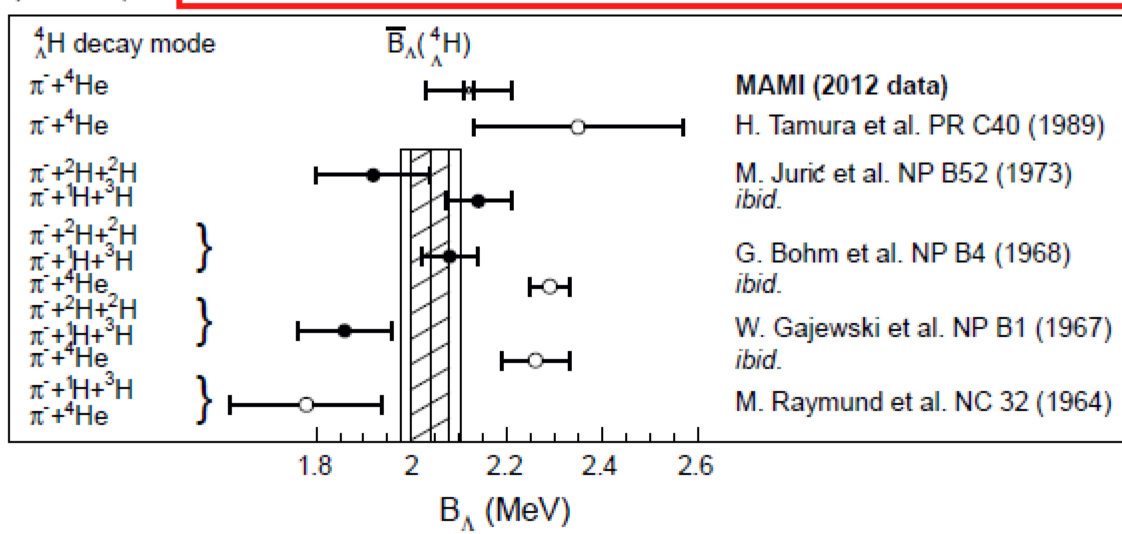
MAMI Result



Emulsion data

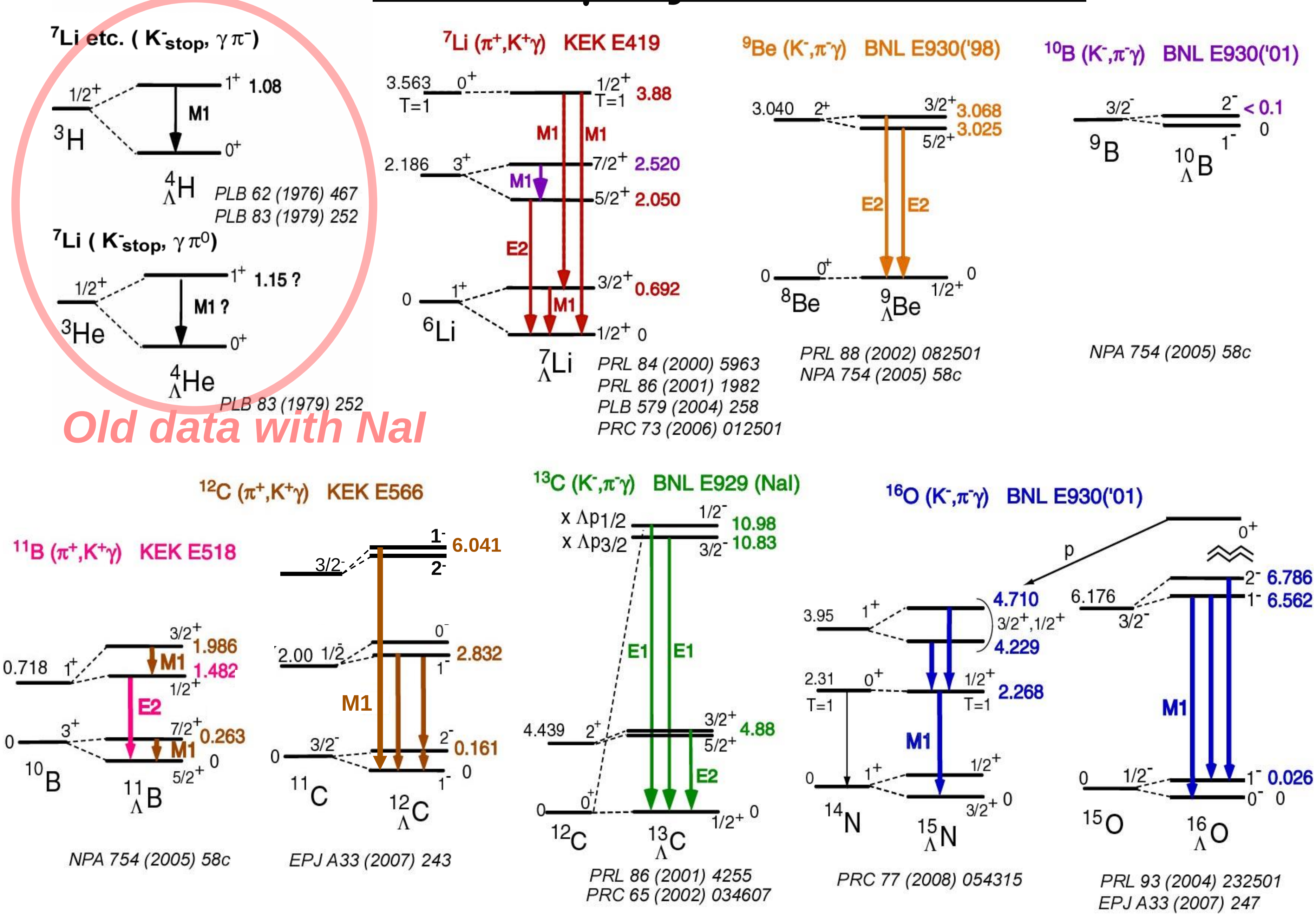
MAMI data

$$B_\Lambda = 2.12 \pm 0.01\ (\text{stat.}) \pm 0.09\ (\text{syst.})\ \text{MeV}$$



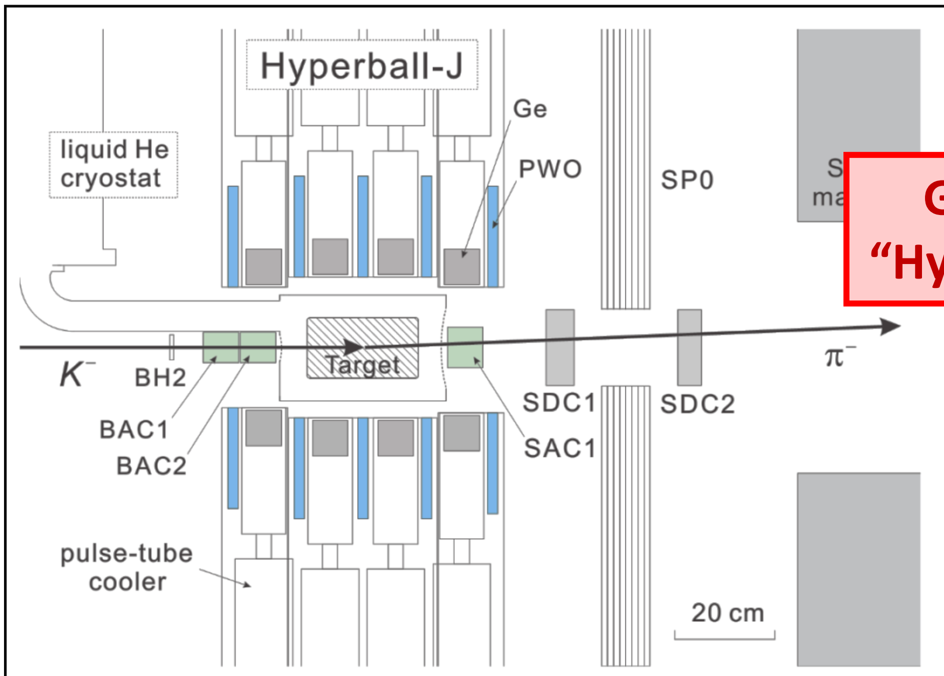
A. Esser et al., PRL 114 (2015) 12501

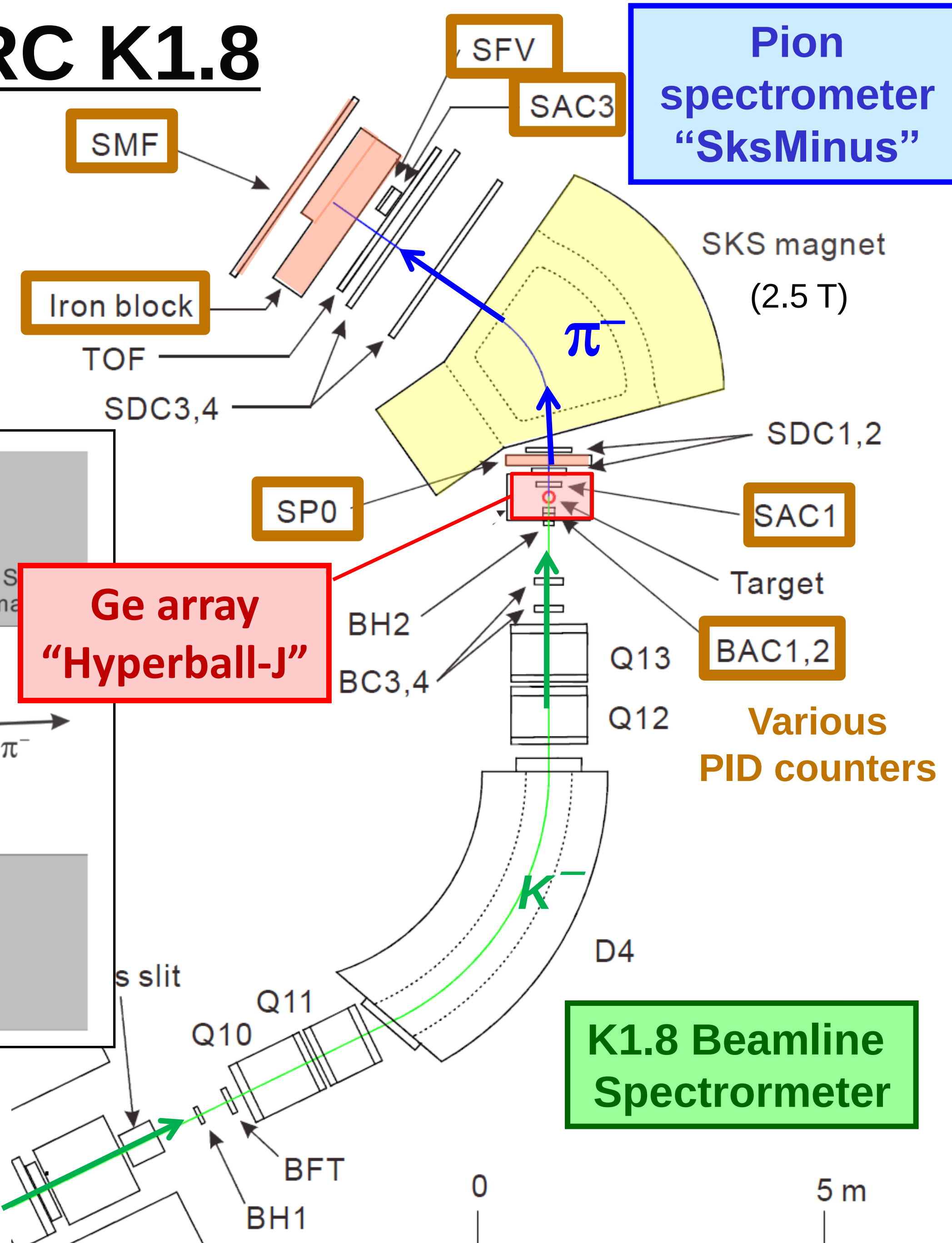
Hypernuclear γ-ray data as of 2014



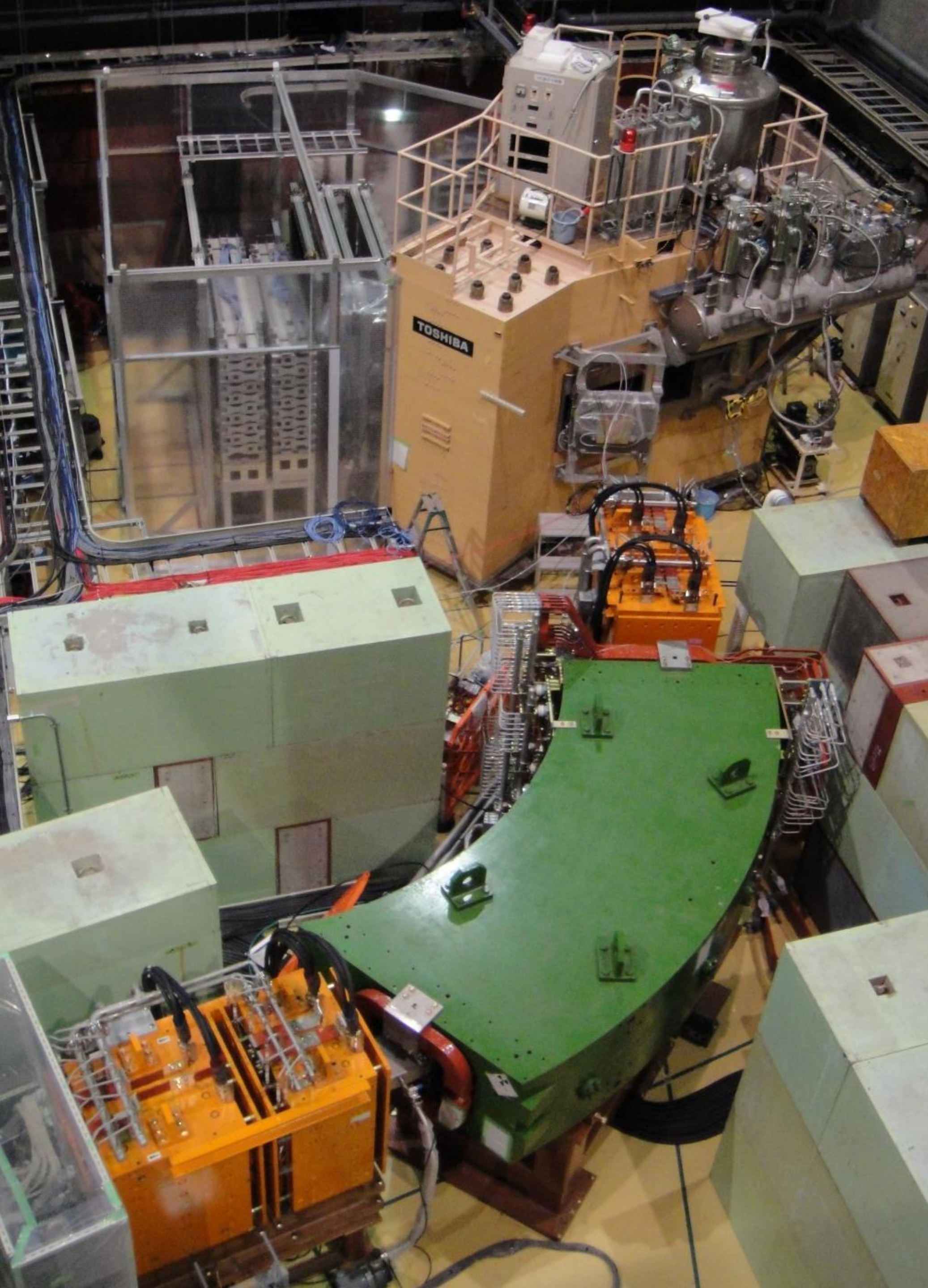
E13 Setup at J-PARC K1.8

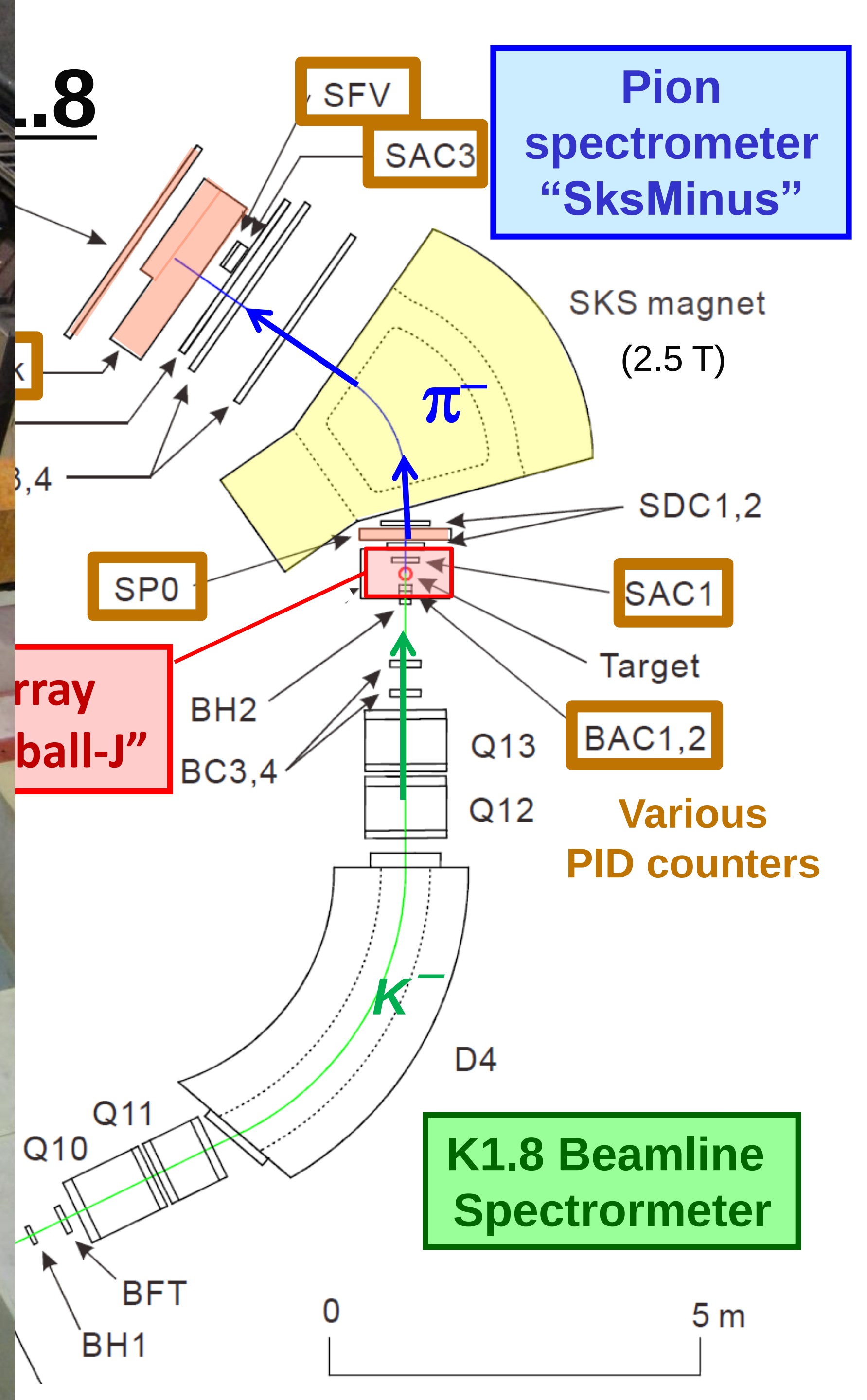
$$ {}^{A}Z\,(K^-,\pi^-)\,{}^{A}_{\Lambda}Z^* \rightarrow {}^{A}_{\Lambda}Z + \gamma $$

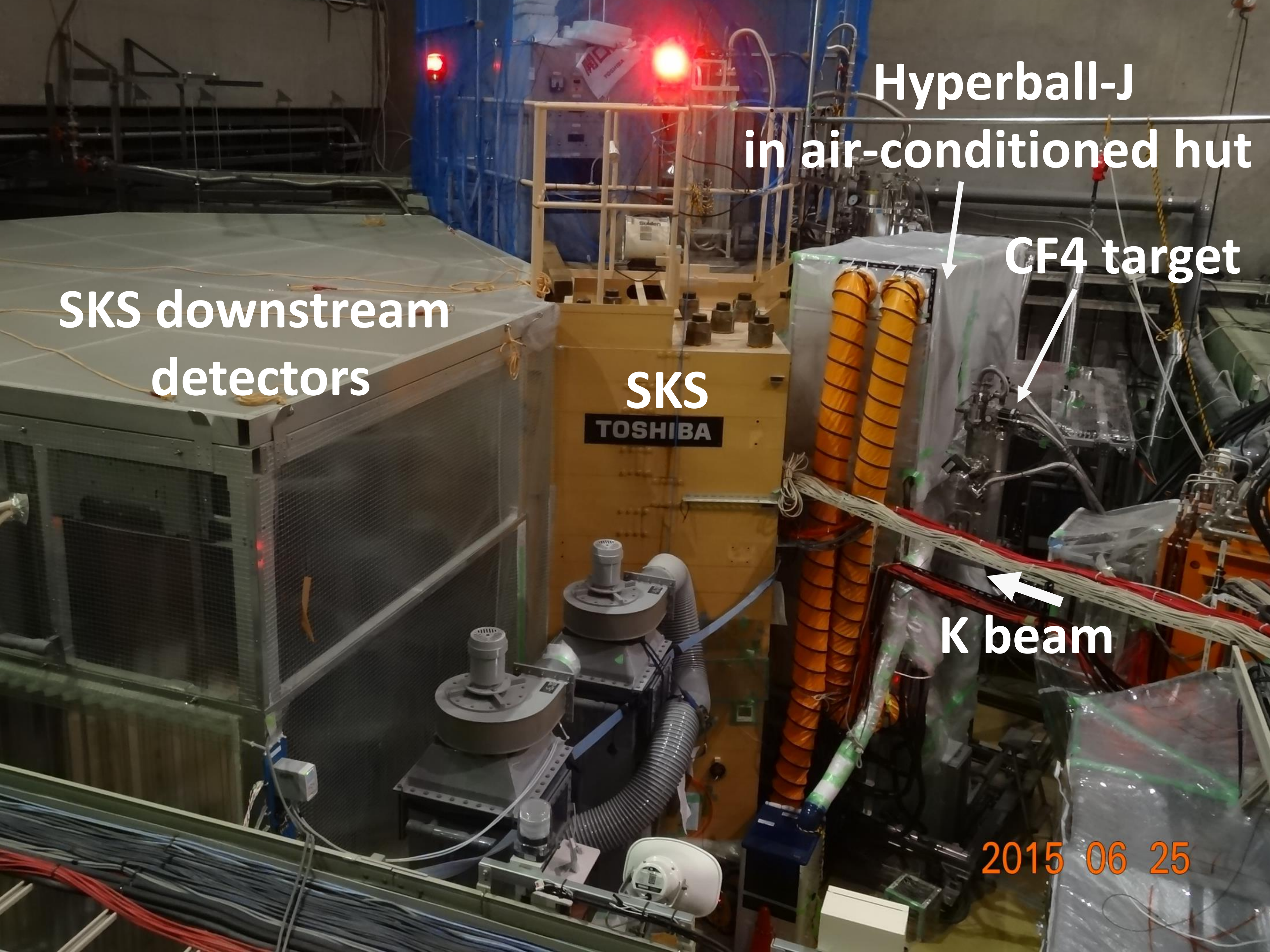




${}^{4}_{\Lambda}$He : liq.He target (2.5 g/cm^2)
p_K = 1.5 GeV/c
${}^{19}_{\Lambda}$F : HF -> CF_4 target (20 g/cm^2)
p_K = 1.8 GeV/c




SFV
SAC3
Pion spectrometer “SksMinus”
SKS magnet
(2.5 T)
π^-
SDC1,2
SP0
SAC1
Target
BH2
BC3,4
Q13
BAC1,2
Q12
Various PID counters
K^-
D4
Q11
Q10
K1.8 Beamline Spectrormeter
BFT
BH1
0
5 m

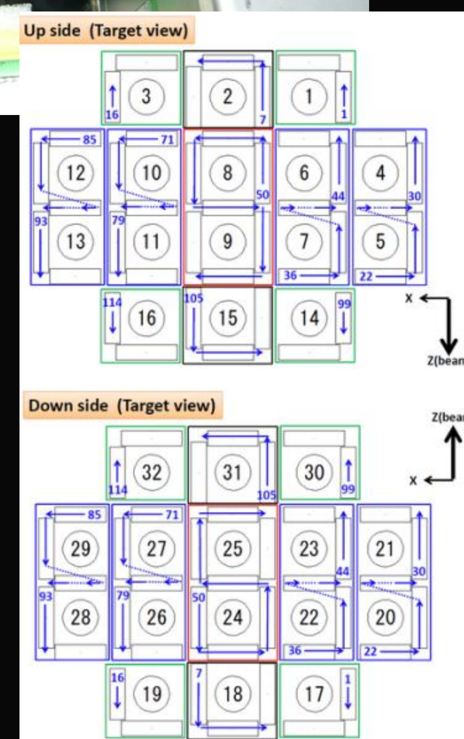

Hyperball-J
in air-conditioned hut
CF4 target
SKS downstream
detectors
SKS
TOSHIBA
K beam
2015 06 25

Hyperball-J

Ge cooled down to ~70K by pulse-tube refrigerator (c.f. 92K w/LN2)

Fast background suppressor made of PWO

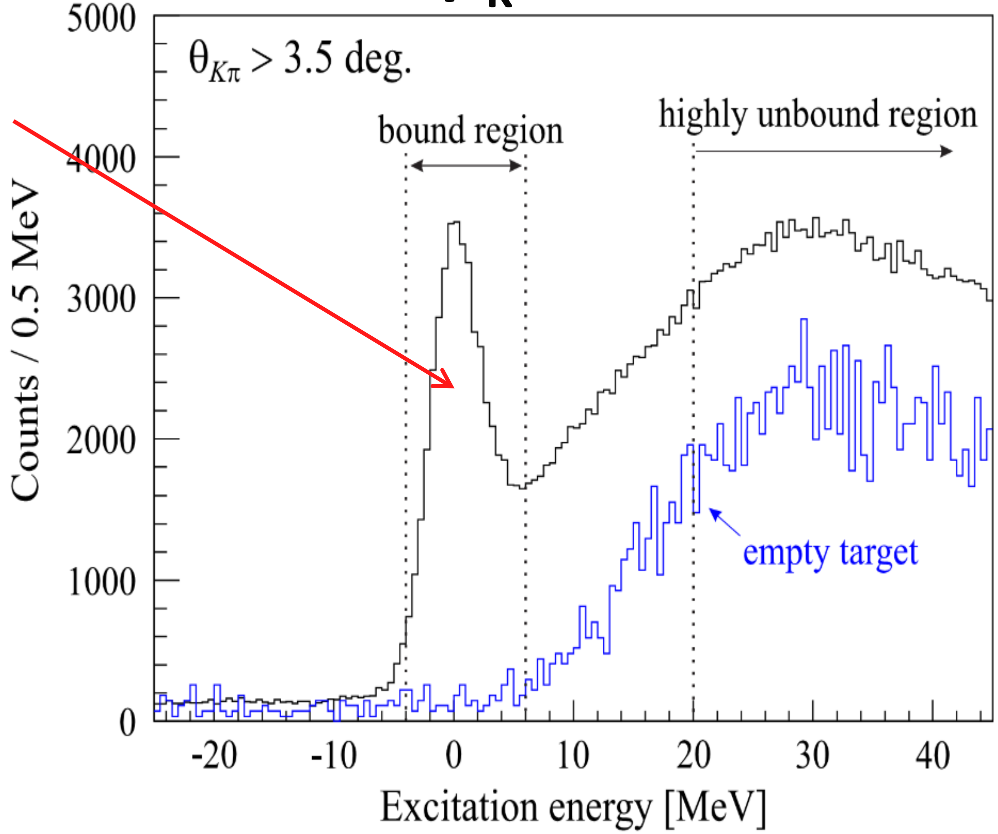
ΔE= 3.1(1) keV at 1.33 MeV
Eff. = 5.4% @1 MeV
with 28 Ge(re=60%)



E13 Missing mass: $^{4}He(K^{-},\pi^{-})\ ^{4}_{\Lambda}He$

p_K=1.5 GeV/c

$^{4}_{\Lambda}He(0^{+})$ dominant
+
$^{4}_{\Lambda}He(1^{+})$



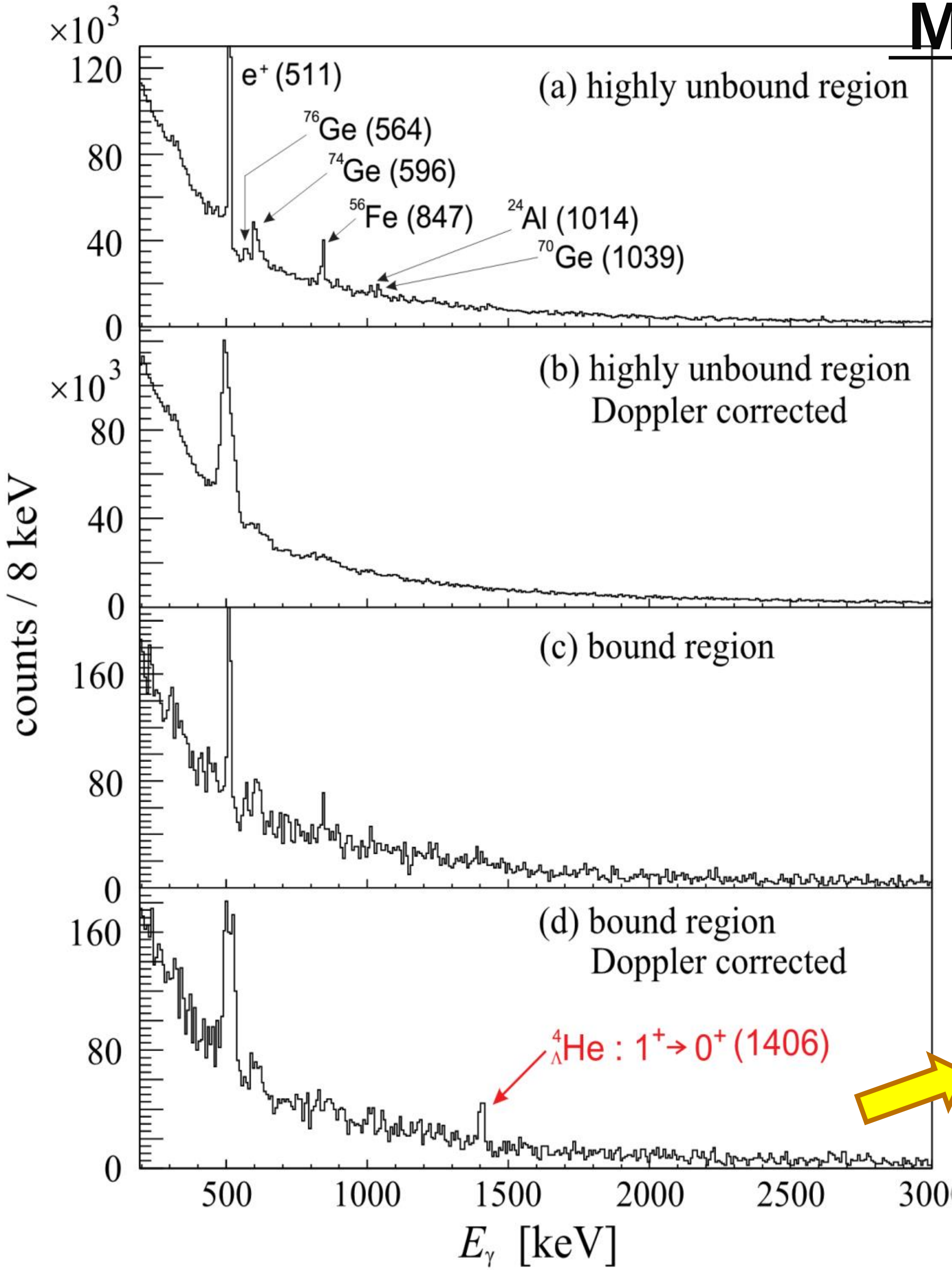
Peak width
= resolution
~5.4 MeV (FWHM)

Black : with liq. He (physics run)

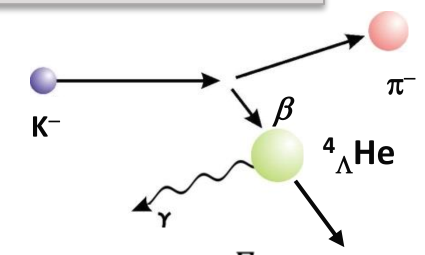
Blue : empty target
(w/o liq. He, w/target cell)

Byproduct:
Spectrum for $^{4}_{\Sigma}He$ (p_K=1.5 GeV/c)
was also successfully taken.

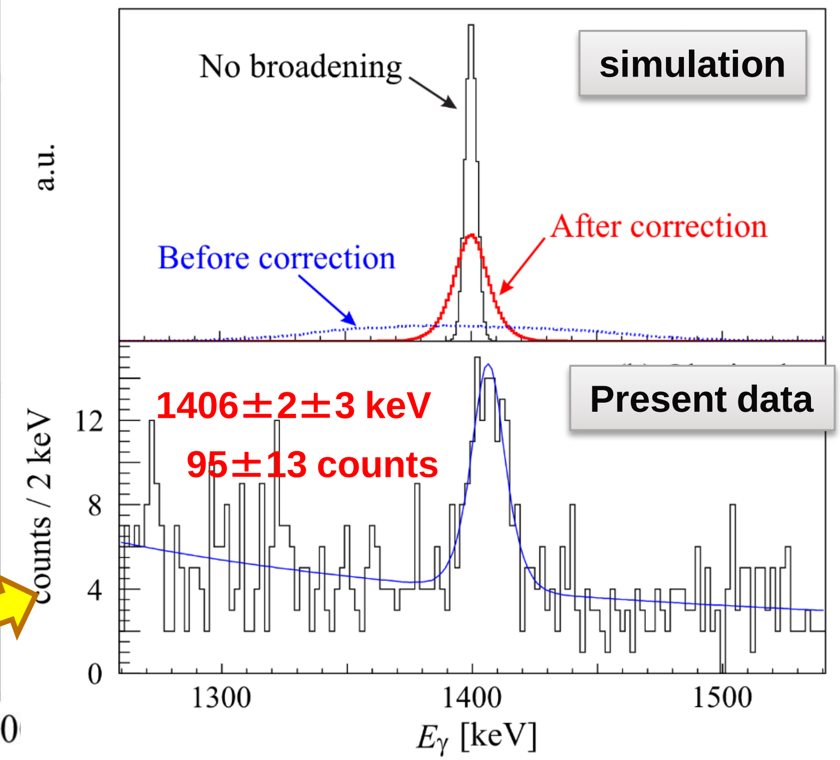
Mass-gated γ spectrum



Doppler shift correction

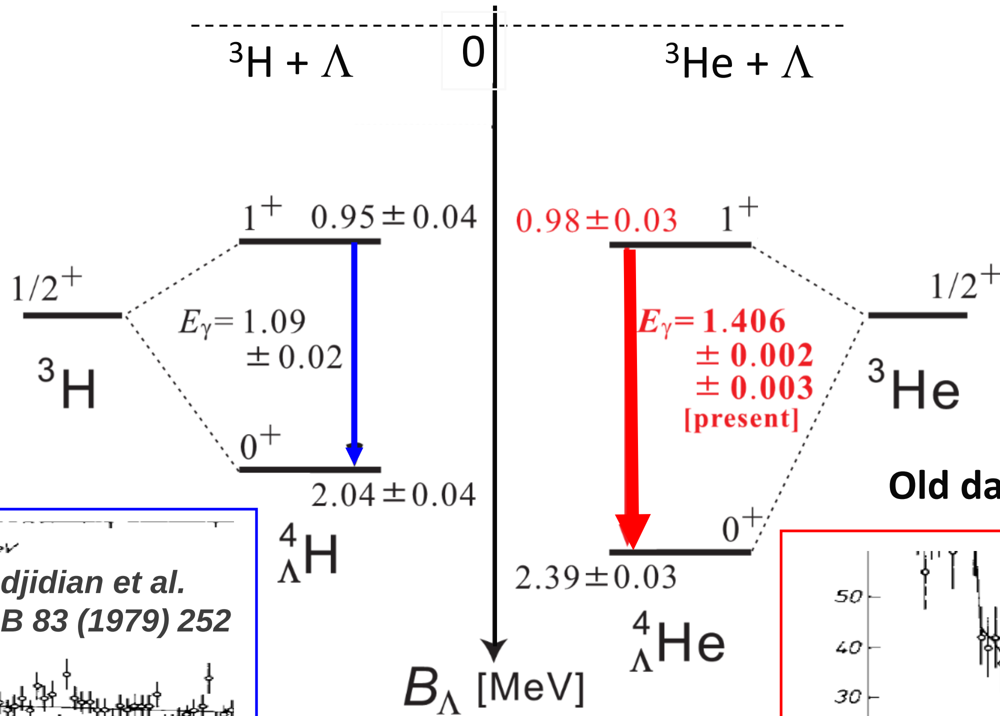


$$E_{corrected} = \frac{E_{measured}}{\gamma(1 + \beta cos\theta_\gamma)}$$

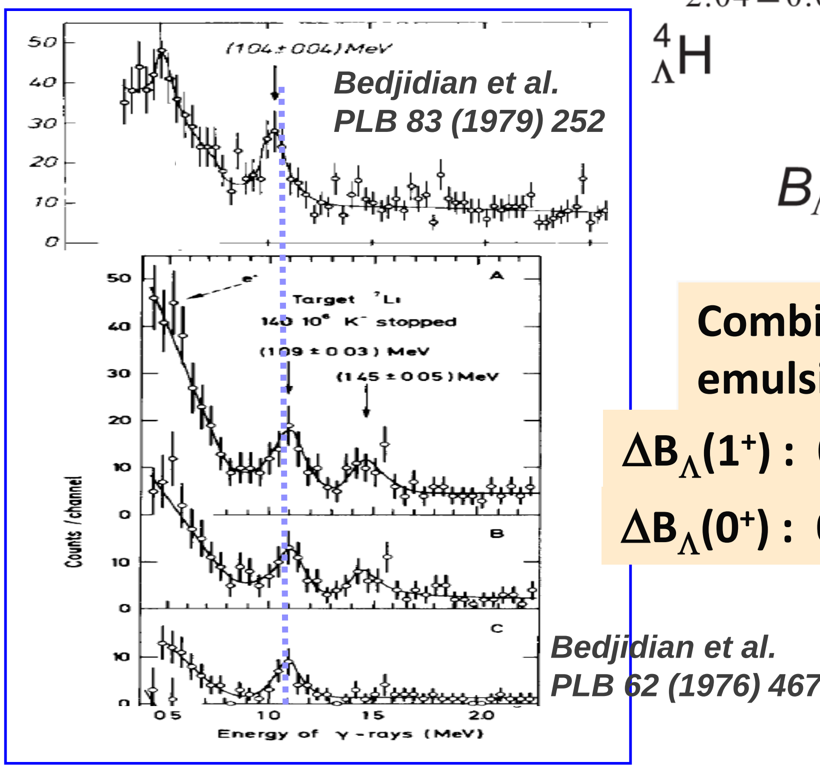


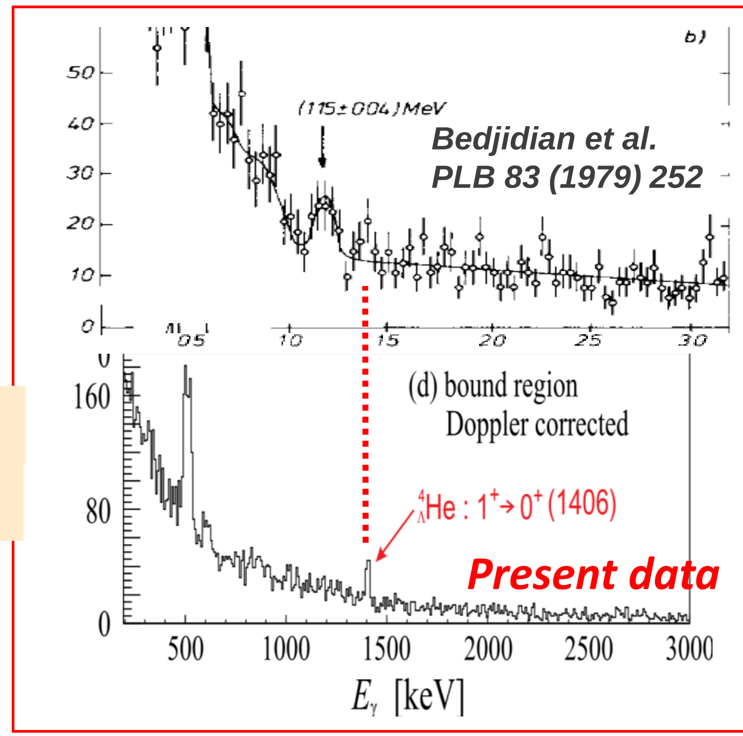
1^+ cross section seems lower by 1/2-1/3

Results



Old data (1.15 MeV) was denied.





Combining with emulsion data,

$\Delta B_\Lambda(1^+)$: 0.03±0.05 MeV

$\Delta B_\Lambda(0^+)$: 0.35±0.05 MeV

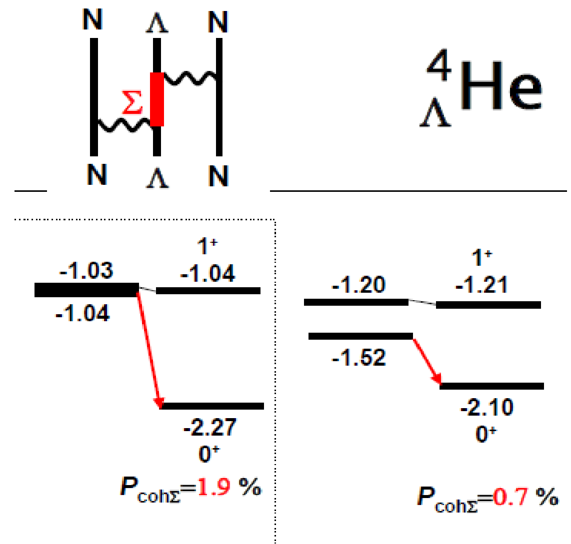
- **Existence of CSB confirmed only by γ-ray data**
- **Large spin dependence in CSB found by combining with emulsion data**

ΛN–ΣN coupling

From Akaishi's slide

	$^4_\Lambda$H	
S=1 pairs	1⁺	0⁺
$\Lambda p \Leftrightarrow -\sqrt{\frac{1}{3}}\Sigma^0 p + \sqrt{\frac{2}{3}}\Sigma^+ n$ $\begin{bmatrix} s_3=1 \\ s_3=0 \\ s_3=-1 \end{bmatrix}$ $\Lambda n \Leftrightarrow \sqrt{\frac{1}{3}}\Sigma^0 n - \sqrt{\frac{2}{3}}\Sigma^- p$ $\begin{bmatrix} s_3=1 \\ s_3=0 \\ s_3=-1 \end{bmatrix}$	-1/3 +1/3 (Cancel) +1/2	+1/2 +1/2 +1/2 (Coherently added)
Contribution to $U_{\Sigma\Lambda}$	1/2	3/2
Λ-Σ coupling energy	1 :	9

Our result strongly suggests that ΛN–ΣN coupling is responsible for CSB, because ΛN–ΣN coupling gives by one order smaller energy shift to 1+ state than to 0+ state.



Y. Akaishi et al.
PRL 84 (2000) 3539

ΛN -ΣN | D2 *central* | SC97e(S) *tensor-dominated*

Table 2: Calculated CSB contributions to $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and total values of $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and $\Delta B^4_\Lambda(1^+_{\rm exc})$, in keV, from several model calculations of the $A=4$ hypernuclei. Recall that $\Delta B^{\rm exp}_\Lambda(0^+_{\rm g.s.}) = 350 \pm 60$ keV [3].

$^4_\Lambda$He–$^4_\Lambda$H model	$P_\Sigma(\%)$ $0^+_{\rm g.s.}$	ΔT_{YN} $0^+_{\rm g.s.}$	ΔV_C $0^+_{\rm g.s.}$	ΔV_{YN} $0^+_{\rm g.s.}$	ΔB^4_Λ $0^+_{\rm g.s.}$	ΔB^4_Λ $1^+_{\rm exc}$
ΛNNN [9]	–	–	−42	91	49	−61
NSC97$_e$ [10]	1.6	47	−16	44	75	−10
NSC97$_f$ [11]	1.8				100	−10
NLO chiral [12]	2.1	55	−9	–	46	
$(\Lambda\Sigma)_e$ [present]	0.72	39	−45	232	226	30
$(\Lambda\Sigma)_f$ [present]	0.92	49	−46	263	266	39

"D2" potential

A. Gal, PLB 744 (2015) 352

Theoretical studies will elucidate the origin of CSB and the ΛN -ΣN interaction.

3. Toward
Strange matter in neutron stars

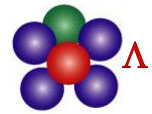
Under preparation
(Partly) took data

Status of Strangeness NP @J-PARC

toward neutron star matter

------- S=-1 --------

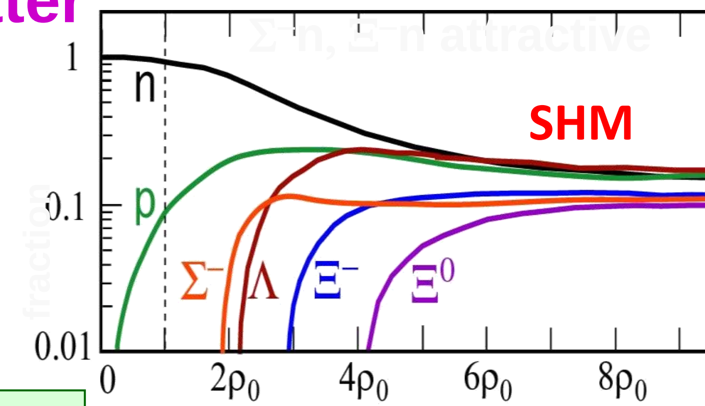
- n-rich Λ hypernuclei by (π^-,K^+) E10



- γ spectroscopy of Λ hypernuclei E13

  -> ΛN, ΛN-ΣN (ΛNN) int.

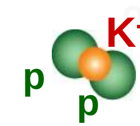
  => Fraction of Λ in n-rich matter



- K^-pp by $^3He(K^-,n)$ E15
- K^-pp by $d(\pi^+,K^+)$ E27

  -> $K^{bar}N$ int. in matter => K condensation in n star?

  Property of high density nuclear systems



- $\Sigma^{\pm}p$ scattering E40

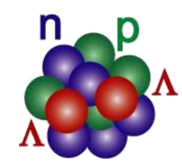
  -> Σ^-n (= Σ^+p) (Quark Pauli effect) , Σ^-p->ΛN int. => Σ^- exists in n-star?

------- S=-2 --------

- ΛΛ hypernuclei E07

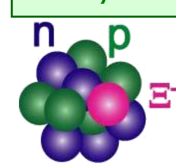
  -> ΛΛ interaction , ΛΛ correlation?

  => Λ fraction in Strange Hadronic Matter



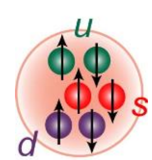
- Ξ hypernuclear spectroscopy E05
- Ξ atomic X rays E03, E07

  -> ΞN interaction => Ξ^- exists in n-star?



- H dibaryon search from H-> ΛΛ, $\Lambda p\pi^-$ E42

  -> Short-range BB force (Color magnetic int.)



First observation of a Ξ-nuclear bound state

KEK E373 "Kiso event"

K. Nakazawa et al. PTEP 2015, 033D02

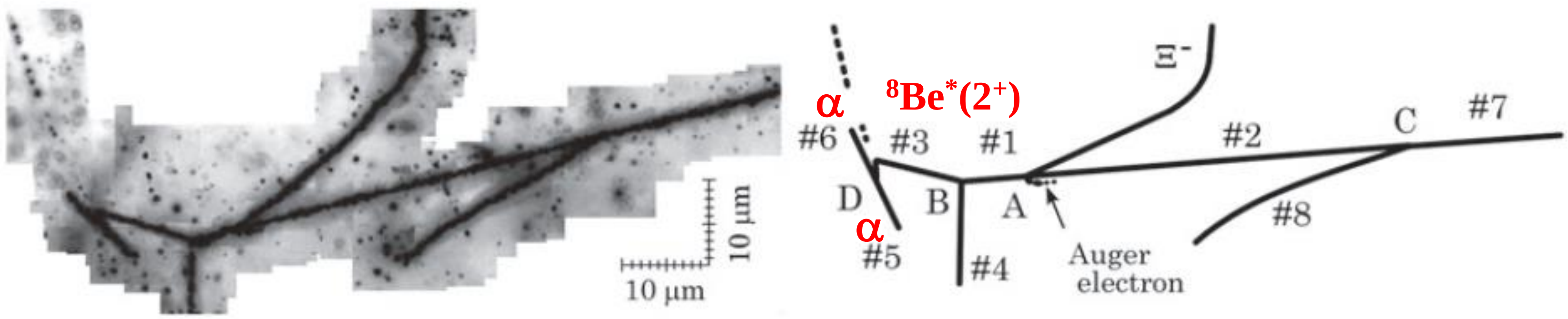


Fig. 1. A superimposed image from photographs and a schematic drawing of the KISO event.

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

$B_{\Xi^-} = \boxed{4.38 \pm 0.25\,\mathrm{MeV}} - \boxed{1.11 \pm 0.25\,\mathrm{MeV}}$ >> E(3D) = 0.17 MeV

${}^{10}_{\Lambda}\mathrm{Be}$ in g.s. ${}^{10}_{\Lambda}\mathrm{Be}$ in highest excited state

(Ehime pot.) $U_{\Xi} \sim 20$ MeV => B_{Ξ} (2p state) = 1.1 MeV

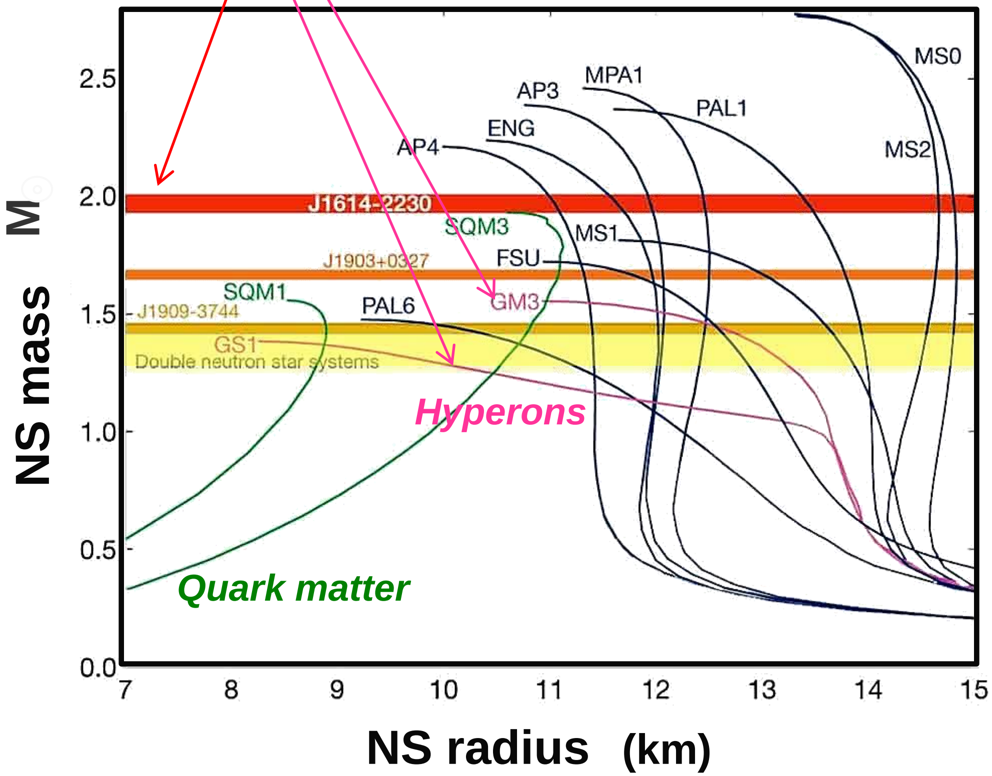
"The heavy neutron star puzzle"

- Hyperons must appear at $\rho = 2\sim3\ \rho_0$
- EOS's with hyperons (or kaons) too soft -> can support $M < 1.5\ M_{sun}$

PSR J1614-2230 (2010) $1.97 \pm 0.04\ M_{sun}$

PSR J0348-0432 (2013) $2.01 \pm 0.04\ M_{sun}$

We do not know BB interaction in high density nuclear matter!



Unknown repulsion at high ρ exists

- Strong repulsion in three-body force including hyperons are necessary. (NNN, YNN, YYN, YYY)
- Phase transition to quark matter ? (quark star or hybrid star)

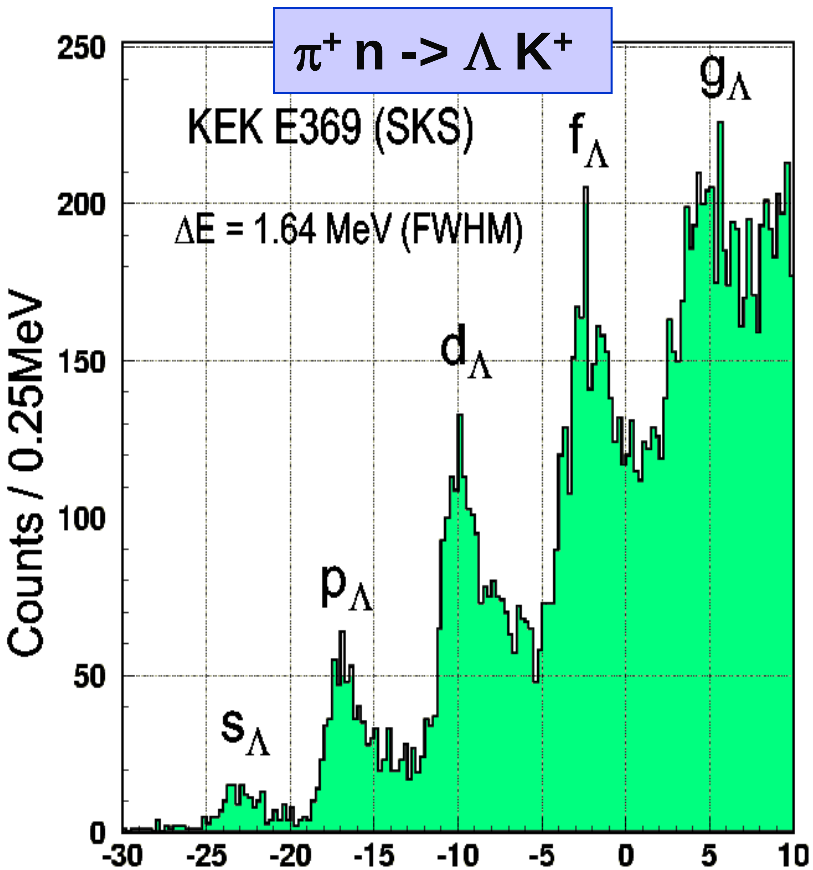
But we have no data on BBB force at high ρ nuclear matter, except for indirect info. in HI collisions.

-> Rijken, Pagliara,..

Previous (π^+,K^+) data and ΛN interaction

SKS at KEK-PS

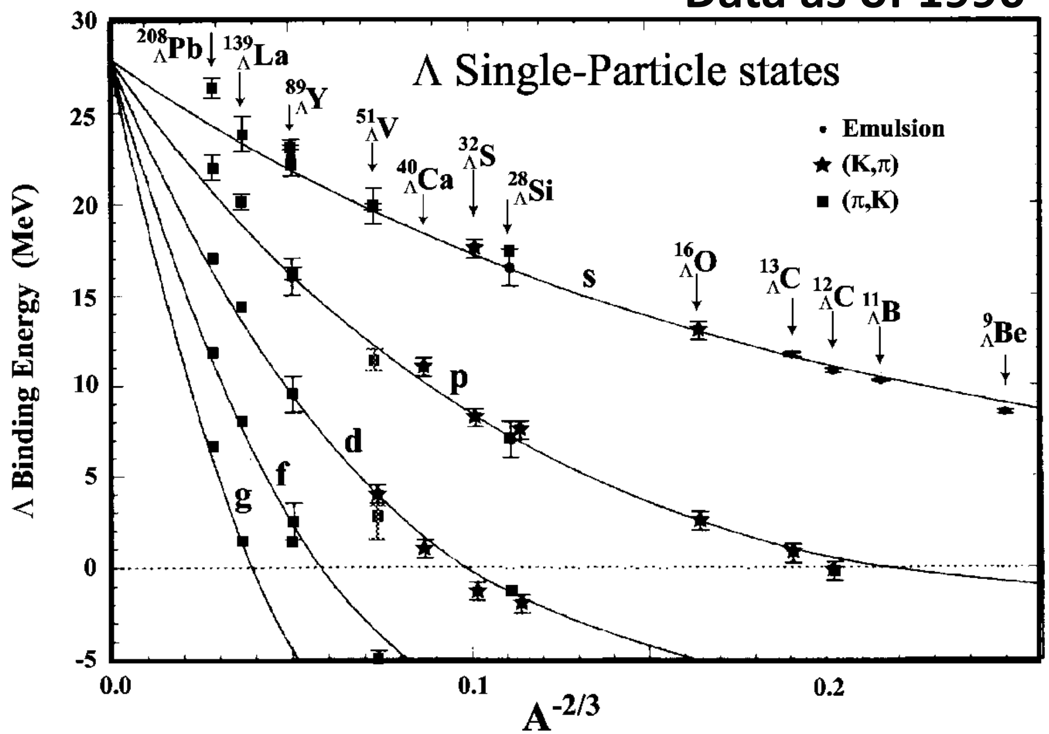
$^{89}Y\,(\pi^+,K^+)\,^{89}_{\Lambda}Y$



Mass of hypernucleus $-B_\Lambda$ (MeV)

Hotchi et al., PRC 64 (2001) 044302

Data as of 1996



U_Λ = - 30 MeV (< U_N = -50 MeV) established

better resolution

n-rich hypernuclei

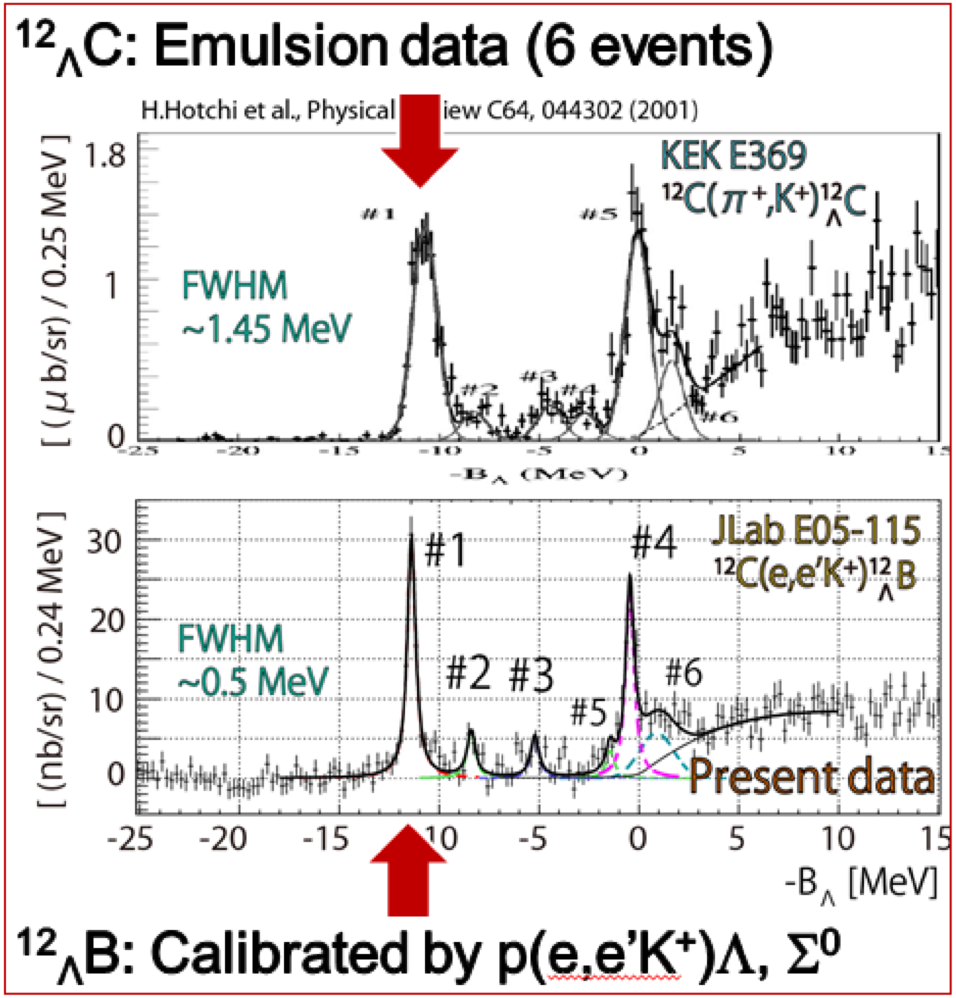
for further info. on ΛN int.

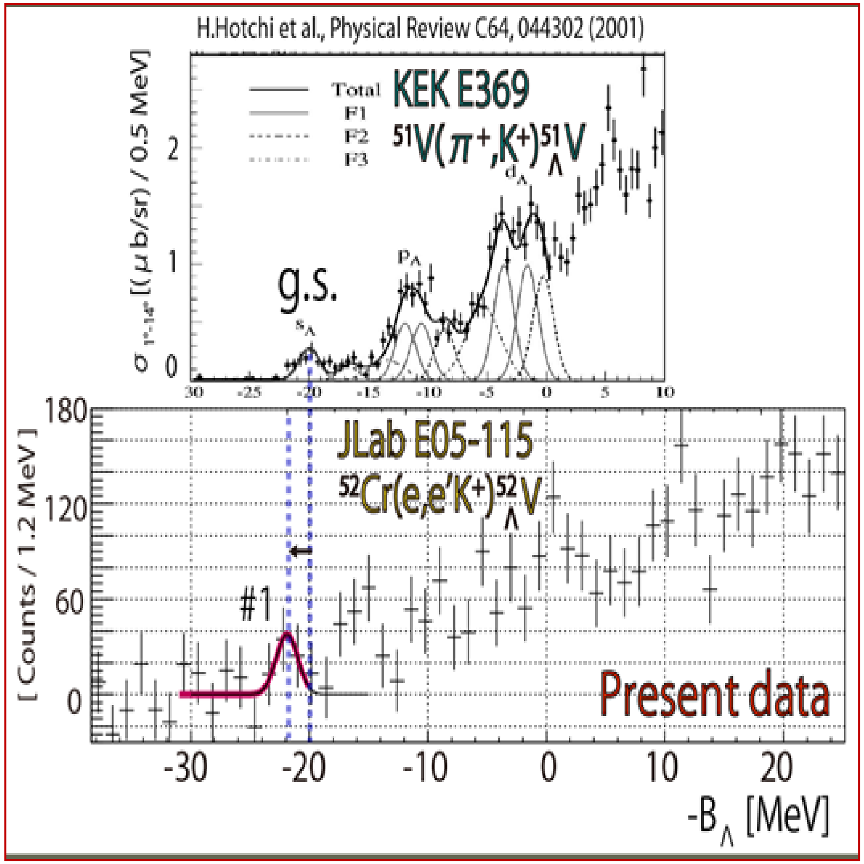
[(e,e'K⁺) at JLab]

[γ spectroscopy and (π⁻,K⁺) at J-PARC]

(e,e'K⁺) data at JLab

Slide by Nakamura





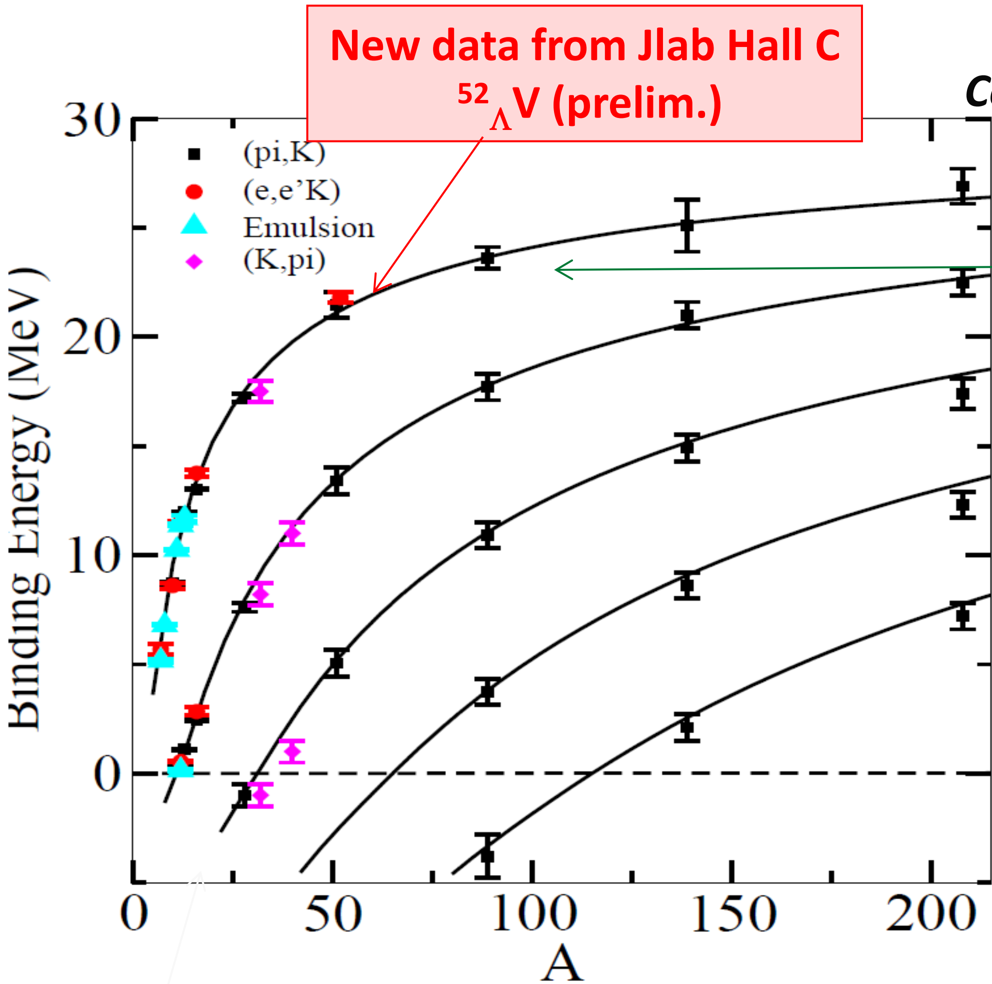
Going to heavier hypernuclei

Resolution ~0.5 MeV (FWHM)
Absolute accurary ~0.1 keV

^{40}Ca/ ^{48}Ca target runs conditionally approved

Precise Hypernuclear B_Λ data provide information on ρ dependence (ΛNN force)?

Compilation by Millener



Slope of the calculated curve changes by ~ 1 MeV between w/o and w/ 3B/4B repulsion

Y. Yamamoto et al.
Phys.Rev. C88 (2013) 2, 022801
Phys.Rev. C90 (2014) 045805

-> Rijken's talk

(π^+,K^+), (K^-,π^-): systematic error ~1 MeV

(e,$e'K^+$): systematic error ~ 0.1 MeV --- B_Λ will be measured at JLab

J-PARC will also measure B_Λ by high resolution (π^+,K^+) with 0.2 MeV resolution

Summary

- Light and heavier hypernuclear data provide information on YN, YY interactions in free space and in nuclear medium.
- New data on CSB in A=4 hypernuclei:

  B_Λ of ${}^4_\Lambda$H(0^+) measured via pion decay spectroscopy

  ---- Consistent with old emulsion data

  ${}^4_\Lambda$He(1^+->0^+) γ-ray measured to be 1.406 MeV

  ⇔1.09 MeV for ${}^4_\Lambda$H

  -- A large CSB effect in ΛN interaction confirmed.

  --CSB has a spin dependence
- Ξ nuclear bound system (Kiso event) was observed for the first time -> Ξ potential is attractive
- To solve the hyperon puzzle, ΛNN 3-body force should be studied via precise B_Λ measurements at JLab (+J-PARC).