2018.9.17
Erice School

Recent results in hypernuclear physics (mainly from J-PARC)

Tohoku University
Japan Atomic Energy Agency
H. Tamura

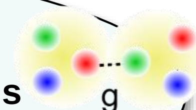
Contents

1. Introduction
2. γ-ray spectroscopy Λ hypernuclei
3. Charge symmetry breaking in Λ hypernuclei
4. S = -2 systems (Ξ and $\Lambda\Lambda$ hypernuclei) at J-PARC
5. Future Plan – Challenge to the hyperon puzzle
6. Summary

1. Introduction

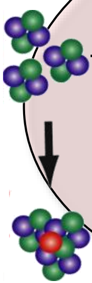
Motivations of Hypernuclear Physics

BB interactions



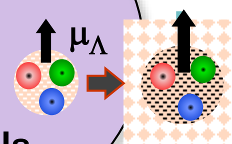
Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures
Test lattice QCD calculations

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

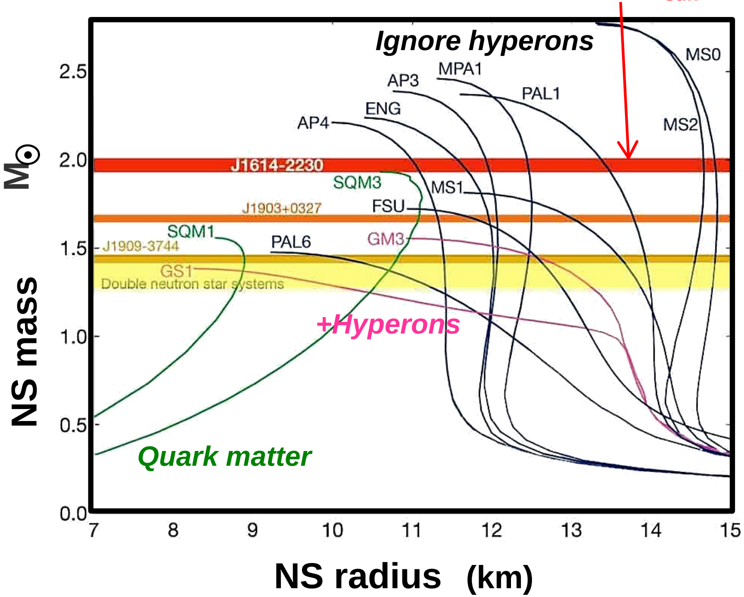
Cold and dense nuclear matter with strangeness

“Hyperon puzzle” in neutron stars

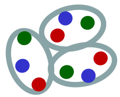
- Hyperons (Λ at least) should appear at $\rho \sim 2\ \rho_0$
- EOS’s with hyperons or kaons too soft -> cannot support $M > 1.5\ M_{sun}$
- Heavy NS’s (~$2.0\ M_{sun}$) were observed.

=> Unknown repulsion at high ρ

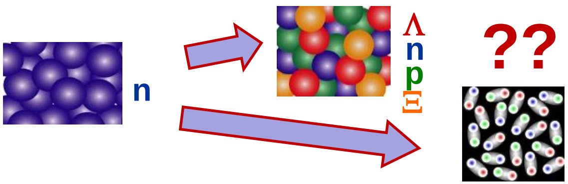
PSR J1614-2230 (2010) $1.97 \pm 0.04\ M_{sun}$
PSR J0348-0432 (2013) $2.01 \pm 0.04\ M_{sun}$



- Strong repulsion in three-body force including hyperons, NNN, YNN, YYN, YYY ?



- Phase transition to quark matter ? (quark star or hybrid star)



We need to know YN, YY, $K^{bar}N$ interactions both in free space and <u>in nuclear medium</u>

HYP2018

June 24 - 29, 2018 @Portsmouth, VA, USA

From summary talk of HYP2018 (June, 2018 @Portsmouth, VA)

Exciting new experimental results since HYP2015

Highlights (personal)

$p\Xi^-$ correlation -> $p\Xi^-$ attractive (ALICE)

$^{12}_{\Xi}$Be hypernuclei -> Ξ–nuclear bound states (J-PARC E05)

K^-pp spectrum (J-PARC E15)

Λ hypernuclei

CSB p-shell data (JLab, FINUDA)

$^{19}_{\Lambda}$F γ-rays (J-PARC E13)

K^-p correlatioan (ALICE)

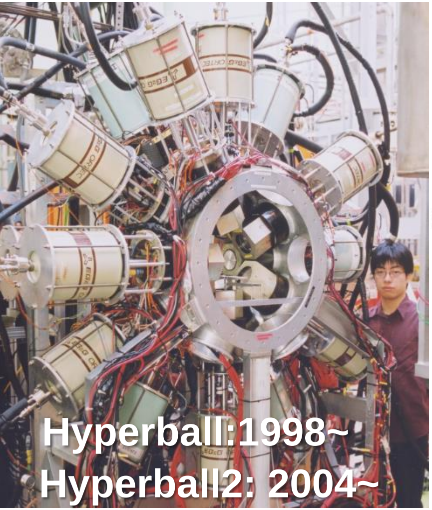
$p\Omega^-$ correlation (STAR)

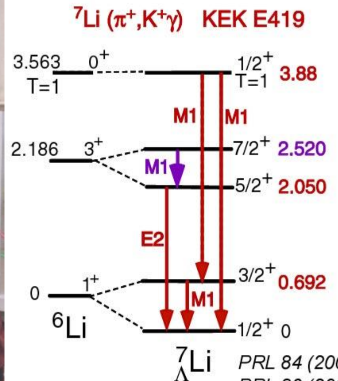
4n state (RIBF)

$^{3}_{\Lambda}$H lifetime and B_{Λ} (ALICE, STAR)

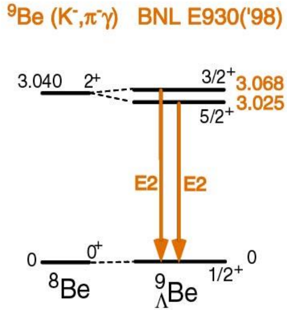
2. Gamma-Ray Spectroscopy of Λ hypernuclei at J-PARC

Hypernuclear γ-ray data (2015)

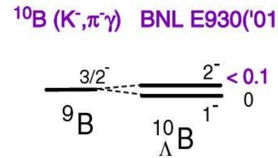




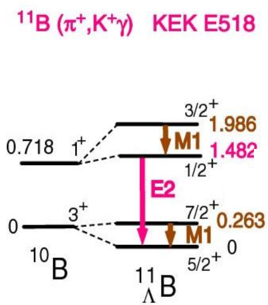
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



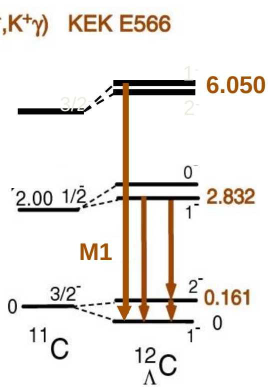
PRL 88 (2002) 082501
NPA 754 (2005) 58c



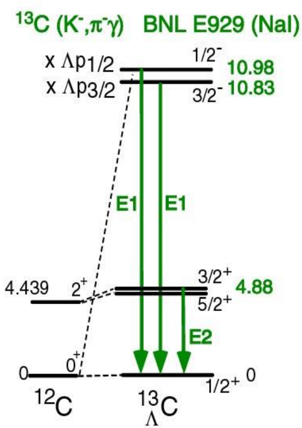
NPA 754 (2005) 58c



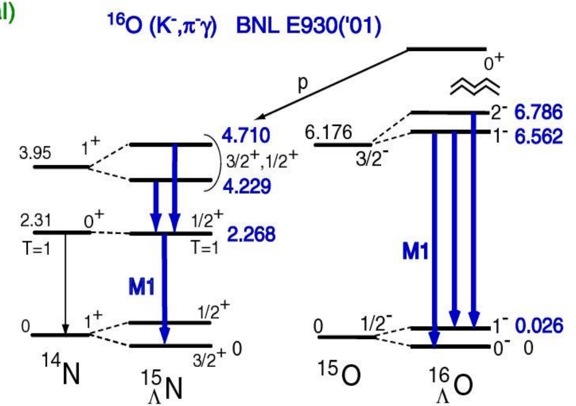
NPA 754 (2005) 58c



EPJ A33 (2007) 243
PTEP (2015) 081D01



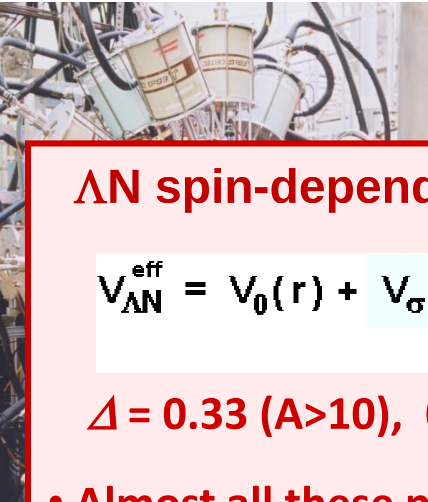
PRL 86 (2001) 4255
PRC 65 (2002) 034607



PRC 77 (2008) 054315

PRL 93 (2004) 232501
EPJ A33 (2007) 247

Hypernuclear γ-ray data (2015)



^{7}Li (π^+,$K^+\gamma$) KEK E419 ^{9}Be (K^-,$\pi^-\gamma$) BNL E930('98) ^{10}B (K^-,$\pi^-\gamma$) BNL E930('01)

ΛN spin-dependent interaction strengths determined:

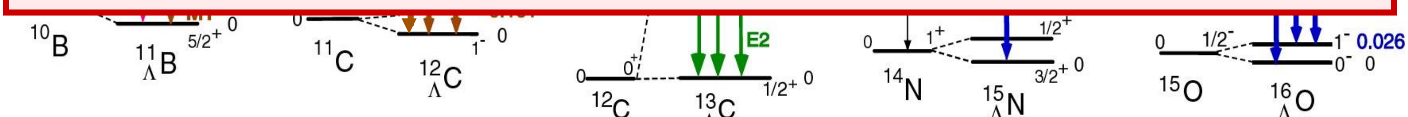
$$V_{\Lambda N}^{\mathrm{eff}} = V_0(r) + V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda + V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N + V_T(r)\, S_{12}$$

Δ, S_Λ, S_N, T

Δ = 0.33 (A>10), 0.42 (A<10), S_Λ = -0.01, S_N = -0.4, T =0.03 MeV

- Almost all these p-shell levels are reproduced within a few 10 keV by this parameter set. (D.J. Millener)
- Feedback to BB interaction models. Nijmegen ESC08 model is almost OK. (But ΛN-ΣN force is not well studied yet.)

=> go to s-shell and sd-shell



NPA 754 (2005) 58c

EPJ A33 (2007) 243

PTEP (2015) 081D01

PRL 86 (2001) 4255
PRC 65 (2002) 034607

PRC 77 (2008) 054315

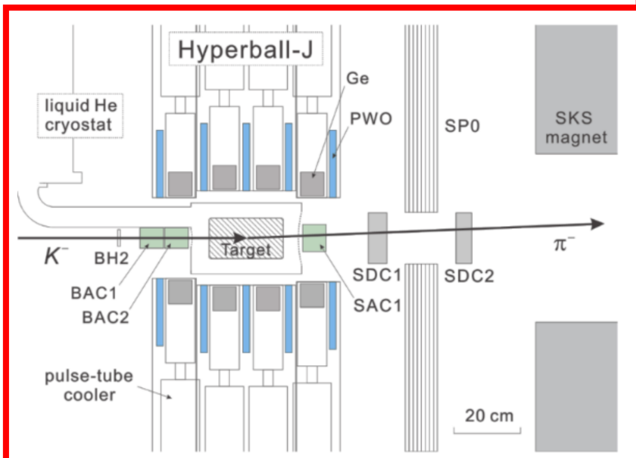
PRL 93 (2004) 232501
EPJ A33 (2007) 247

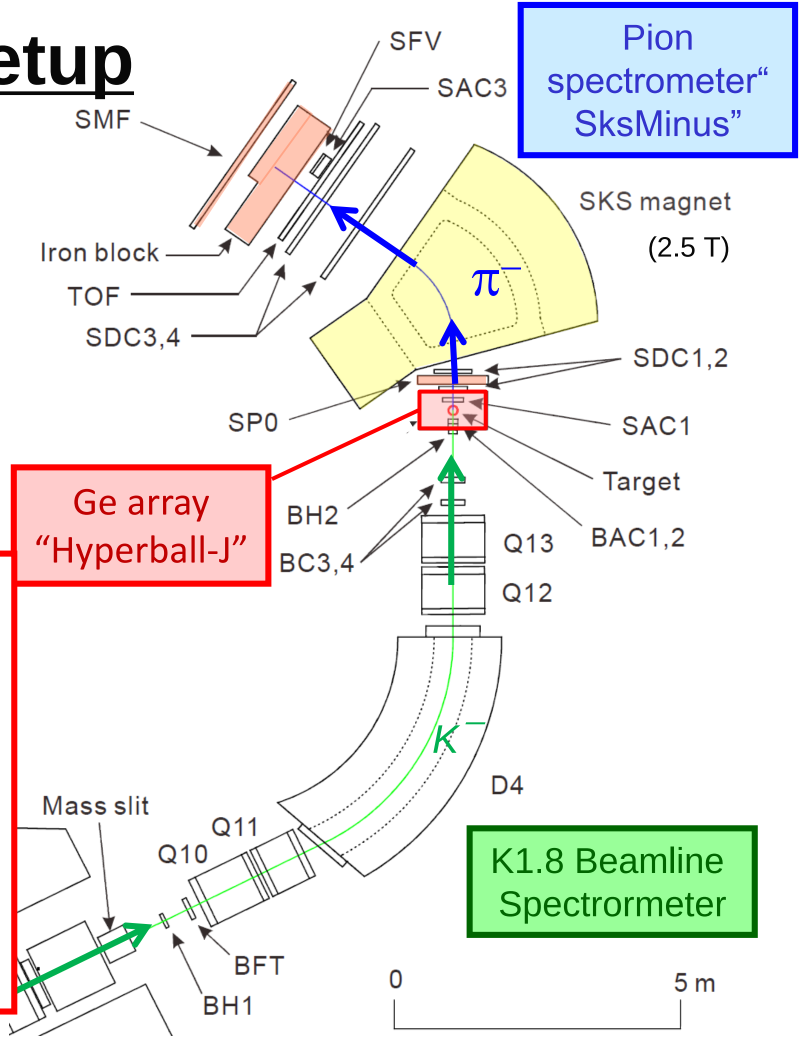
J-PARC E13 Setup

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

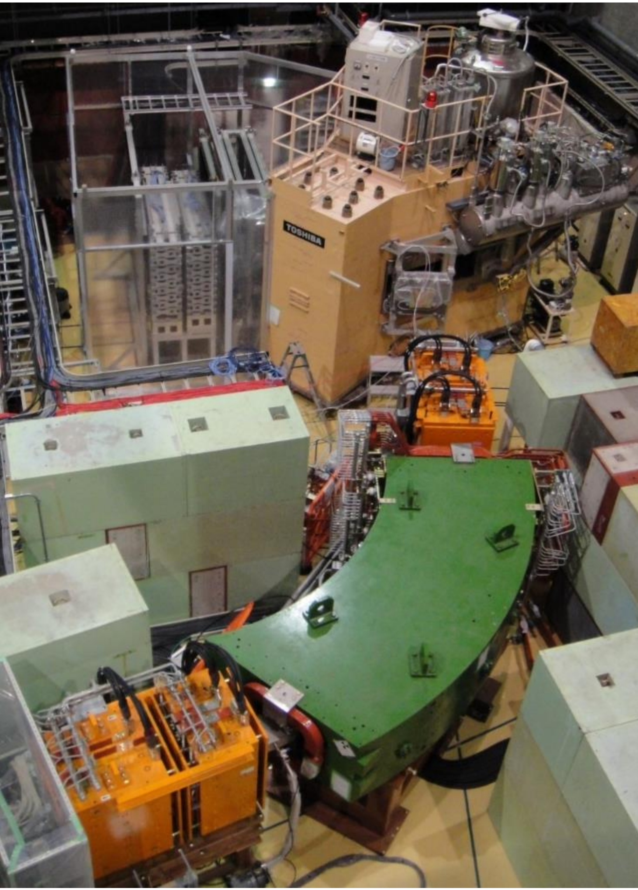
- Tag production of hypernuclei
- Detect γ-rays from hypernuclei

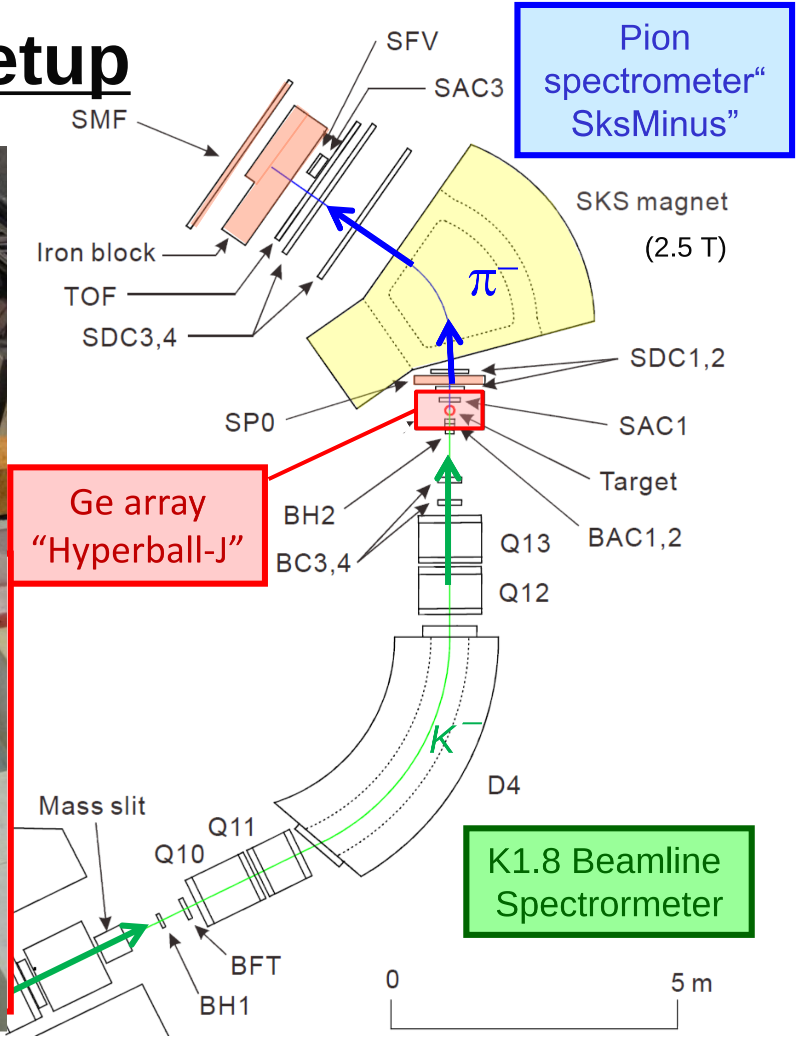
^{4}He -> $^{4}{}_{\Lambda}He$, ^{19}F -> $^{19}{}_{\Lambda}F$





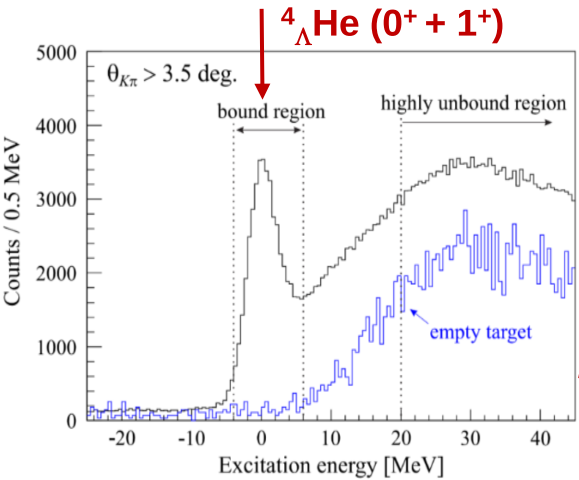
J-PARC E13 Setup

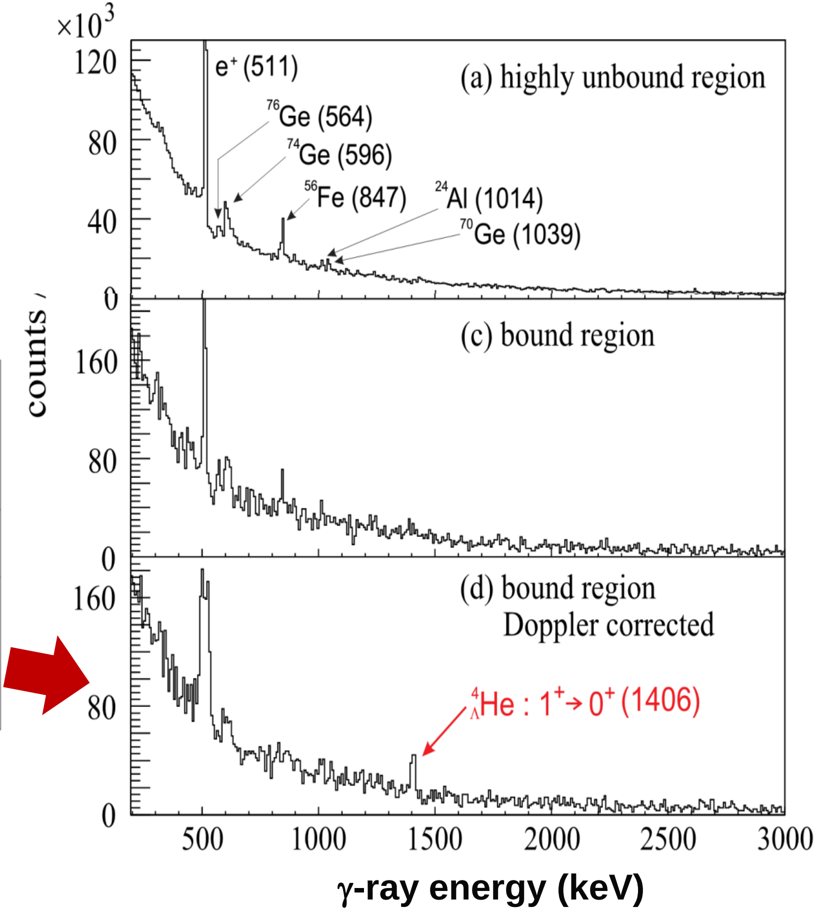




$^{4}_{\Lambda}$He Result

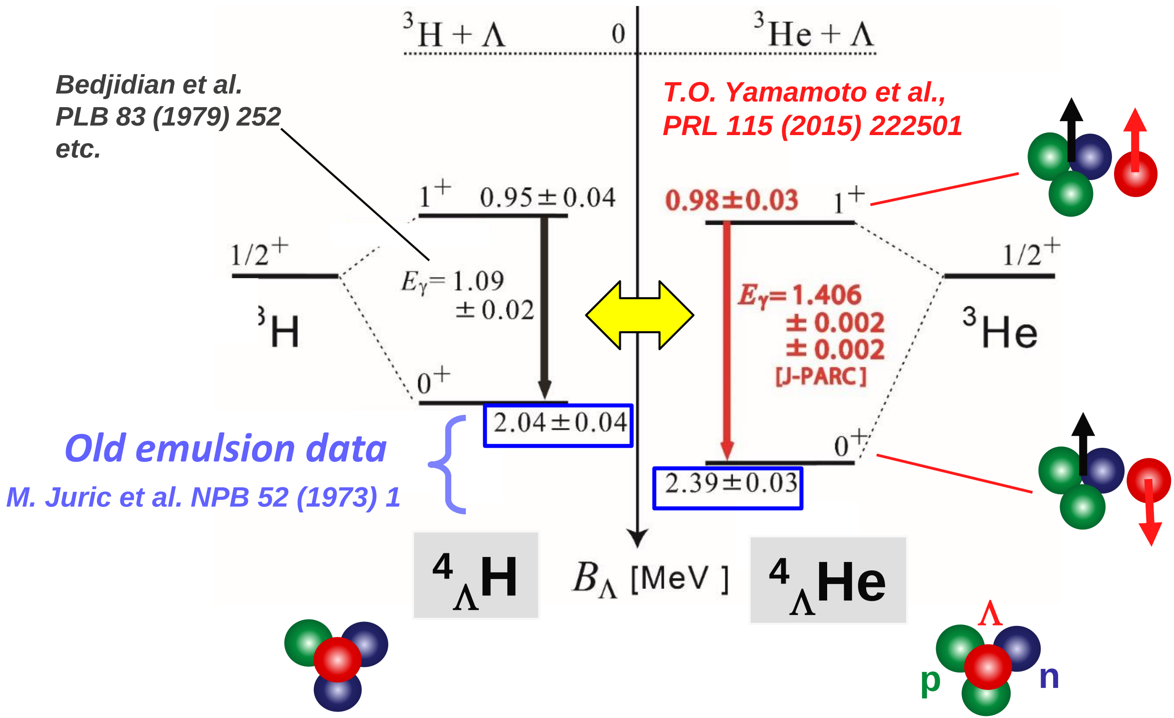
^{4}He(K^{-},π^{-}) missing mass





A peak observed at
1406±2±2 keV

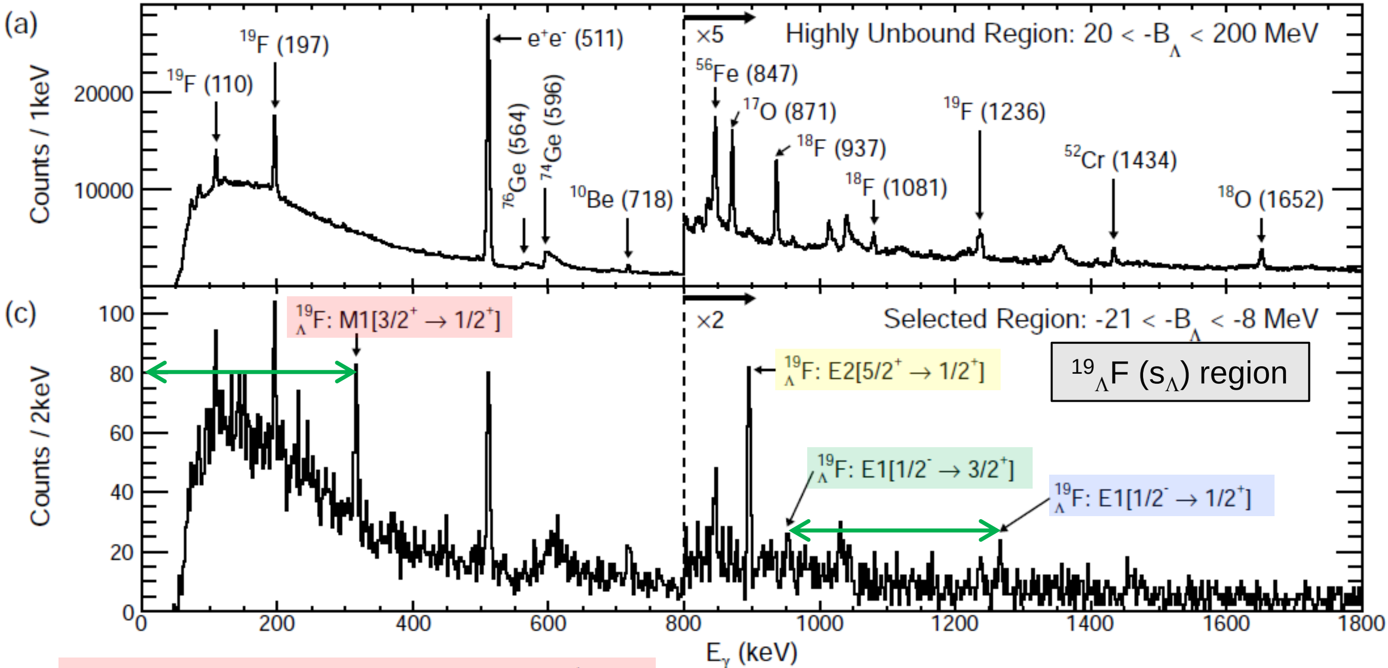
Energy levels of A=4 mirror hypernuclei



A large Charge Symmetry Breaking effect is confirmed!

$^{19}_{\Lambda}F$ result: Mass-gated γ-ray spectra

S.B. Yang et al., PRL120 (2018) 132505



$315.5 \pm 0.4(\text{stat})^{+0.6}_{-0.5}(\text{syst})$ keV

$5.0 \pm 0.9^{+0.5}_{-0.3}$ keV (FWHM)

Doppler broadened => M1 (or E1)

$895.2 \pm 0.3(\text{stat})^{+0.6}_{-0.5}(\text{syst})$ keV

Not Doppler broadened => E2

$952.8 \pm 1.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ keV

$1265.9 \pm 1.2(\text{stat}) \pm 0.7(\text{syst})$ keV

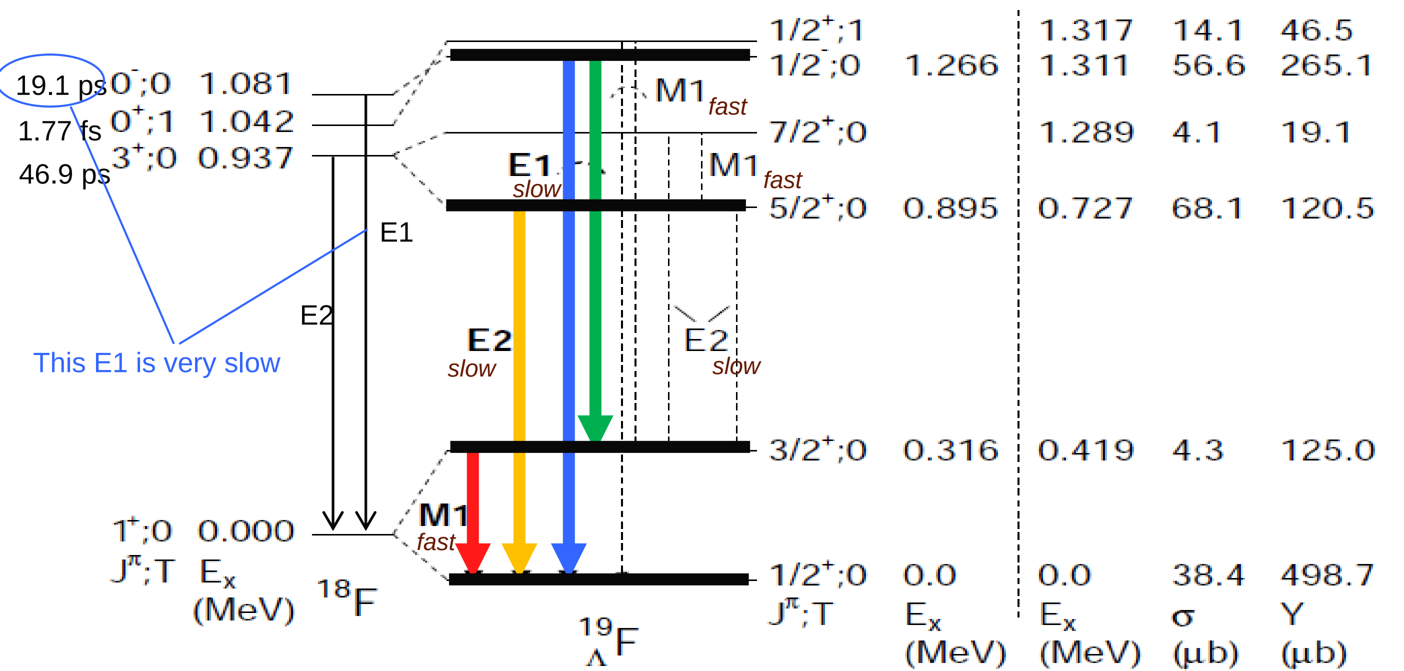
Not Doppler broadened

Level scheme of $^{19}_{\Lambda}F$

S.B. Yang et al., PRL120 (2018) 132505

Assigned from the peak width (Doppler broadening or not) and the expected yield.

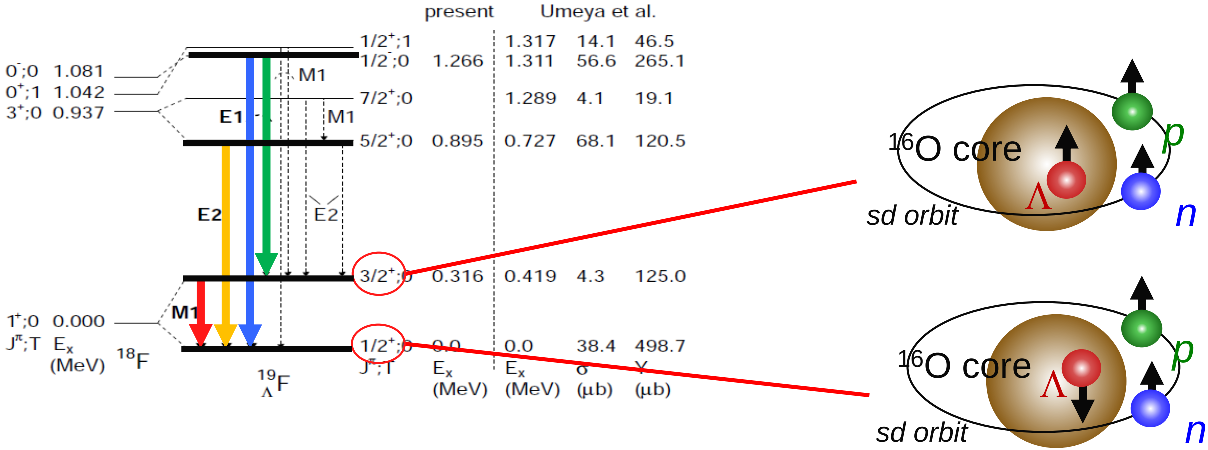
present Umeya et al. *



fast: Doppler broadening (< 1 ps)
slow: No Doppler broadening (> 1 ps)

* *A. Umeya and T. Motoba, Nucl. Phys. A954 (2016) 242.*
Shell model calculation with NSC97f interaction

Comparison with theoretical calculations



g.s. doublet ($3/2^+$,$1/2^+$) spacing

		ΛN interaction
Millener	305 keV	Effective spin-spin interaction strength from p-shell hypernuclear data (Δ=0.33 MeV)
Umeya	346 keV	[NSC97e] + [NSC97f], the ratio adjusted to reproduce $^{7}_{\Lambda}$Li ($3/2^+$,$1/2^+$) spacing
	419 keV	NSC97f
	245 keV	NSC97e
Exp.	316 keV	

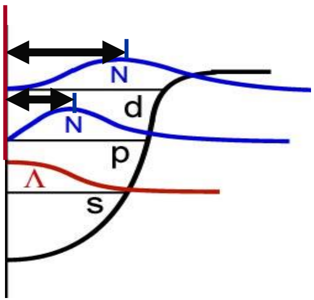
=> *The level energy is reproduced very well, suggesting that*

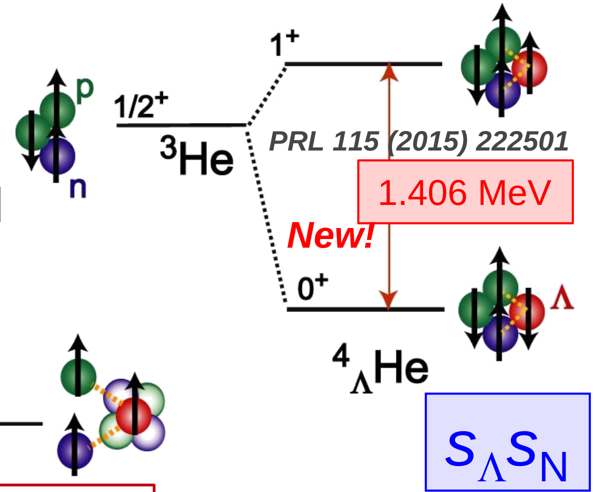
the theoretical framework and inputs (ΛN interaction strength and range) are good even for heavier hypernuclei. ***-> Study heavier hypernuclei to see ΛNN force effect?***

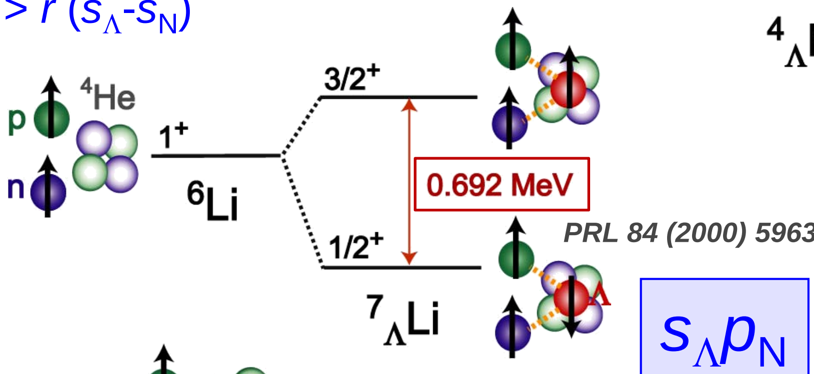
A-dependence of ΛN interaction strength

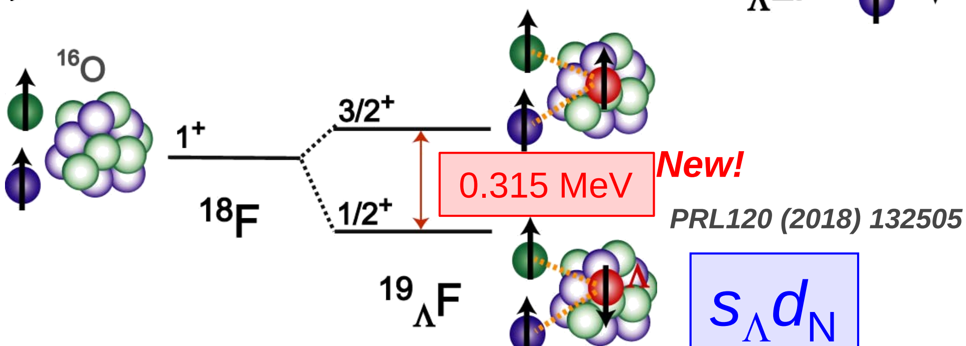
Sensitive to wavefunction overlap and interaction range

$\bar{r}\,(s_\Lambda\text{-}d_N) > \bar{r}\,(s_\Lambda\text{-}p_N) > \bar{r}\,(s_\Lambda\text{-}s_N)$



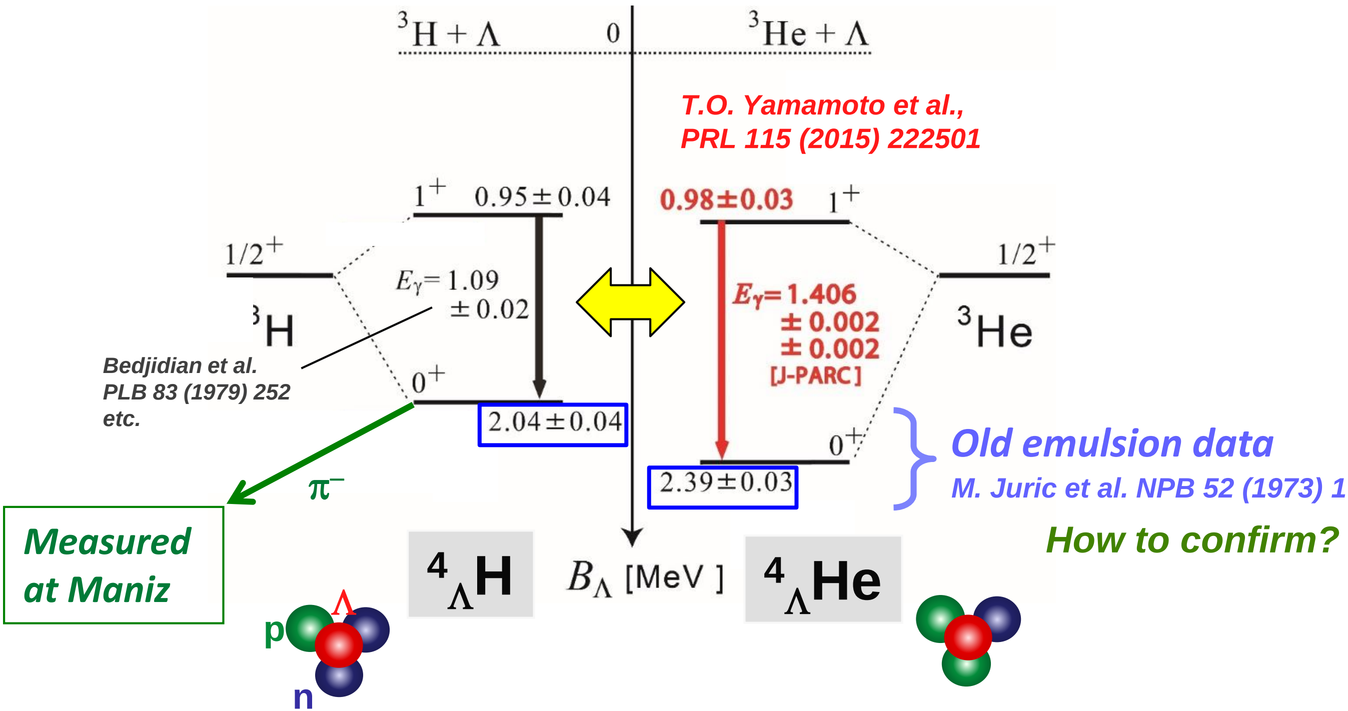






3. Charge symmetry breaking in Λ hypernuclei

Energy levels of A=4 mirror hypernuclei

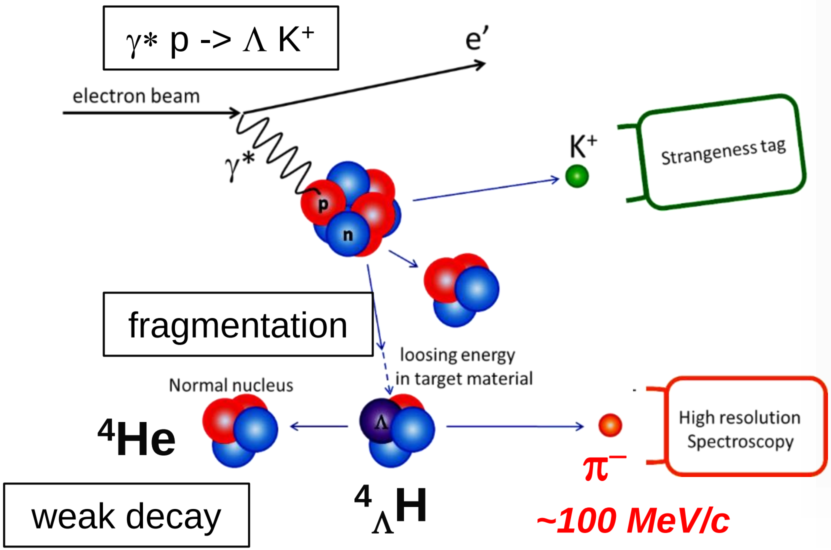


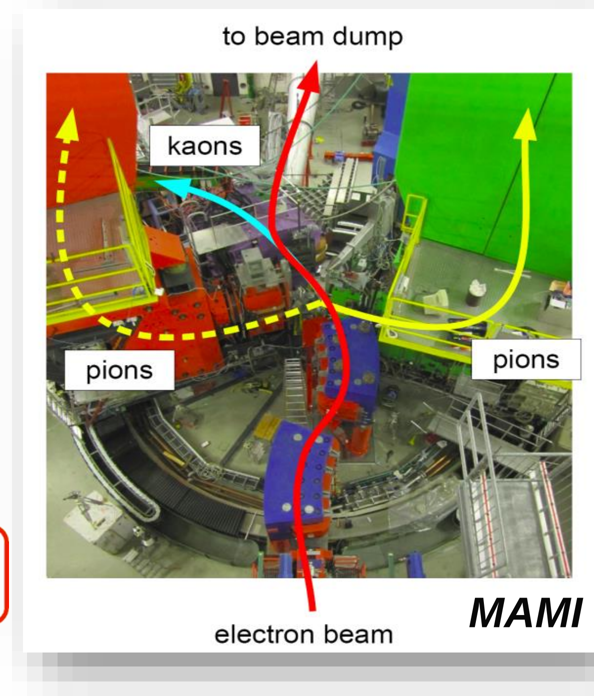
$\Delta E(^4{}_\Lambda He)-\Delta E(^4{}_\Lambda H)$ = 320 keV >> $B(^3H)-B(^3He)$ ~70 keV

A large CSB has been confirmed only from γ-ray data!

Decay-pion spectroscopy of hypernuclei with electron beams

Slide by P. Achenbach



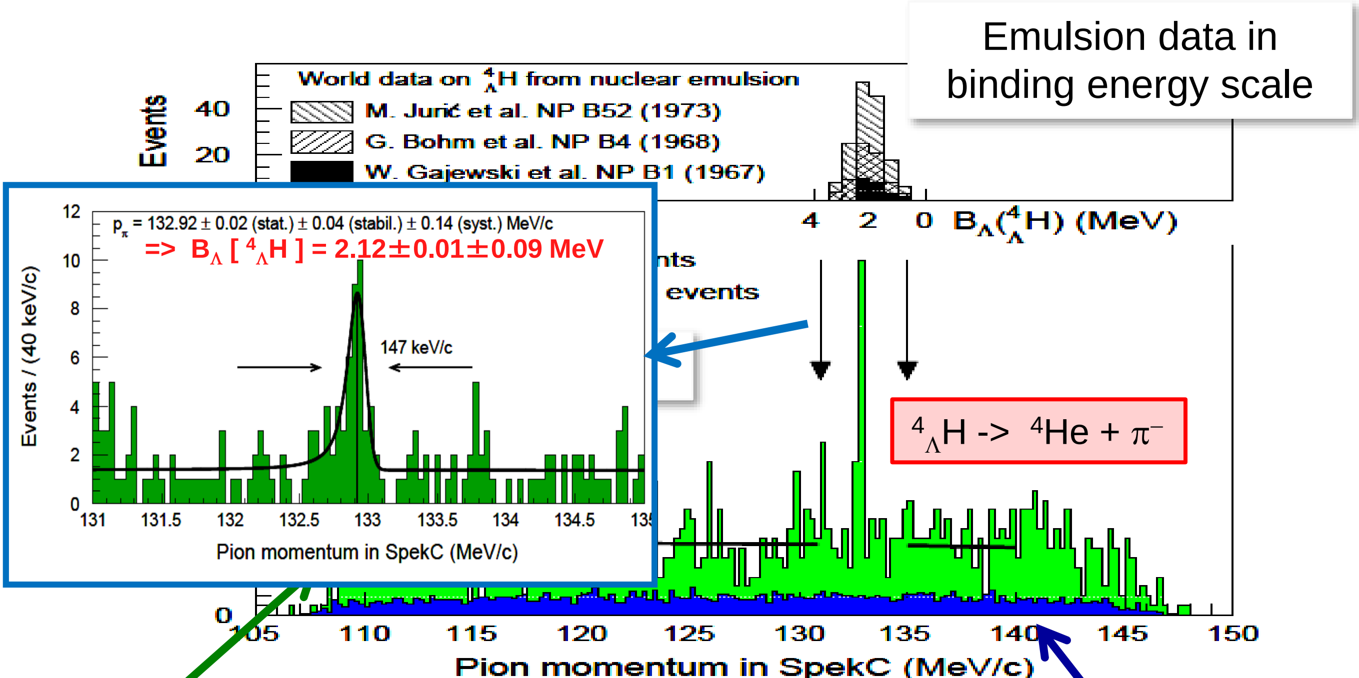


Two-body decay at rest ⇒ mono-energetic pions

=> ***precise mass of the hypernucleus***

Slide by P. Achenbach

Decay-pion spectrum



decays of quasi-free produced hyperon

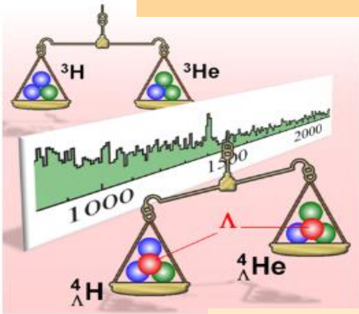
A. Esser et al., PRL 114 (2015) 12501

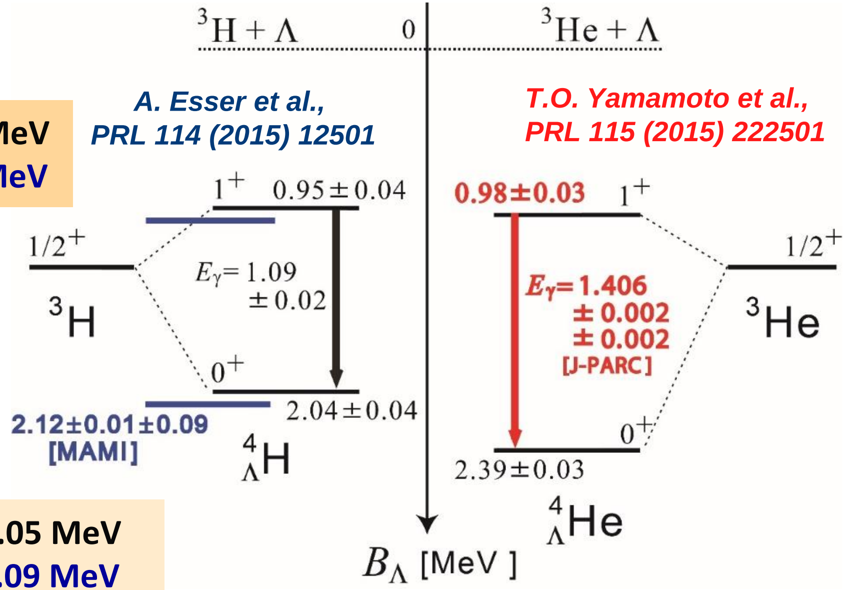
accidental background

New method of precise mass measurement developed.

Combined Results

$\Delta B_\Lambda(1^+)$: 0.03±0.05 MeV
0.11±0.09 MeV





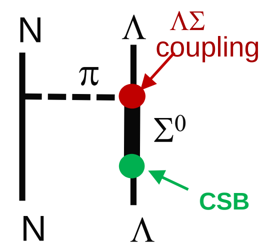
$\Delta B_\Lambda(0^+)$: 0.35±0.05 MeV
0.26±0.09 MeV

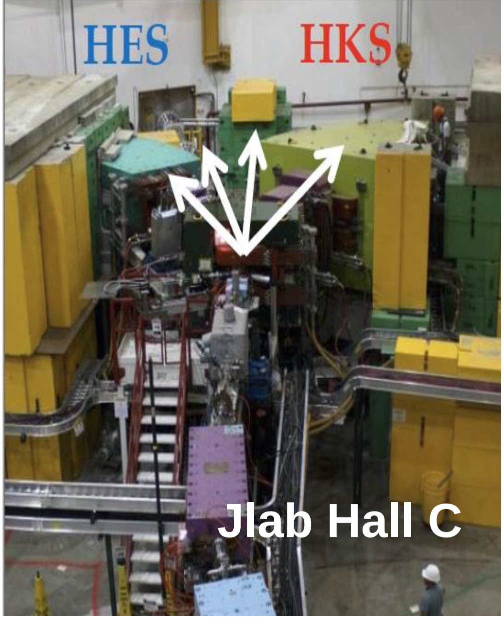
- B_Λ [$^4_\Lambda$H(0^+)] is confirmed, suggesting the emulsion $^4_\Lambda$He(0^+) data also reliable.
- Large spin dependence in CSB found.

Recent theories: This CSB effect is sensitive to ΛN-ΣN coupling.

A. Gal, PLB 744 (2015) 352

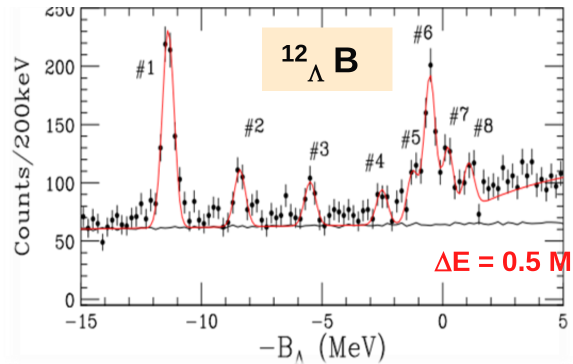
D. Gazda and A. Gal, PRL 116 (2016) 122501





High resolution (e,e'K$^+$) Spectroscopy at JLab

Jlab E05-115

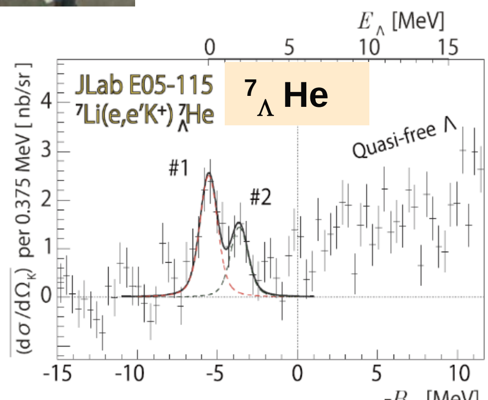


L. Tang et al., PRC90 (2014) 034320

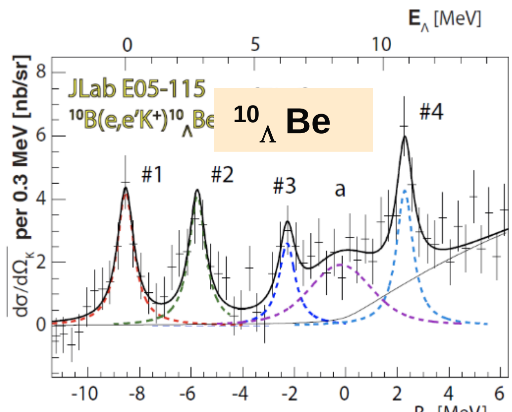
ΔE = 0.5 MeV (FWHM) achieved

Accuracy of absolute energy in (e,e'K$^+$) ~ 100 keV

(π^+,K$^+$), (K$^-$,π^-) ~ 1 MeV



T. Gogami et al., PRC 94 (2016) 21302(R)

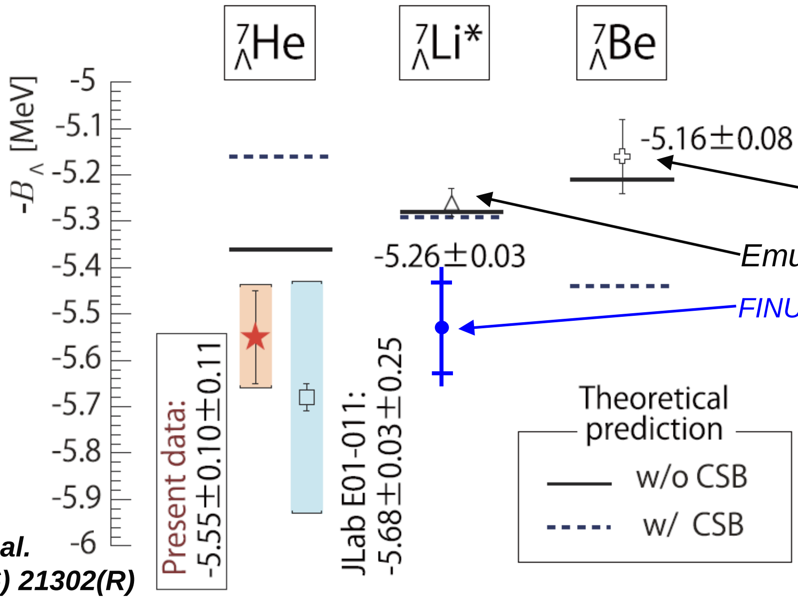


T. Gogami et al., PRC 93 (2016) 034314

CSB in p-shell hypernuclei

-> A key to understand the origin

A=7



Phenom. CSB int. which accounts for A=4 (Hiyama et al.)

T. Gogami et al. PRC 94 (2016) 21302(R)

A=12, 16

FINUDA (K^-_{stop},π^-) – JLab (e,e'K^+) **Nucl.Phys. A960 (2017) 165.**

⇒ Suggesting rather small (~100 keV) CSB in p-shell hypernuclei

⇒ Need more precise data

4. S=-2 Systems at J-PARC

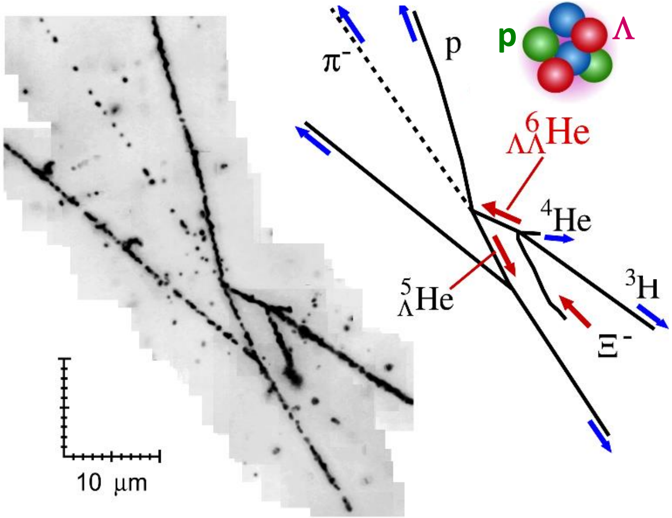
Ξ and $\Lambda\Lambda$ hypernuclei

Ξ atomic X-rays

Emulsion Results (KEK E373)

New analysis!

Nagara event



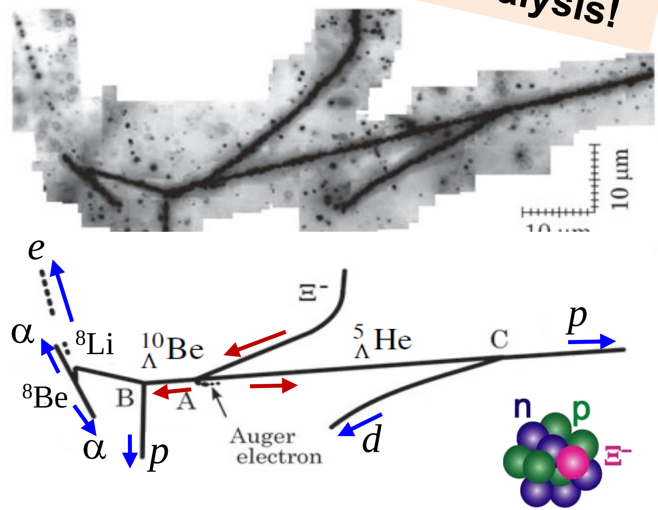
$^{6}{}_{\Lambda\Lambda}$He -> $^{5}{}_{\Lambda}$He + p + π^-

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

Kiso event



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

The first clear Ξ hypernucleus

$$B_{\Xi^-} = 4.38 \pm 0.25\ \mathrm{MeV},$$
$$-\ 1.11 \pm 0.25\ \mathrm{MeV}$$

K. Nakazawa et al. PTEP 2015, 033D02

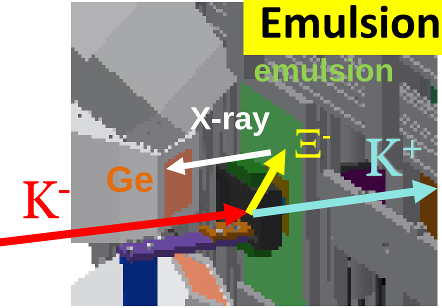
Ξ-N is attractive !

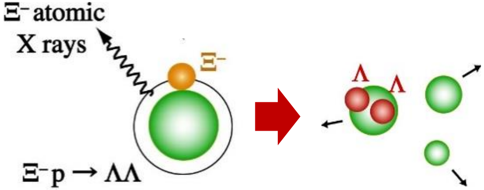
More S=-2 events with emulsion

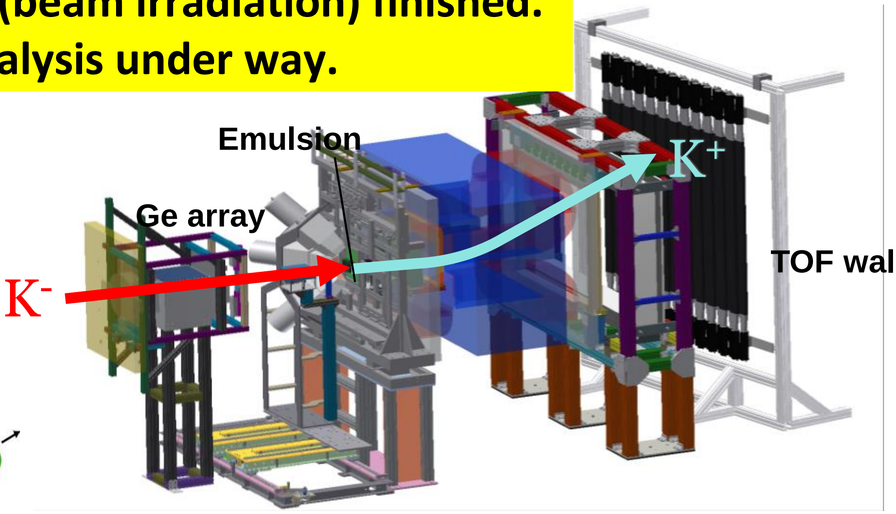
J-PARC E07
K. Nakazawa et al.

- **Collect ~10^2 $\Lambda\Lambda$ hypernuclear events from ~10^4 Ξ^-_{stop}**
  - Confirm $\Lambda\Lambda$ int. and extract $\Lambda\Lambda$–ΞN effect
  - More Ξ-nuclear events -> Ξ-N interaction
- **Measure Ξ^- -atomic X-rays for the first time**
  - Shift and width of X-rays -> Ξ-nuclear potential

Data-taking (beam irradiation) finished.
Emulsion analysis under way.



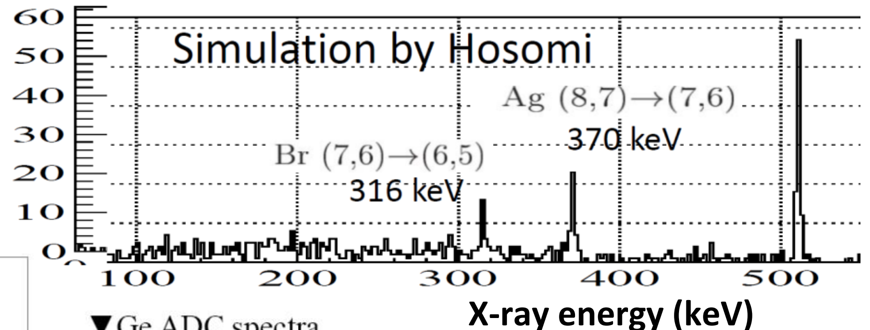


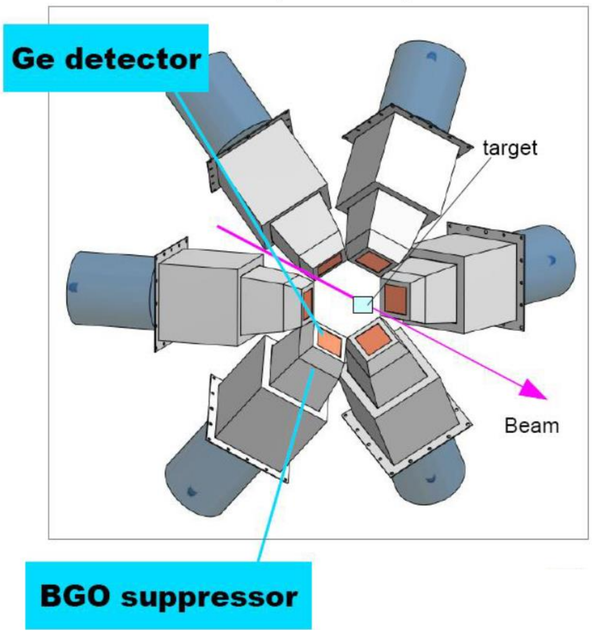


KURAMA spectrometer

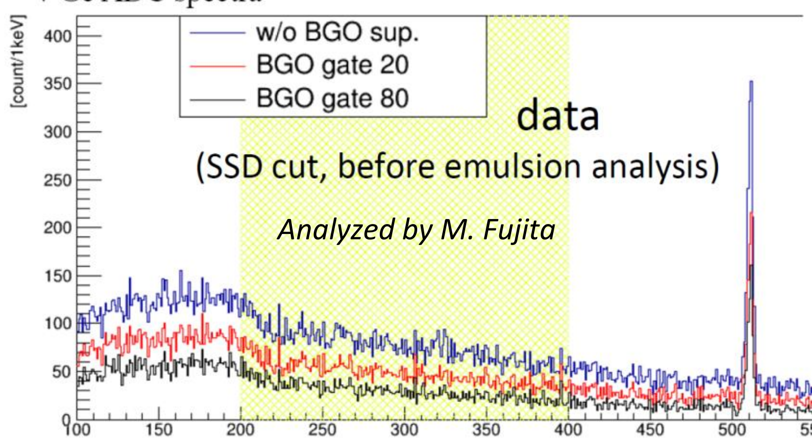
E07: Preliminary X-ray spectrum

	(n,l)	X-ray Energy [keV]
Ag	(9,8)→(8,7)	254.7
	(8,7)→(7,6)	371.5
Br	(8,7)→(7,6)	206.0
	(7,6)→(6,5)	317.4





▼Ge ADC spectra



Going to remove background by looking at emulsion image

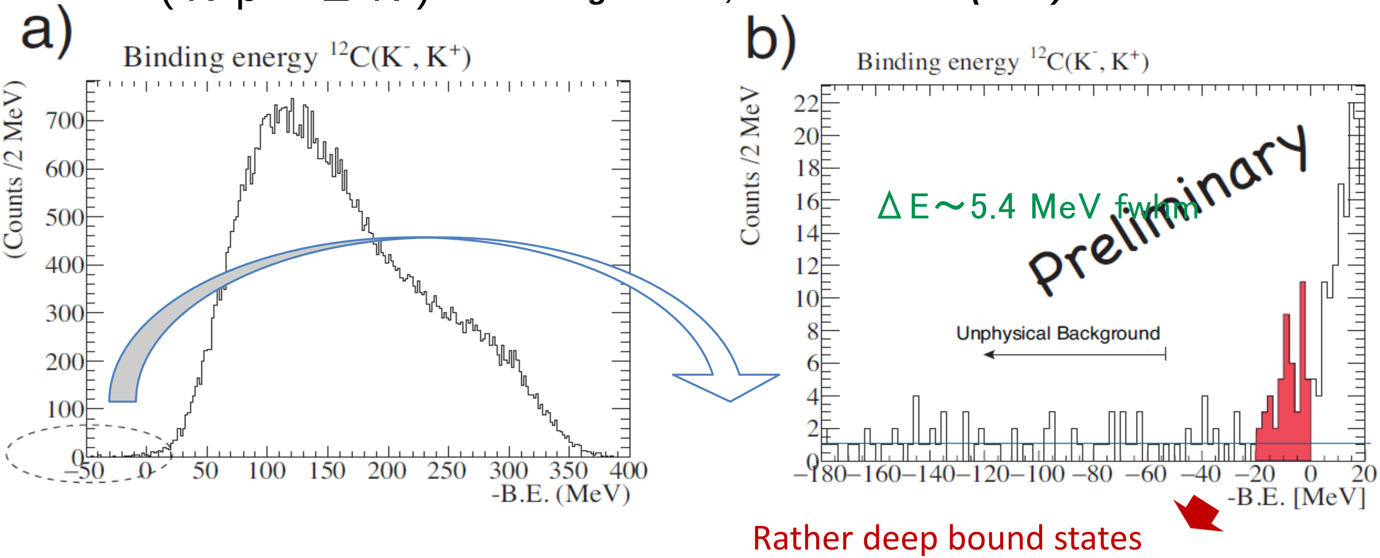
Ξ-Hypernuclear Spectroscopy via (K^-,K^+) Reaction

^{12}C (K^-,K^+) $^{12}{}_{\Xi}Be$ with SKS spectrometer

(K^- p -> Ξ^- K^+)

Nagae et al., J-PARC E05

T. Nagae et al., PoS INPC2016 (2017) 038



If U_Ξ is as deep as U_Λ , Ξ^- should appear first at $\rho \sim 2\,\rho_0$

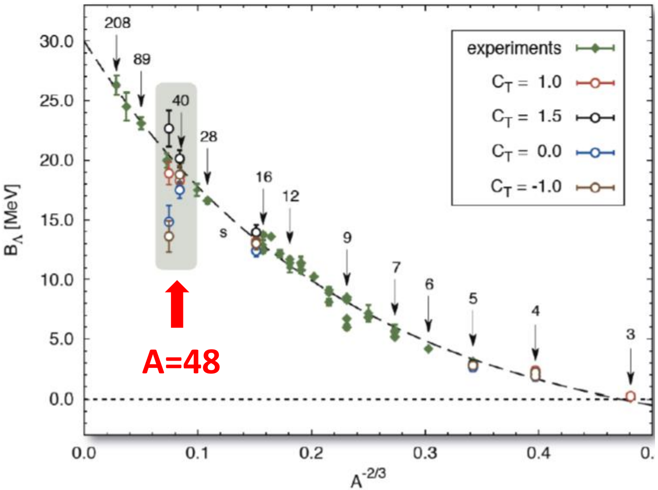
-> "Hyperon puzzle" more difficult to solve?

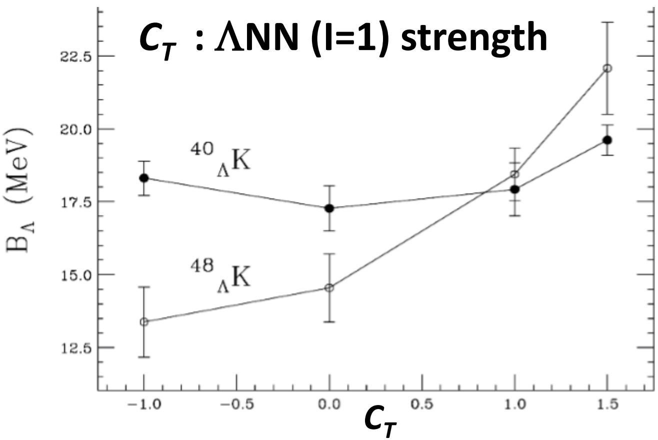
5. Future Plan

Challenge to the hyperon puzzle

Isospin dependence of Λ B.E. in matter (Λnn force)

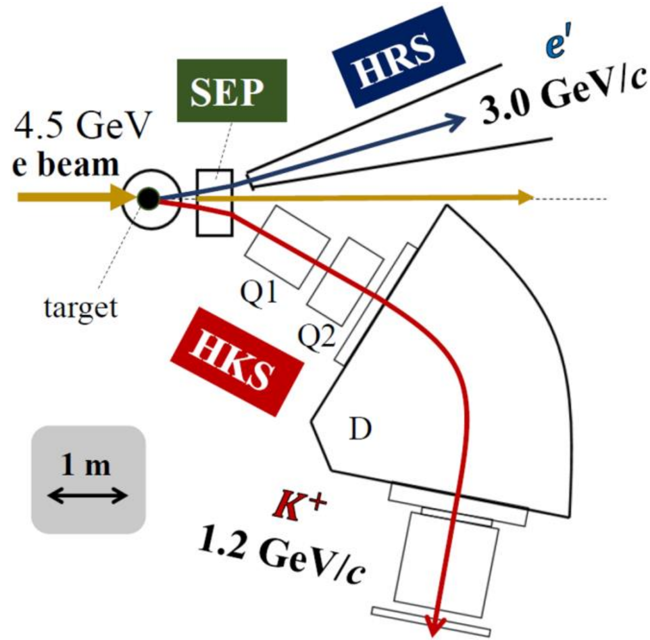
D. Lonardoni et al.





JLab E12-15-003 (run in ~2020)

^{40}Ca, ^{48}Ca (e,e'K$^+$)^{40}K, ^{48}K



Density dependence of ΛN int. in matter

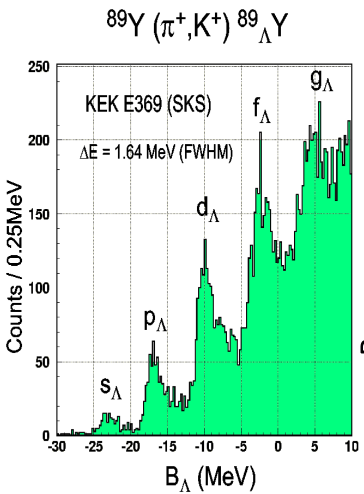
Ab-initio calc. of nuclear binding energies => NNN repulsion necessary
Similar YNN (YYN, YYY) repulsive forces?

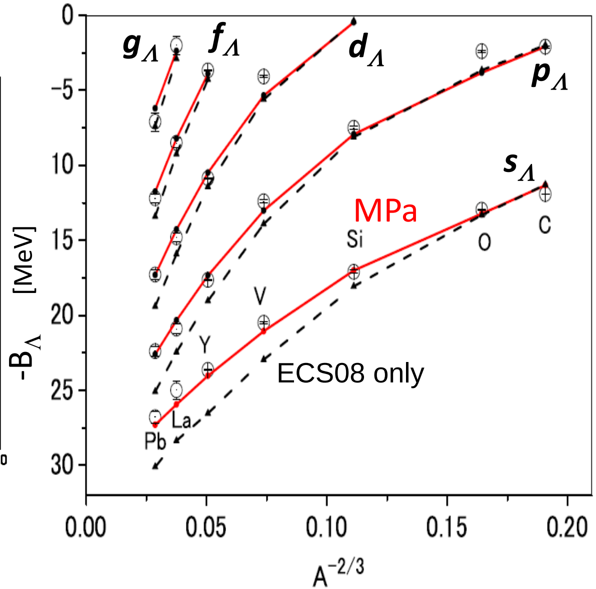
Yamamoto, Furumoto, Rijken et al.
PRC88 (2013) 2, 022801
PRC90 (2014) 045805

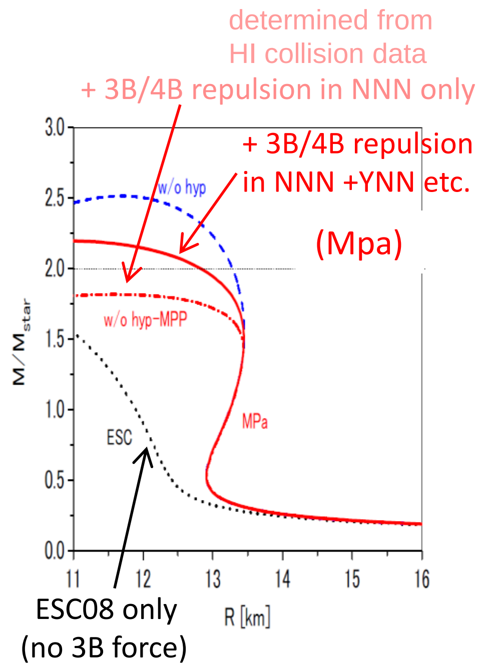
Experimentally approach:

Precise B_Λ data for wide A of Λ hypernuclei

0.1 MeV accuracy is necessary







Extension Plans of J-PARC Hadron Hall

S= -2 Systems

ΛΛ, Ξ hypernuclei
H dibaryon

- < 2.0 GeV/c
- ~10^6 K^-/spill

- < 1.1 GeV/c
- ~10^5 K^-/spill

S= -1 Systems

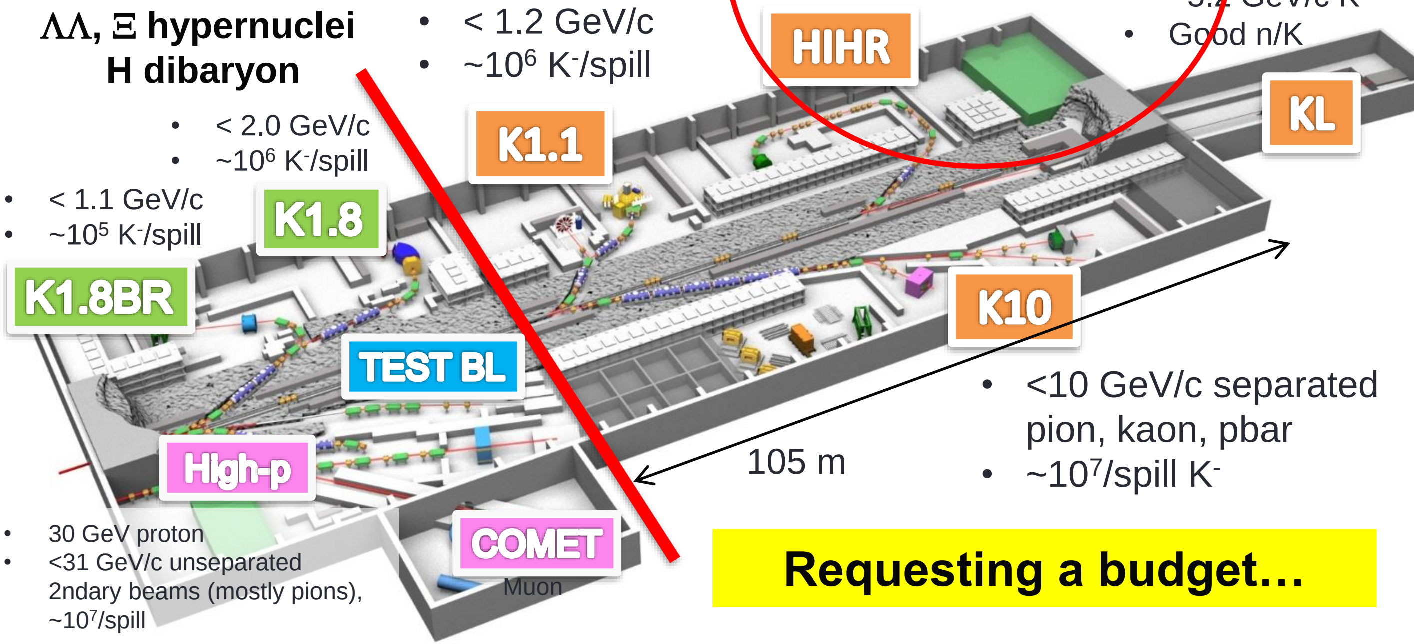
γ-ray spectroscopy
weak decays
ΛN scattering

- < 1.2 GeV/c
- ~10^6 K^-/spill

High precision
Λ hypernuclear spectroscopy

- < 2.0 GeV/c
- 1.8x10^8 pion/spill
- x10 better Δp/p

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

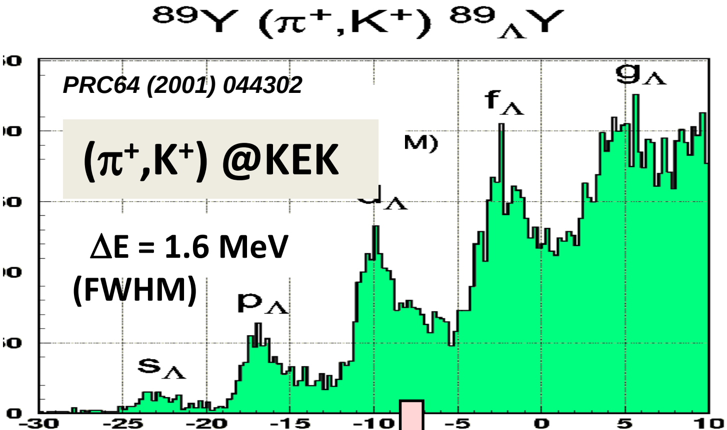


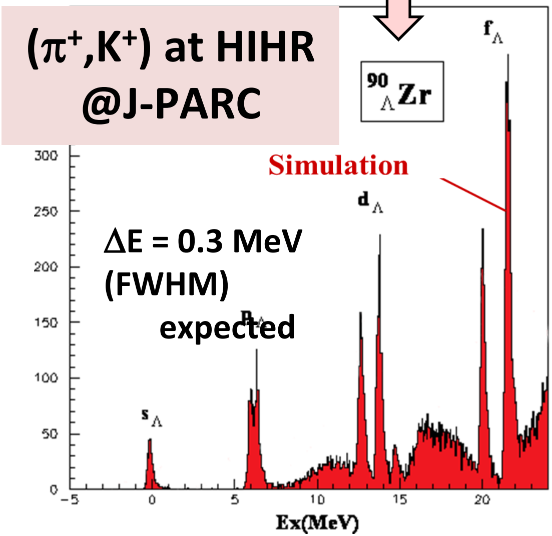
- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

Requesting a budget…

PARC Hadron Hall





High precision
Λ hypernuclear spectroscopy

< 2.0 GeV/c
1.8x10^8 pion/spill
x10 better Δp/p

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

Requesting a budget…

6. Summary

- γ-ray data for $^{4}_{\Lambda}He(0^{+} \to 1^{+})$ and precise $^{4}_{\Lambda}H \to {}^{4}_{\Lambda}He\ \pi^{-}$ data confirmed large CSB effects in A=4 hypernuclei.
- γ-ray data of $^{19}_{\Lambda}F$ provided its level scheme, which is well reproduced by theoretical calc's with our knowledge of ΛN interaction.

- Ξ–nucleus bound system ($\Xi^{-14}N$) was observed in emulsion.
- $^{12}C(K^{-},K^{+})$ spectrum at J-PARC suggests bound Ξ hypernuclear states.
- A new emulsion experiment for more $\Lambda\Lambda$ and Ξ hypernuclei + Ξ-atomic X-rays has been performed.

- In future, we will challenge the “hyperon puzzle” at JLab and at the extended Hadron Hall at J-PARC.