Gamma-ray spectroscopy of Hypernuclei
-- Resent results and prospects at J-PARC--

H. Tamura
Tohoku University
for the E13 Collaboration

1. Introduction
2. $^{4}_{\Lambda}$He results and CSB
3. $^{19}_{\Lambda}$F results
4. Future prospects
5. Summary

J-PARC E13 collaboration

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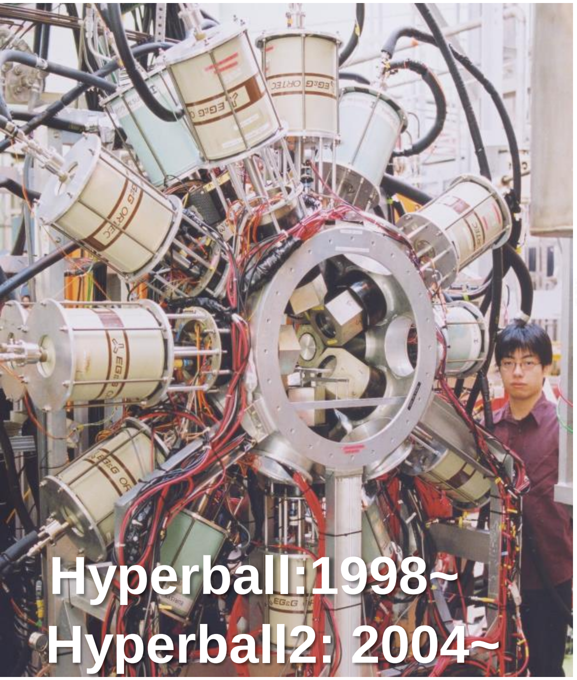
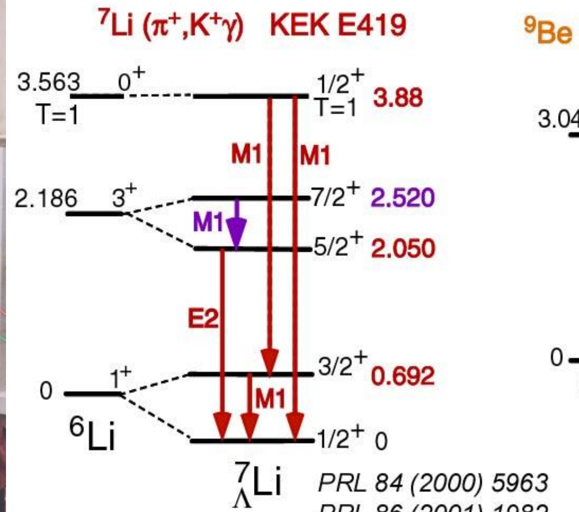
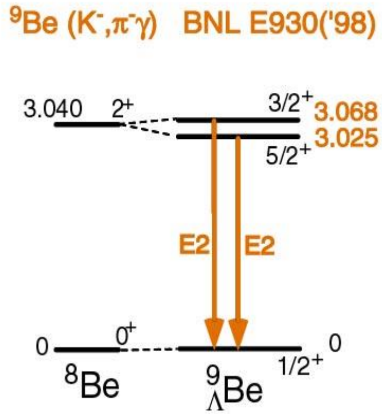
1. Introduction

Hypernuclear γ-ray data

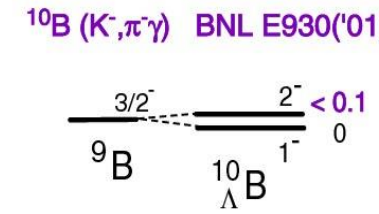




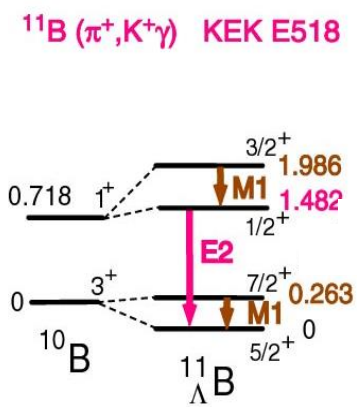
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



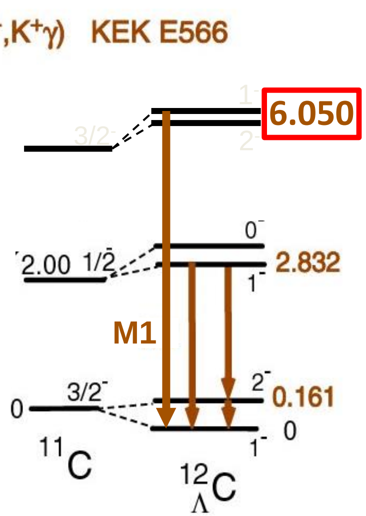
PRL 88 (2002) 082501
NPA 754 (2005) 58c



NPA 754 (2005) 58c

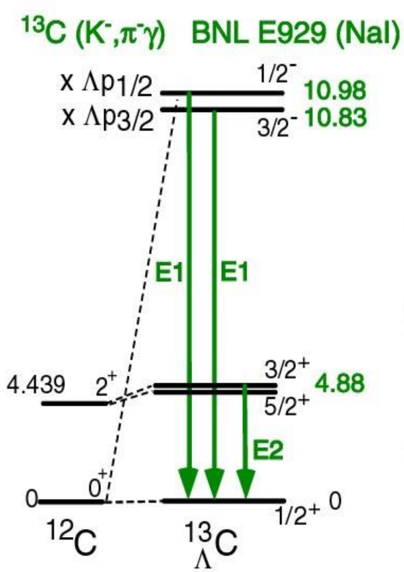


NPA 754 (2005) 58c

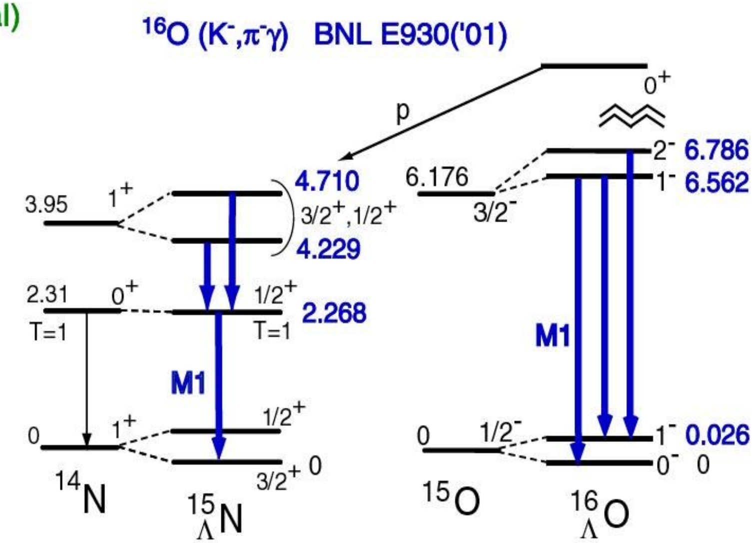


EPJ A33 (2007) 243

PTEP (2015) 081D01



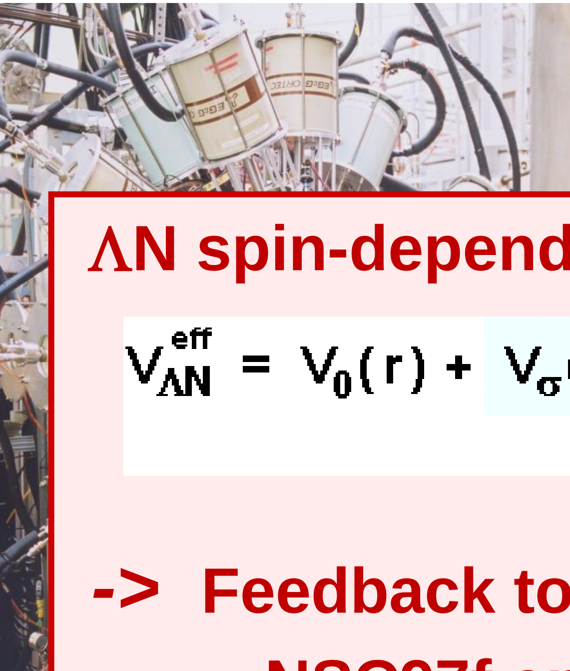
PRL 86 (2001) 4255
PRC 65 (2002) 034607

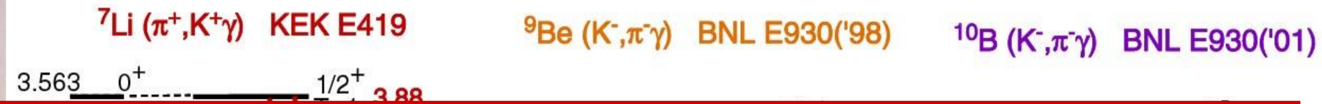


PRC 77 (2008) 054315

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

Hypernuclear γ-ray data



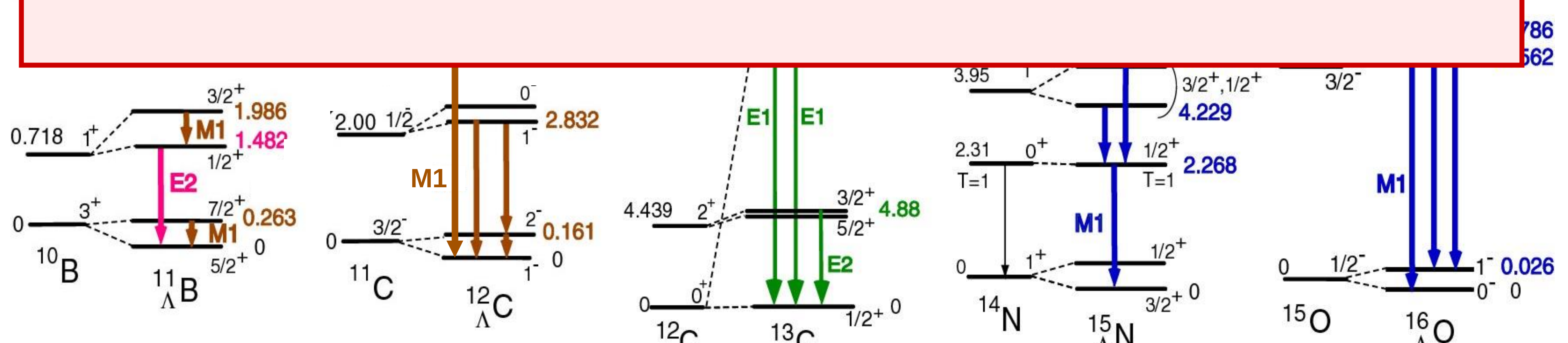


ΛN spin-dependent interaction strengths determined:

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

-> Feedback to BB interaction models :

NSC97f and updated Nijmegen models (ESC08) are OK



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EPJ A33 (2007) 243

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EPJ A33 (2007) 247

Reproduction of level energies

D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

Millener's parameter set

Δ = 0.33 (0.43 for A=7), S_Λ = -0.015, S_N = -0.35, T= 0.024 [MeV]

doublet spacing

Calculated from G-matrix using ΛN–ΣN force in NSC97f

contribution of each term (keV) | keV

	J_u^π	J_l^π	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
$^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
$^{7}_{\Lambda}$Li	$7/2^+$	$5/2^+$	74	557	−32	−8	−71	494	471
$^{8}_{\Lambda}$Li	2^-	1^-	151	396	−14	−16	−24	450	(442)
$^{9}_{\Lambda}$Li	$5/2^+$	$3/2^+$	116	530	−17	−18	−1	589	
$^{9}_{\Lambda}$Li	$3/2_2^+$	$1/2^+$	−80	231	−13	−13	−93	−9	
$^{9}_{\Lambda}$Be	$3/2^+$	$5/2^+$	−8	−14	37	0	28	44	43
$^{10}_{\Lambda}$B	2^-	1^-	−15	188	−21	−3	−26	120	$<$ 100
$^{11}_{\Lambda}$B	$7/2^+$	$5/2^+$	56	339	−37	−10	−80	267	264
$^{11}_{\Lambda}$B	$3/2^+$	$1/2^+$	61	424	−3	−44	−10	475	505
$^{12}_{\Lambda}$C	2^-	1^-	61	175	−12	−13	−42	153	161
$^{15}_{\Lambda}$N	$1/2_1^+$	$3/2_1^+$	44	244	34	−8	−214	99	
$^{15}_{\Lambda}$N	$3/2_2^+$	$1/2_2^+$	65	451	−2	−16	−10	507	481
$^{16}_{\Lambda}$O	1^-	0^-	−33	−123	−20	1	188	23	26
$^{16}_{\Lambda}$O	2^-	1_2^-	92	207	−21	1	−41	248	224

Reproduction of level energies

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doubl

${}^{7}_{\Lambda}$Li									
${}^{7}_{\Lambda}$Li									
${}^{8}_{\Lambda}$Li									
${}^{9}_{\Lambda}$Li									
${}^{9}_{\Lambda}$Li									
${}^{9}_{\Lambda}$Be									
${}^{10}_{\Lambda}$B									
${}^{11}_{\Lambda}$B									
${}^{11}_{\Lambda}$B									
${}^{12}_{\Lambda}$C									
${}^{15}_{\Lambda}$N									
${}^{15}_{\Lambda}$N									
${}^{16}_{\Lambda}$O									
${}^{16}_{\Lambda}$O	2^-	1^-_2	92	207	−21	1	−41	248	224

- ***Most of the p-shell level data were taken. They are reproduced very well (except for a few levels in A=10-12)***

⇒ Let us go to s-shell and sd-shell

- ***ΣΛ coupling from NSC97f looks good, but more data and further study needed.***

What's next at J-PARC?

⇒ Go to s-shell (${}^{4}_{\Lambda}$He)

⇒ Go to sd-shell (${}^{19}_{\Lambda}$F)

⇒ Measure B(M1) for g_Λ in nucleus

J-PARC E13

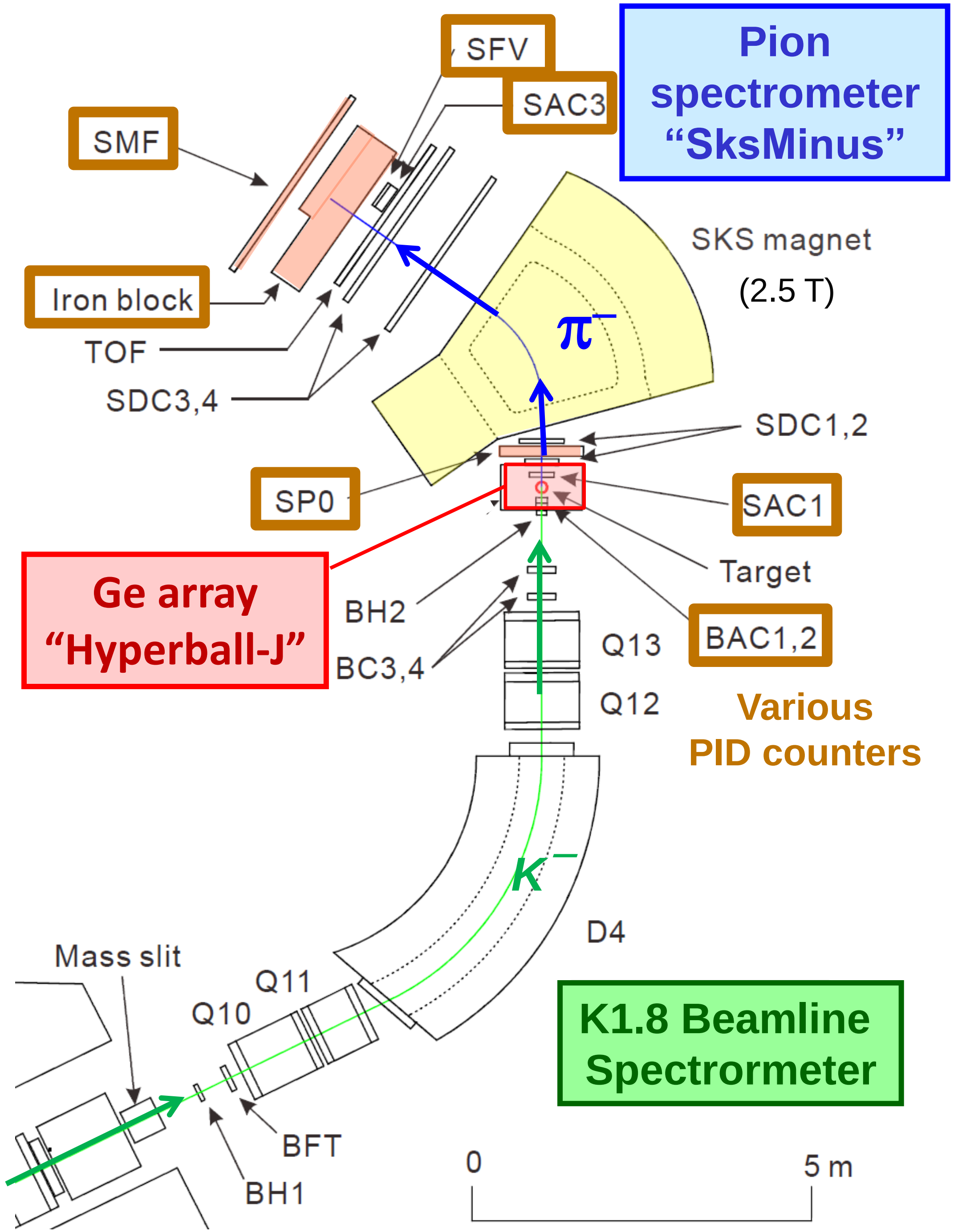
Setup at J-PARC K1.8

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

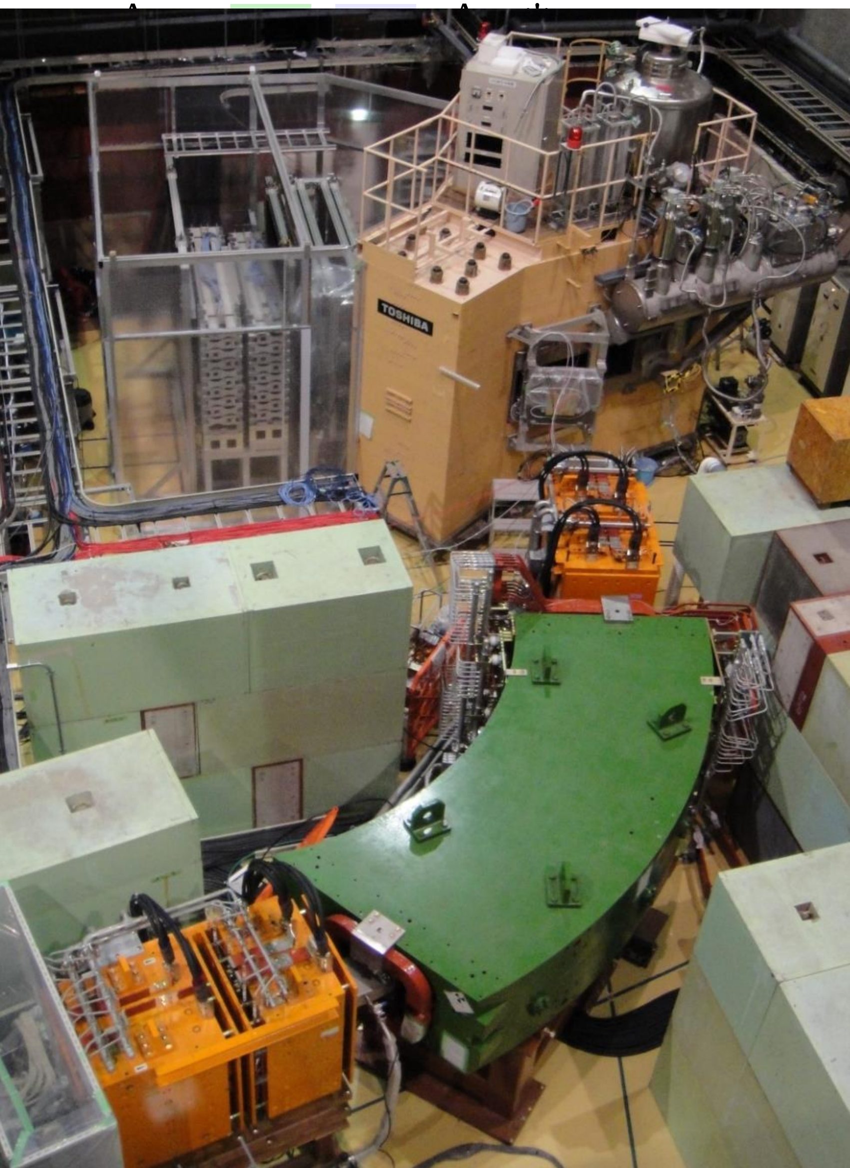
- Tag production of hypernuclei
- Detect γ-rays from hypernuclei

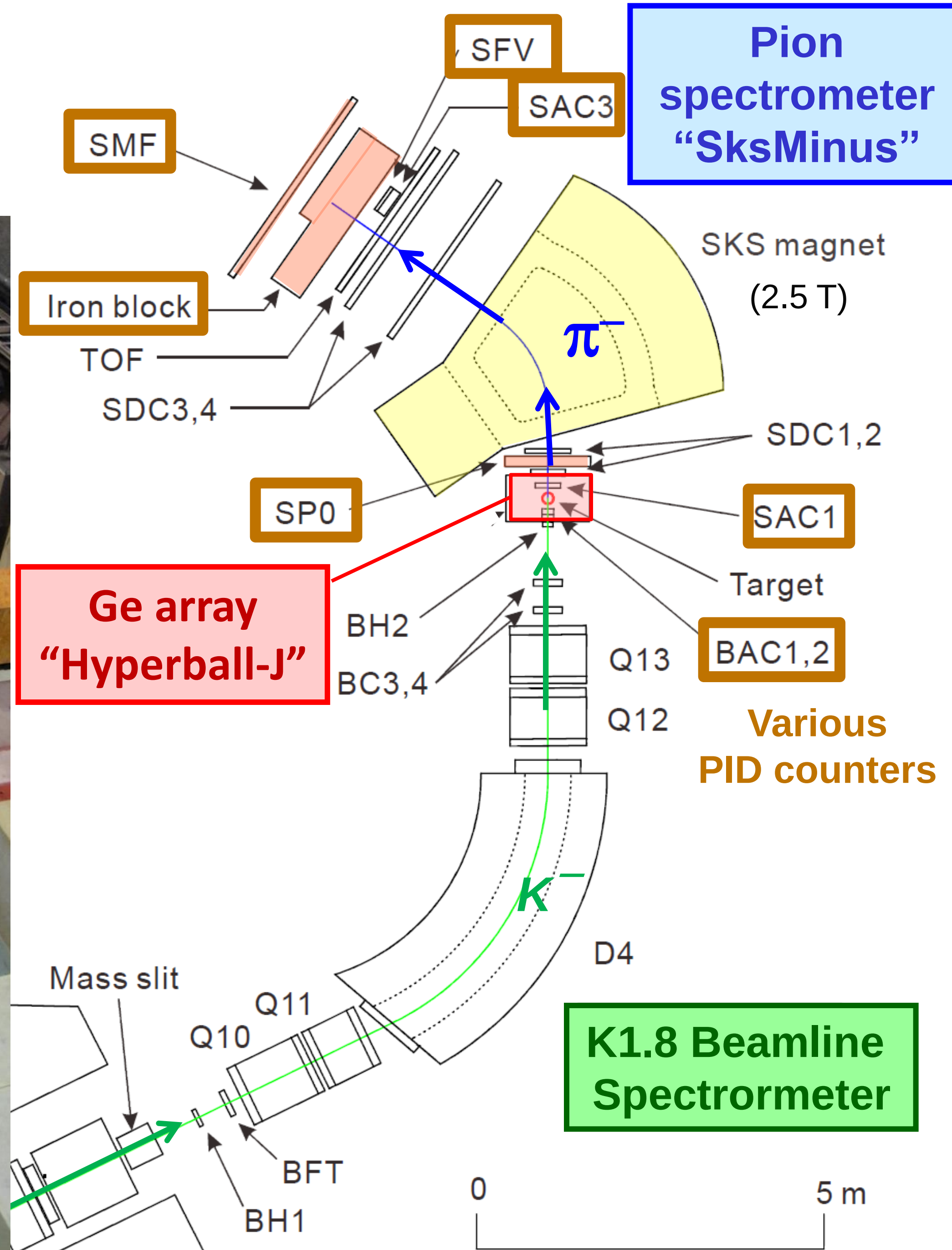
$^{4}_{\Lambda}$He : liq.He target (2.5 g/cm^2)
p_K = 1.5 GeV/c

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



Setup at J-PARC K1.8





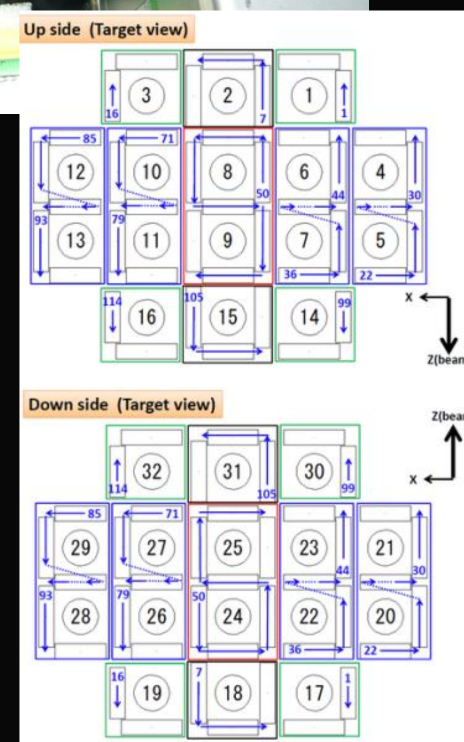
Hyperball-J

Ge cooled down to ~70K (c.f. 92K w/LN2) to reduce radiation damage

Fast background suppressor made of PWO

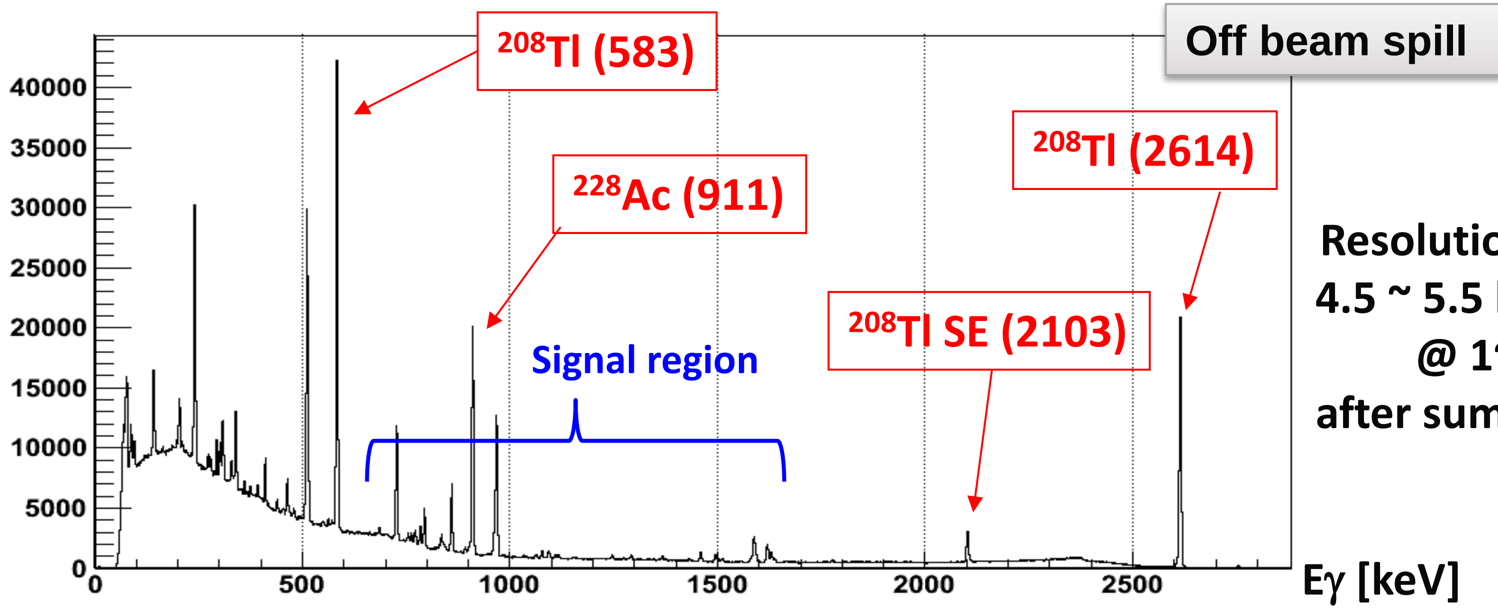
Pulse-tube refrigerator

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

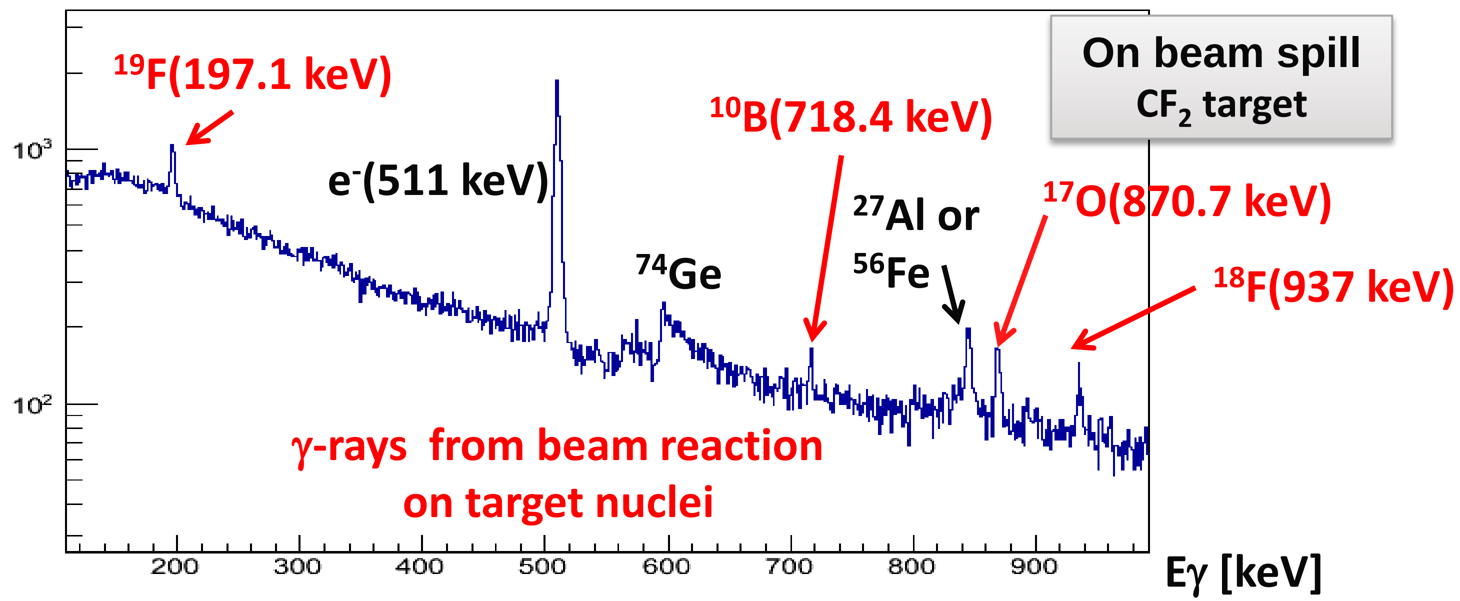


<u>Ge ADC</u>

Calibration (off beam spill) using Th-series gamma rays



Resolution (off spill) :
4.5 ~ 5.5 keV (FWHM)
@ 1~2 MeV
after summing all Ge's



2. ${}^{4}_{\Lambda}$He run

Parallel 1b (Mon) T.O. Yamamoto

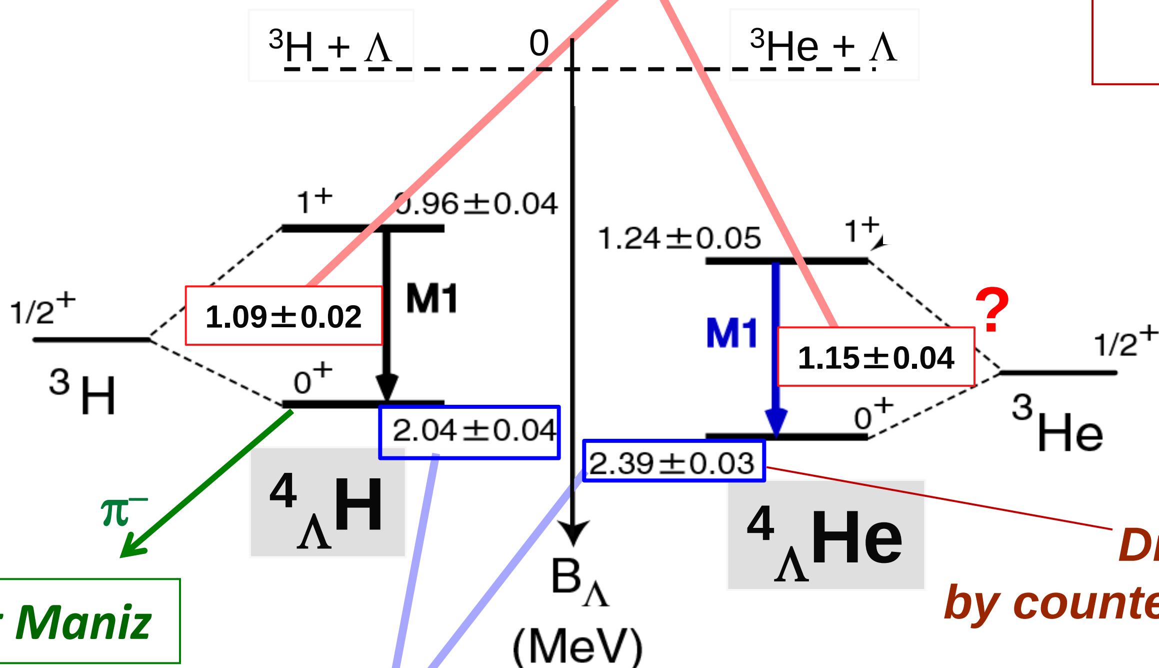
Charge Symmetry Breaking puzzle in A=4

Origin: Unkown. ΛN-ΣN coupling?
But 4-body calc's with Λ–Σ mixing
using Nijmegen interactions failed
=> Long standing puzzle

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

Old NaI data

Should be measured with Ge -> E13



Difficult by counter experiments

Measured at Maniz

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

2.12±0.01±0.09

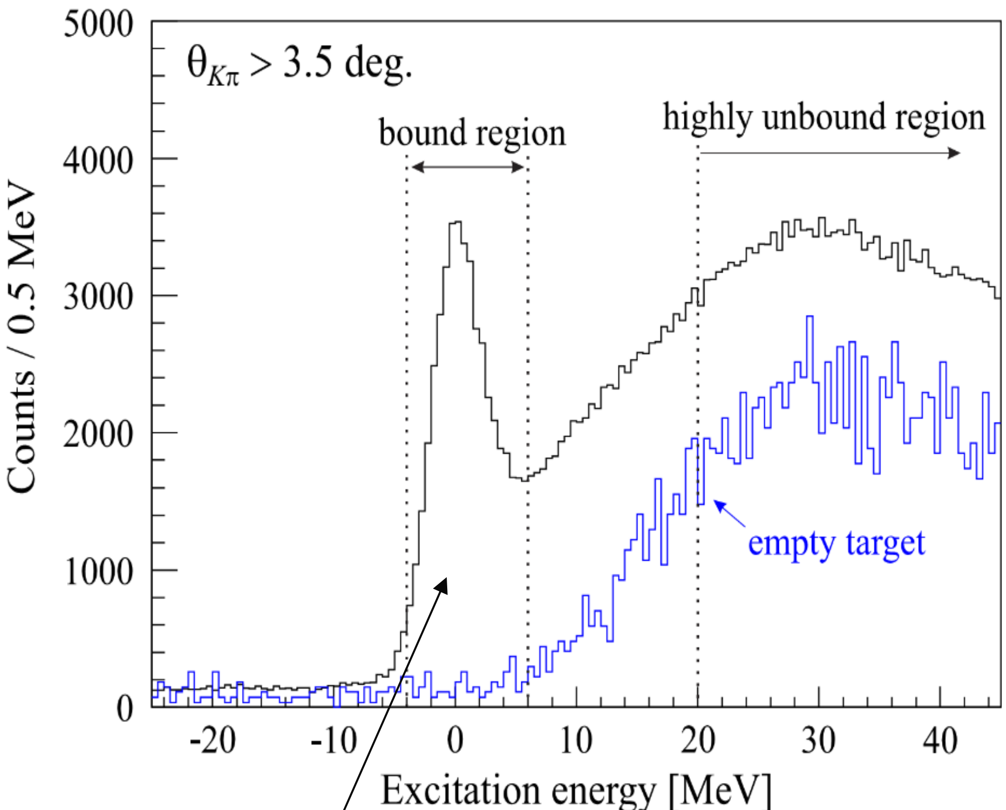
no systematic error

Old emulsion data

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

Experimental confirmation of CSB is necessary

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



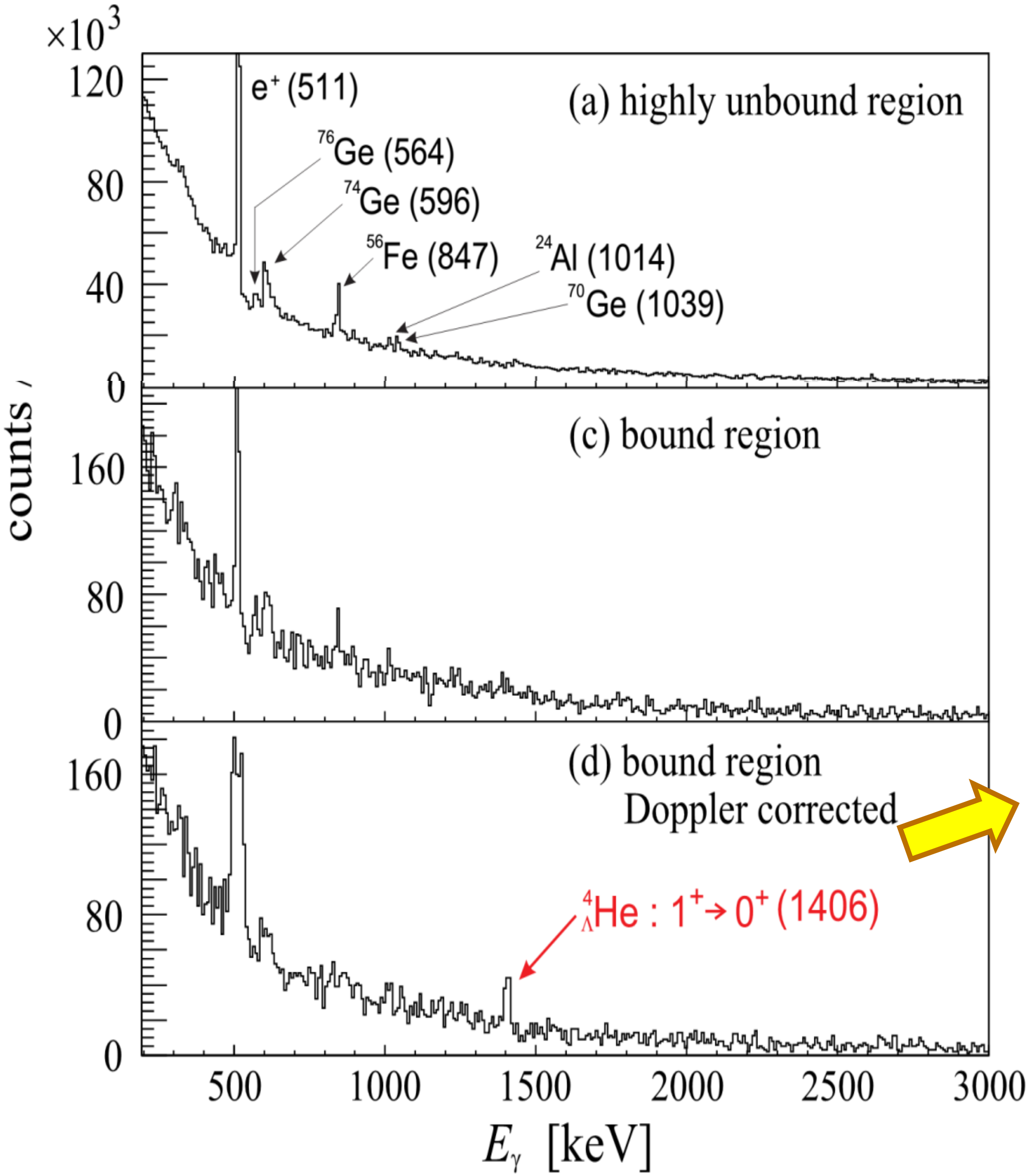
Black : with liq. He
(physics run)

Blue : empty target
(w/o liq. He, w/target cell)
mainly from $K^{-} \rightarrow \pi^{-} + \pi^{0}$

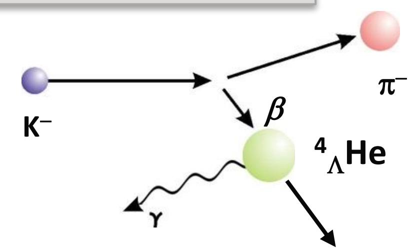
$^{4}_{\Lambda}He(0^{+})$ dominant + $^{4}_{\Lambda}He(1^{+})$

Peak width = resolution ~ 5.4 MeV (FWHM)

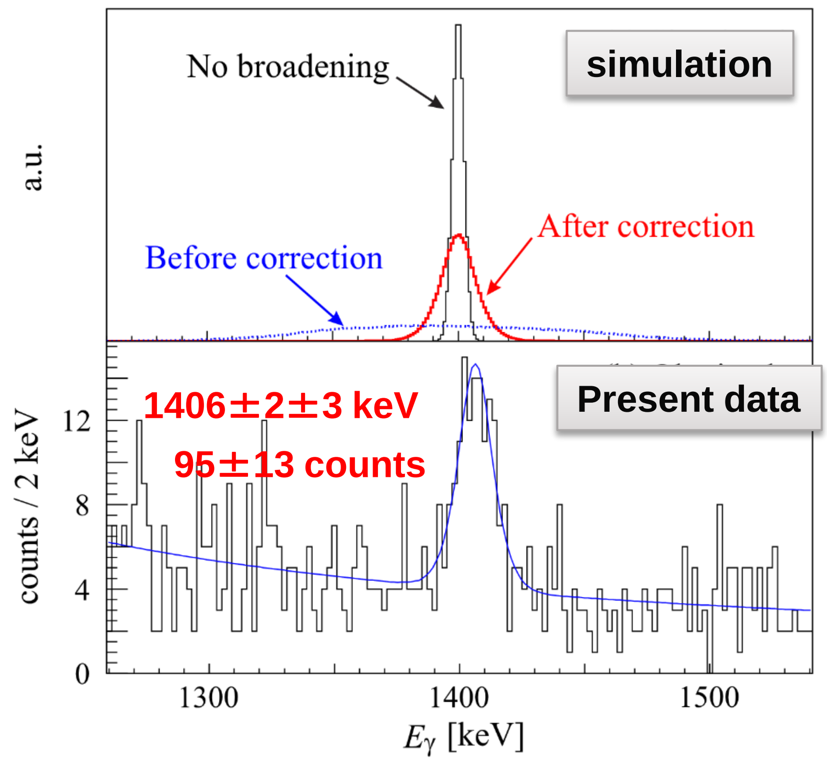
Mass-gated γ spectrum



Doppler shift correction

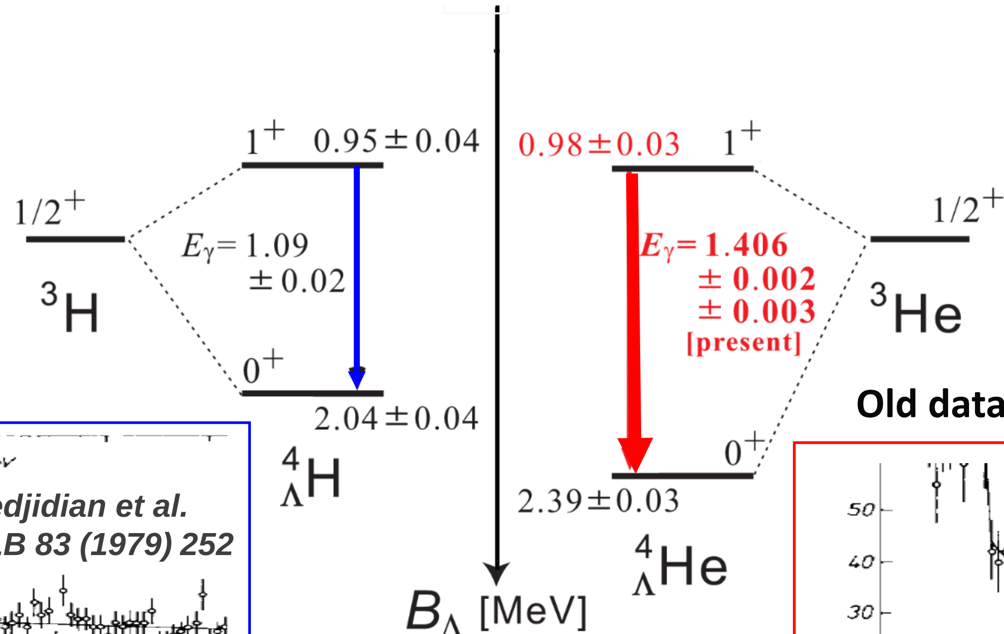


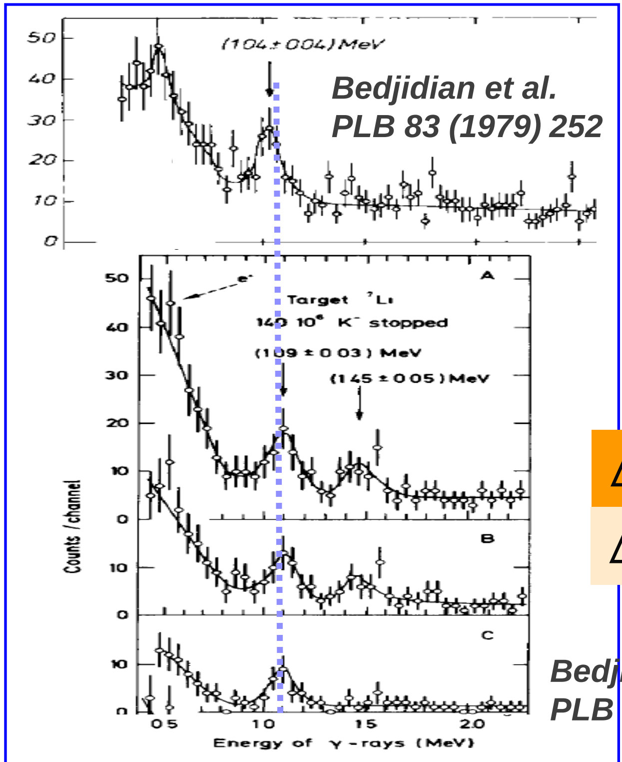
$$E_{corrected} = \frac{E_{measured}}{\gamma(1 + \beta cos\theta_{\gamma})}$$



- Existence of CSB confirmed <u>only by γ-ray data</u>
- Large <u>spin dependence</u> in CSB found by combining with emulsion data

<u>Results</u>





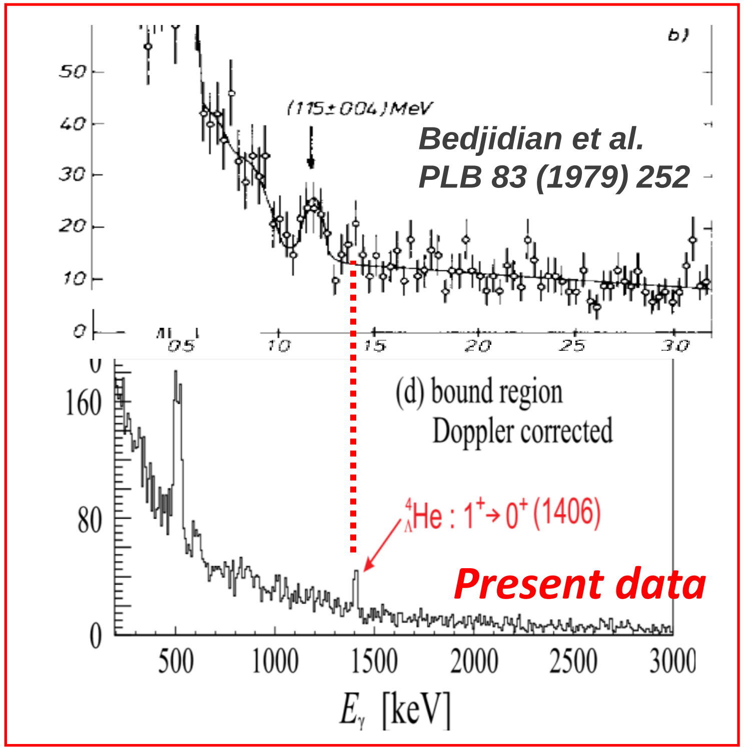
Bedjidian et al.
PLB 62 (1976) 467

Combining with emulsion data,

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

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

Old data (1.15 MeV) was denied.

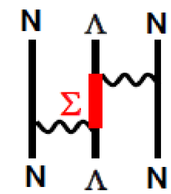


ΛN–ΣN coupling

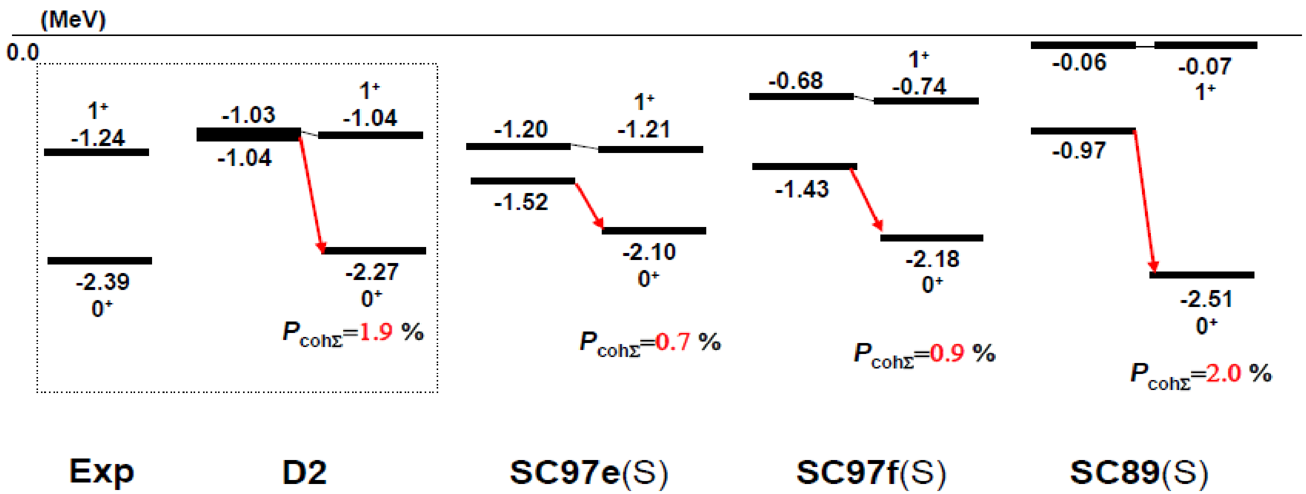
S=1 pairs	$^4_\Lambda$H 1⁺	0⁺
$\Lambda p \Leftrightarrow -\sqrt{\frac{1}{3}}\Sigma^0 p+\sqrt{\frac{2}{3}}\Sigma^+ n$ $\begin{bmatrix} s_3=1 \\ s_3=0 \\ s_3=-1 \end{bmatrix}$	-1/3 +1/3 Cancel	+1/2
$\Lambda n \Leftrightarrow \sqrt{\frac{1}{3}}\Sigma^0 n-\sqrt{\frac{2}{3}}\Sigma^- p$ $\begin{bmatrix} s_3=1 \\ s_3=0 \\ s_3=-1 \end{bmatrix}$	+1/2	+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.

$^4_\Lambda$He



Slide by Akaishi



Y. Akaishi, T. Harada, S. Shinmura & Khin Swe Myint, Phys. Rev. Lett. 84 (2000) 3539

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

A. Gal, PLB 744 (2015) 352. reproduced the present data well .

=> Invited talk in 1a session (Mon)

arXiv:1508.00376v1

Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of ${}^4_\Lambda$He

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(Dated: August 4, 2015)

Parallel 1a (Mon) Yamamoto

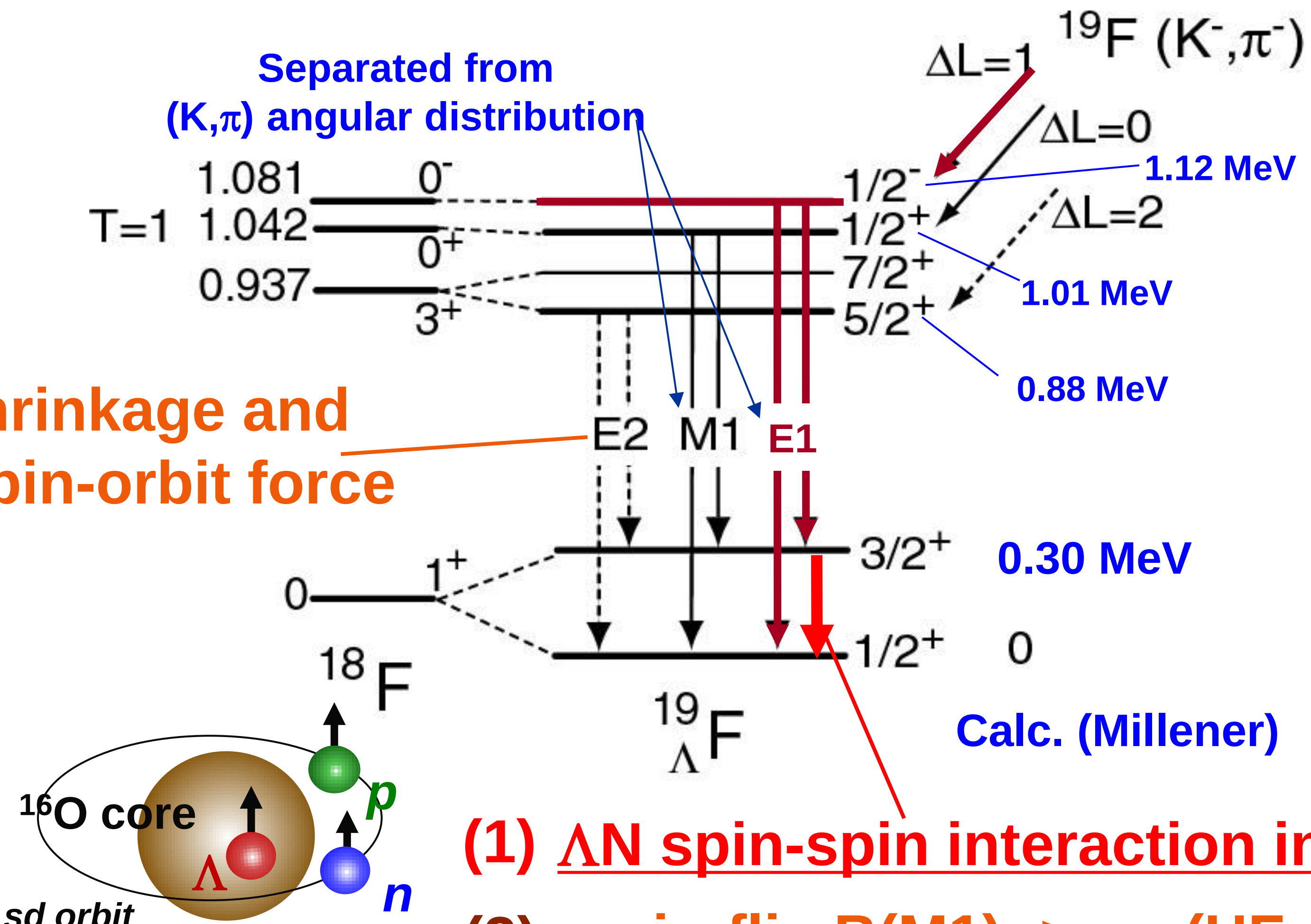
3. $^{19}_{\Lambda}F$ run

Parallel 4b (Tue) Yang

Poster A1 Y. Sasaki

$^{19}_{\Lambda}F$ spectroscopy

The first study of sd-shell hypernuclei



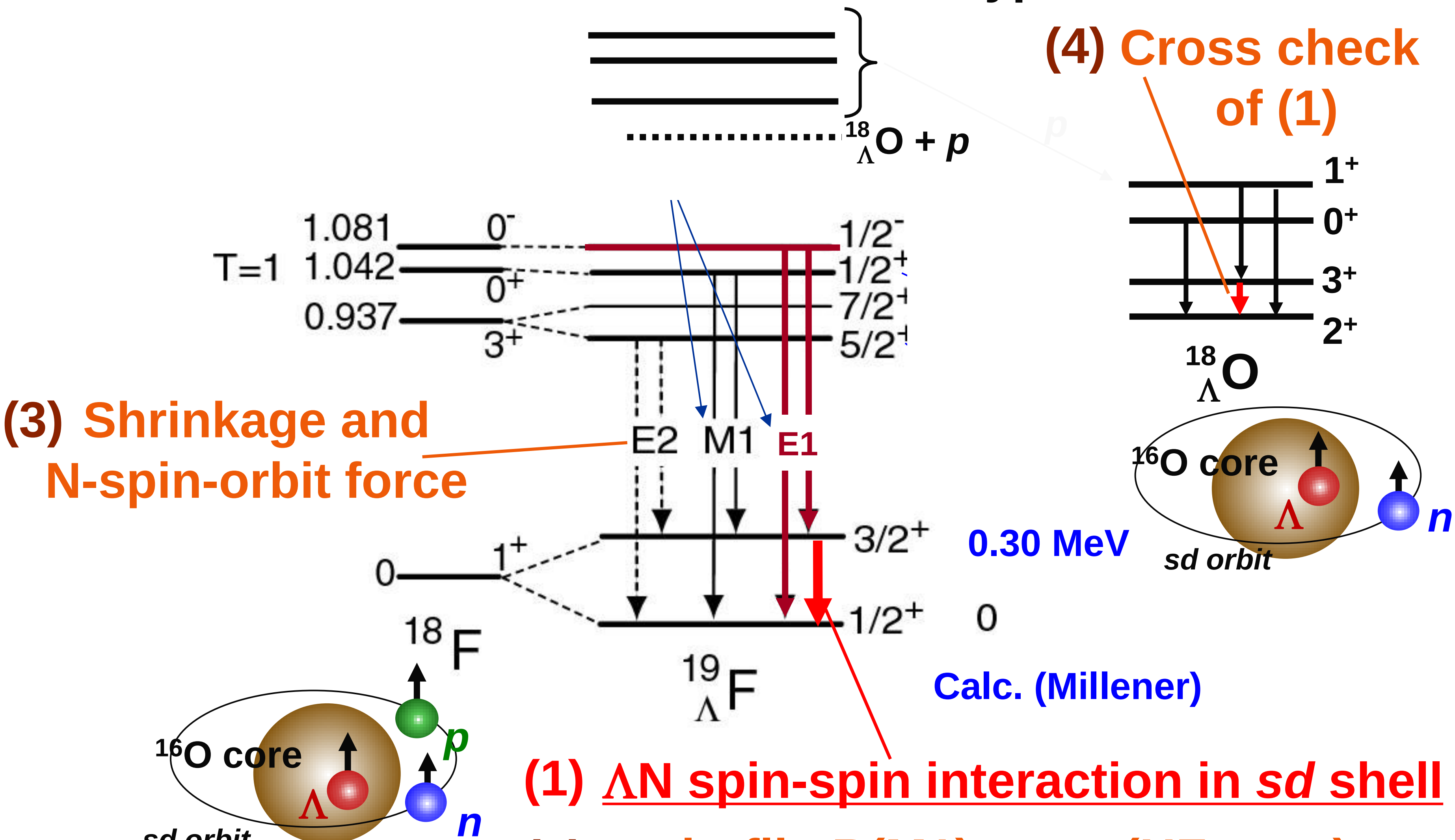
(3) Shrinkage and N-spin-orbit force

(1) ΛN spin-spin interaction in *sd* shell

(2) spin-flip B(M1) -> g_{Λ} (HF case)

$^{19}_{\Lambda}$F spectroscopy

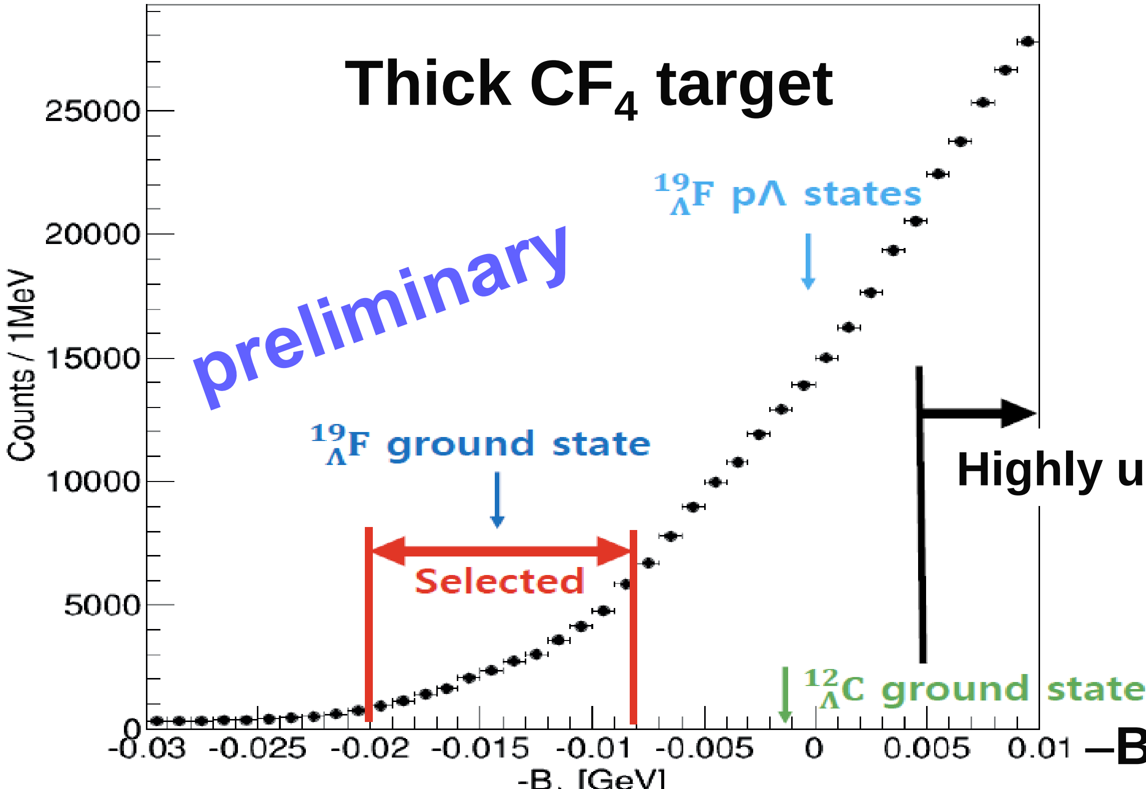
The first study of sd-shell hypernuclei



(1) **ΛN spin-spin interaction in *sd* shell**

(2) spin-flip B(M1) -> g_{Λ} (HF case)

Missing mass for $^{19}{}_{\Lambda}F$

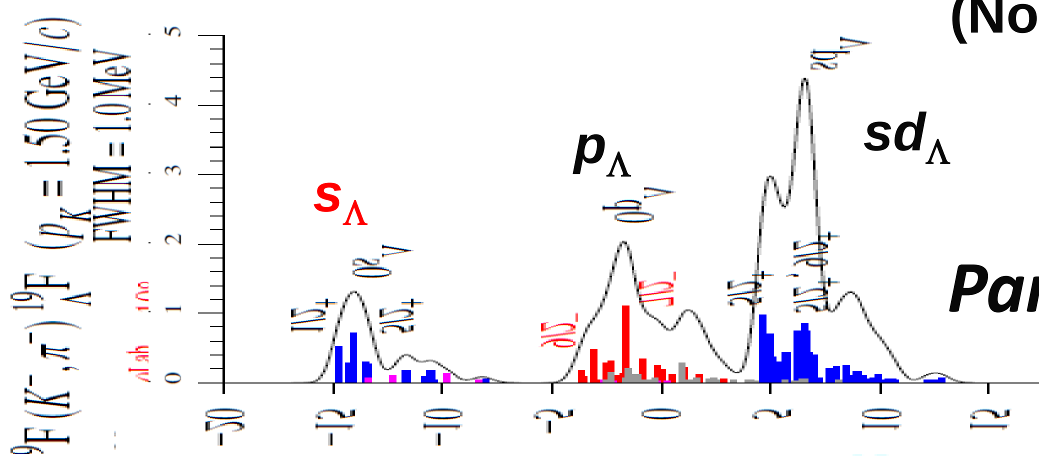


Highly unbound region

$-B_{\Lambda}$ (GeV)

(Not calibrated well)

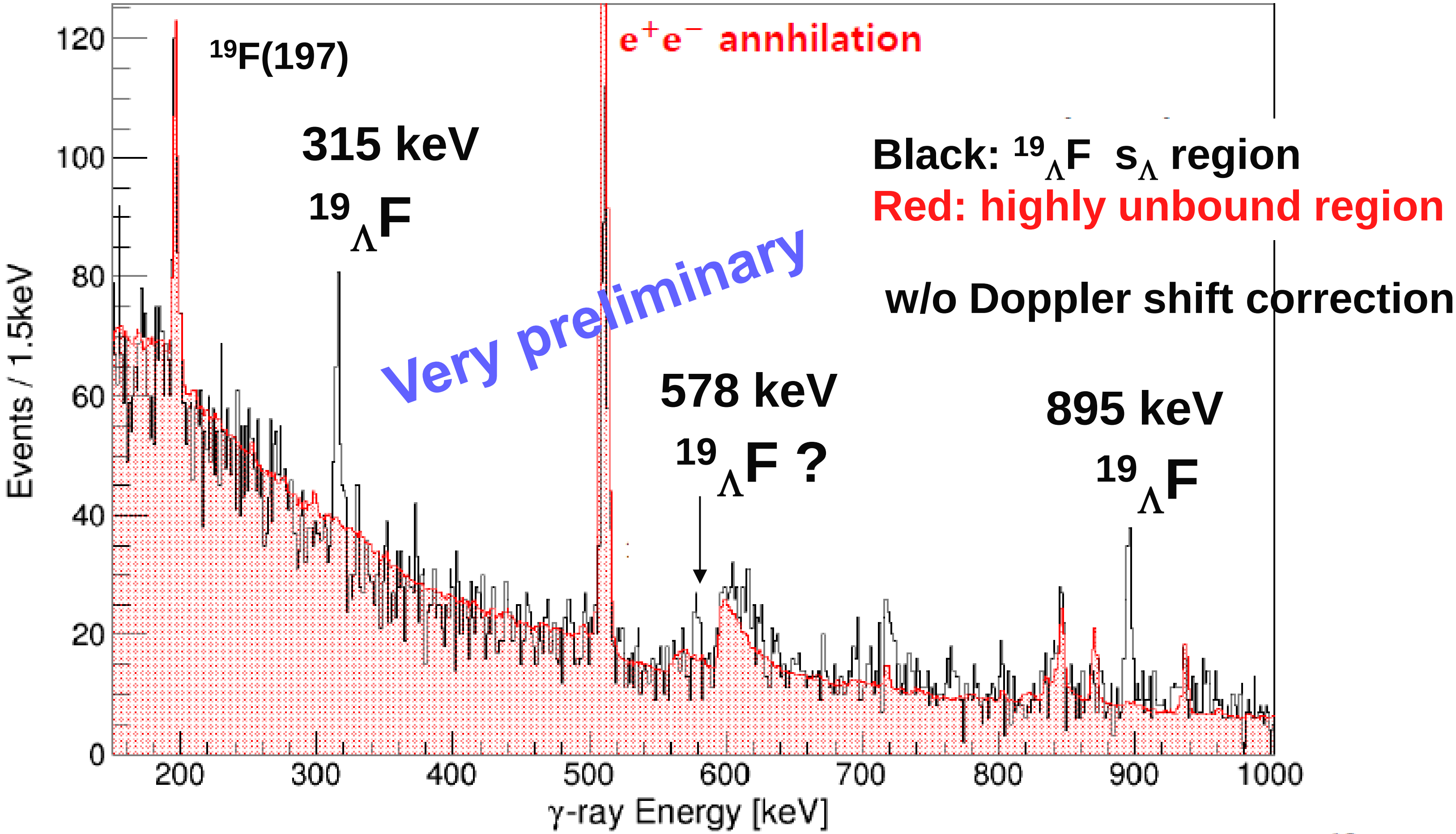
Shell model calc. by Umeya



Parallel 4b (Tue)

Umeya

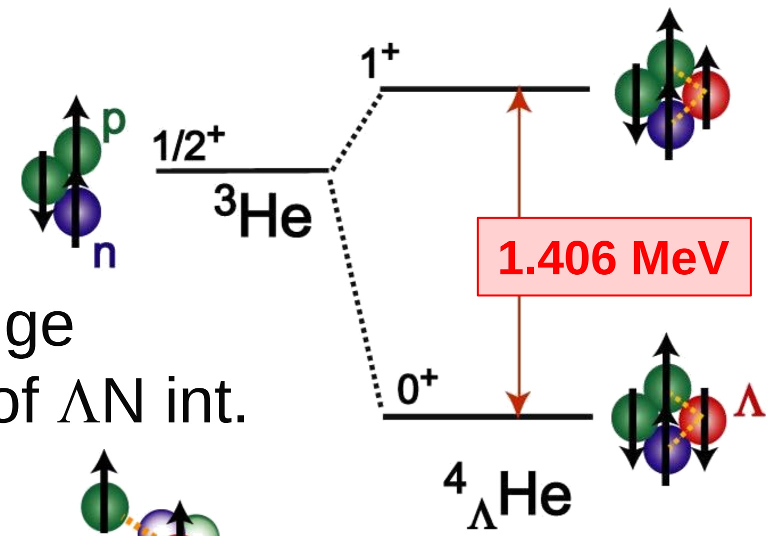
Mass-gated γ-ray spectrum



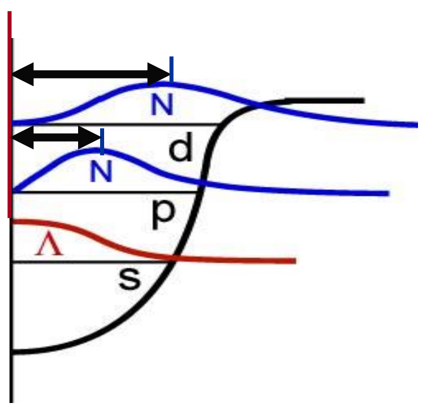
- Most likely, the 315 keV peak is assigned as the g.s. doublet M1 transition, $^{19}{}_{\Lambda}$F($3/2^+ \rightarrow 1/2^+$)
- Several other peaks are also seen.

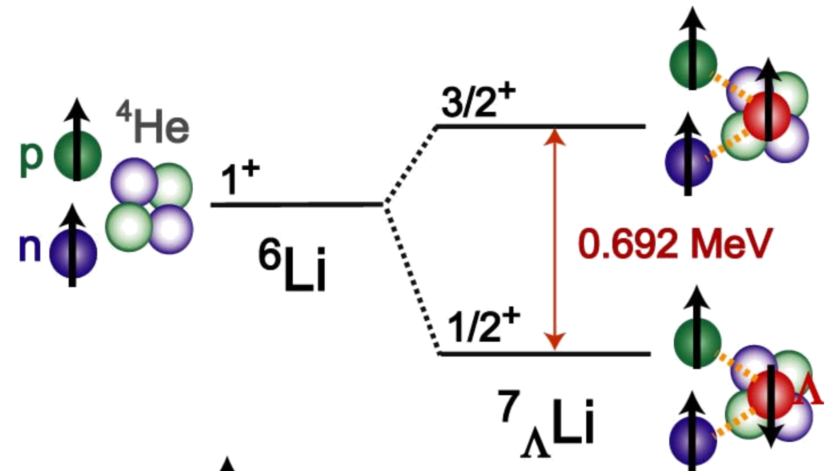
A-dependence of ΛN interaction strength

=> Information on
wave functions and interaction range
=> confirm short-range nature of ΛN int.

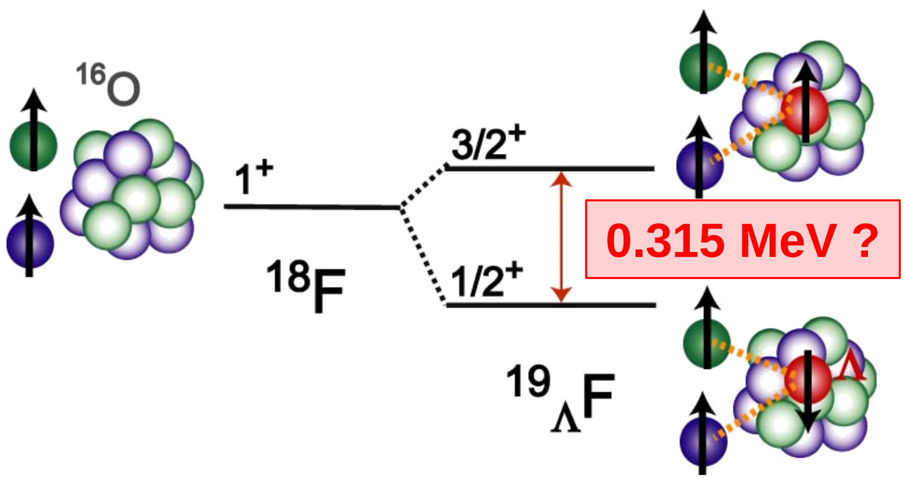


$s_\Lambda s_N$





$s_\Lambda p_N$



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

$s_\Lambda d_N$

4. Future Prospect

Experimental Plans of γ-spectroscopy

1. Spin-flip B(M1) and in-medium g_{Λ}
   $^{7}_{\Lambda}$Li (E13-2nd) and heavier

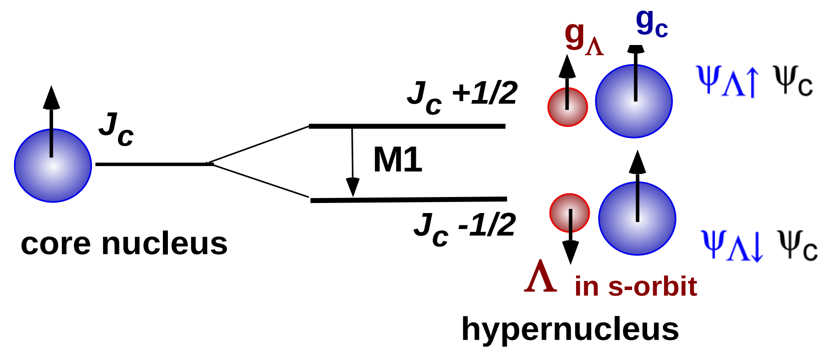
2. Light hypernuclei $^{4}_{\Lambda}$H (CSB), $^{3}_{\Lambda}$H*(1^{+})

3. E1(p_{Λ}->s_{Λ}) for B_{Λ} (-> ΛNN force) and LS splitting

4. Impurity effects (change of deformation/clustering)
   sd-shell: $^{25}_{\Lambda}$Mg, $^{28}_{\Lambda}$Si, $^{20}_{\Lambda}$Ne

Magnetic moment of a Λ in a nucleus

Λ-spin-flip M1 transition:
B(M1) -> g_Λ in medium



$$B(M1) = (2J_{up}+1)^{-1}\,|\langle\,\Psi_{low}\,\|\,\mu\,\|\,\Psi_{up}\rangle|^2$$
$$= (2J_{up}+1)^{-1}\,|\langle\,\psi_{\Lambda\downarrow}\,\psi_c\,\|\,\mu\,\|\,\psi_{\Lambda\uparrow}\,\psi_c\rangle|^2$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$$

$$= \frac{3}{8\pi}\,\frac{2J_{low}+1}{2J_c+1}\,(g_\Lambda - g_c)^2 \quad [\mu_N^2]$$

Doppler Shift Attenuation Method

$$\Gamma = \overset{\sim 100\%}{BR} / \tau = \frac{16\pi}{9}\,E_\gamma^3\,B(M1)$$

Effect of chiral symmetry restoration?

$$\mu_q = \frac{e\hbar}{2m_q c}$$

m_q **: Constituent quark mass**

m_q decrease -> μ_q increase ?

Nuclear density dependence

Λ–Σ mixing?

Isospin dependence

Preliminary previous data on g_Λ

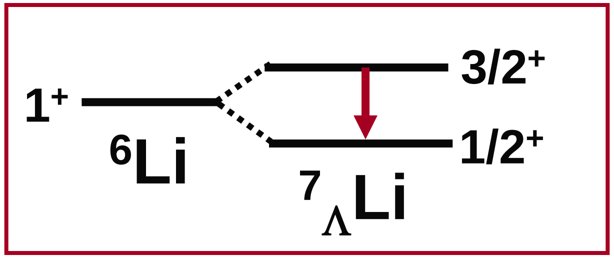
Systematic errors can not be estimated

- **BNL E930** **(M. Ukai)**

$$\boxed{g_\Lambda = \ -1.1\,^{+0.6}_{-0.4}\ \mu_N}$$

τ **from DSAM**

$^{10}B\ (K^-, \pi^-)\ ^{10}{}_\Lambda B^*$
$\rightarrow\ ^{7}{}_\Lambda Li^* + {}^3He$

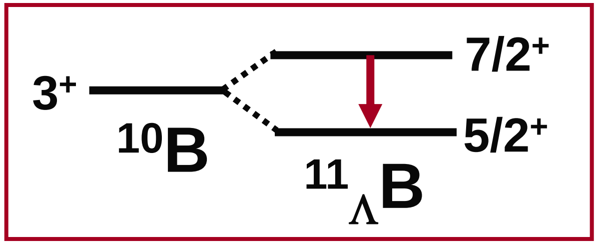


- **KEK E566** **(Y. Ma)**

$$\boxed{g_\Lambda > \ -1.76\ \mu_N}$$

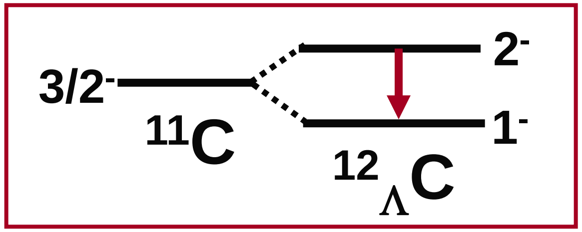
τ **from DSAM**

$^{12}C\ (K^-, \pi^-)\ ^{12}{}_\Lambda C^*$
$\rightarrow\ ^{11}{}_\Lambda B^* + p$



$$\boxed{g_\Lambda = \ -1.04 \pm 0.41\ \mu_N}$$

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

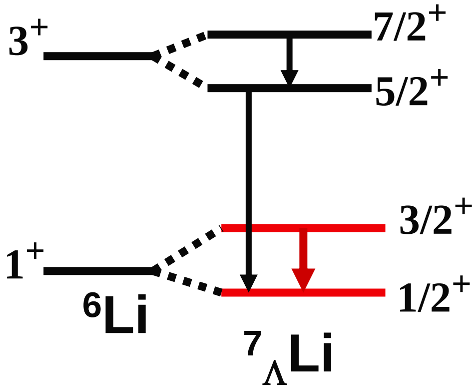


- Yield ratio for $[\ 2^- \rightarrow 1^-\ ]\ /\ [1^-_2 \rightarrow 2^-]$ γ-rays
  -> $Br(2^- \rightarrow 1^-) = 0.19 \pm 0.12$ (80% of 2^- weakly decays)
- Weak decay rate of 2^- and 1^- are <u>assumed</u>
  to be the same, Γ_{weak} = (lifetime 230.7 ± 6.3 ps)$^{-1}$
  => $\Gamma_{M1} = Br\ /(1 - Br)\ \ \Gamma_{weak}$

$\Leftrightarrow$ **g_Λ(free) = $-1.226\ \mu_N$**

- **J-PARC E13** **$^{19}F\ (K^-, \pi^-)\ ^{19}{}_\Lambda F^*$** **To be analyzed but difficult**

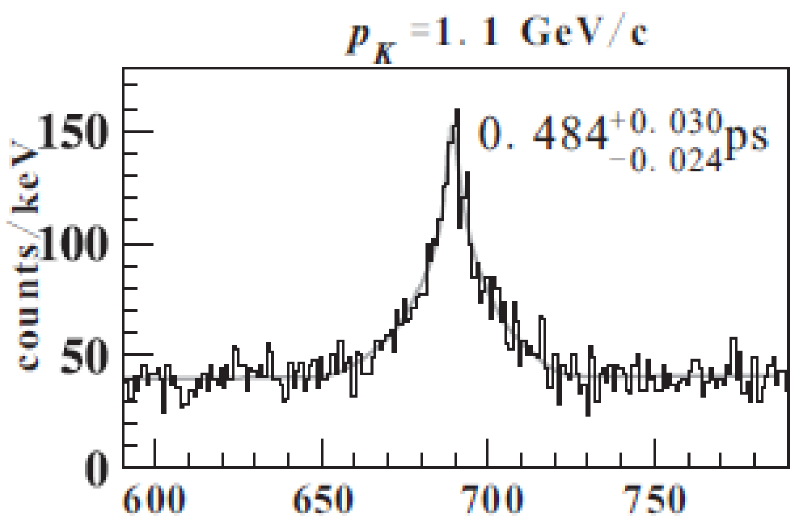
Dedicated measurement at J-PARC (E13-2nd)



Directly produce the best-known hypernucleus, $^7_\Lambda$Li.

- Energies of all the bound states and γ-ray background were measured.
- Cross sections are reliably calculated.
- τ = 0.5ps, t_{stop} ~2.2 ps for 1.1 GeV/c (K^-,π^-) and Li_2O target (DSAM works only when $\tau < t_{stop}$)

p_K = 1.1 GeV/c at K1.1+SKS
4 weeks
50 kW (Pt)



E13-2nd: Simulation

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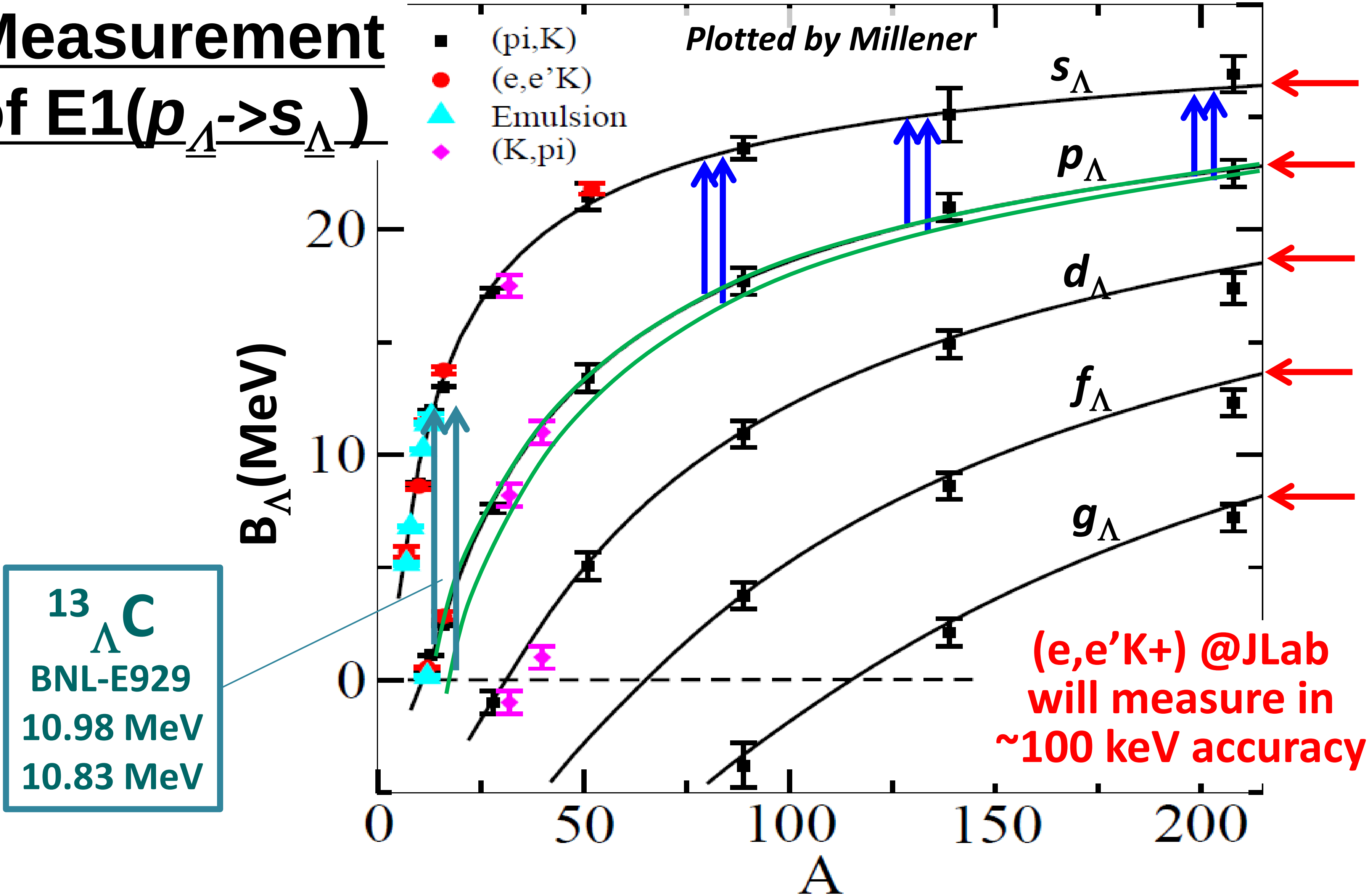
- Stat. error $\Delta\tau/\tau = 5.6\%$

$$\Rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

SKS and all the detectors will be installed at a new line "K1.1"

Measurement of E1(p_Λ->s_Λ)



p_Λ-s_Λ spacing and $(p_{1/2})_\Lambda$-$(p_{3/2})_\Lambda$ splitting can be precisely (~keV accuracy) measured.

⇒ LNN force and neutron star puzzle

⇒ Origin of nuclear LS splitting¥

6. Summary

- Hypernuclear gamma-ray spectroscopy has extended to s-shell and sd-shell regions at J-PARC.
  We took data for ${}^{4}_{\Lambda}$He and ${}^{19}_{\Lambda}$F .

- We observed ${}^{4}_{\Lambda}$He(1^+->0^+) transition at 1406±2±2 keV. It clearly confirmed existence of Charge Symmetry Breaking in ΛN interaction.
- Combined with old emulsion values, we found that $B_\Lambda(1^+)$ difference is by one order of magnitude smaller than $B_\Lambda(0^+)$ difference, suggesting that Λ–Σ coupling is responsible for the CSB..

- We observed a few hypernuclear γ-ray peaks from ^{19}F target.
- A peak at 315 keV is most likely assigned as ${}^{19}_{\Lambda}$F(M1: $3/2^+$->$1/2^+$).

- Next step is a B(M1) measurement for in-medium g_Λ, and then E1(p_Λ->s_Λ) and impurity effects.

HYPER
BALL
TOHOKU

Thank you
for your attention.