Gamma spectroscopy of hypernuclei
--E13 and beyond--

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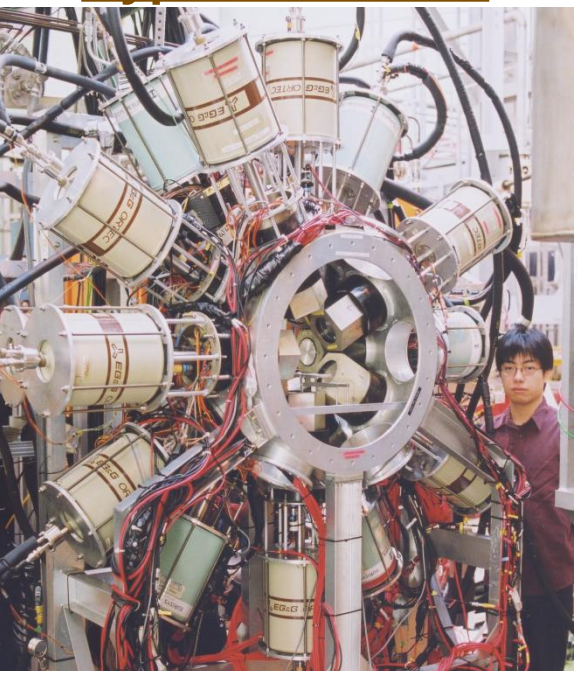
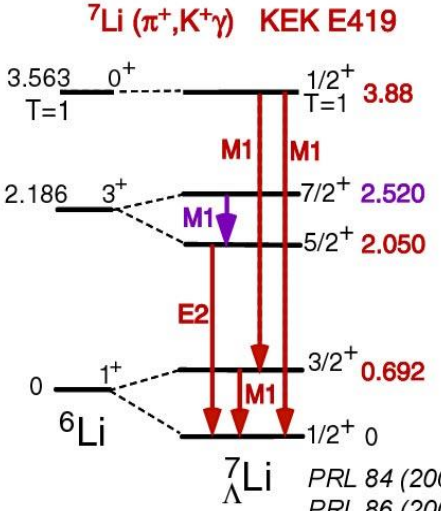
1. Introduction
2. E13: purposes and present status
3. Beyond E13
4. Summary

1. Introduction

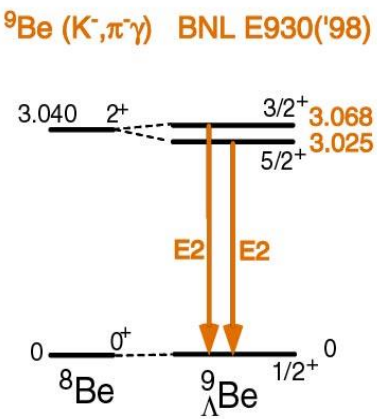
Hyperball 1998~



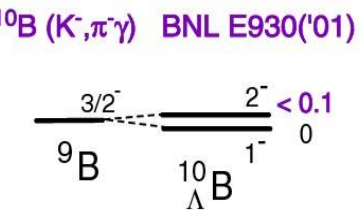
Hypernuclear γ-ray data



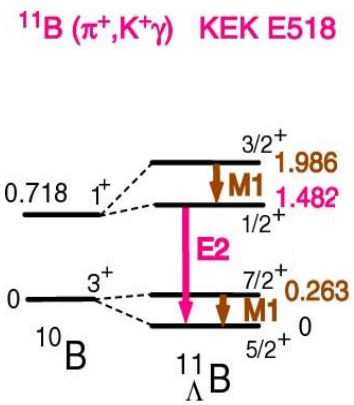
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



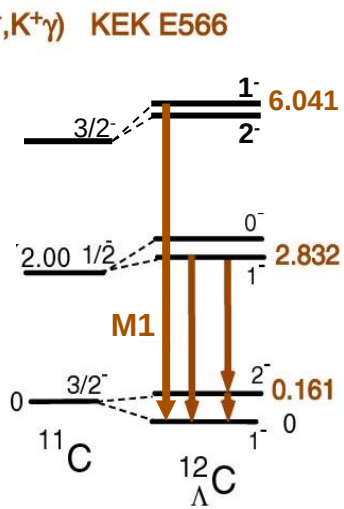
PRL 88 (2002) 082501
NPA 754 (2005) 58c



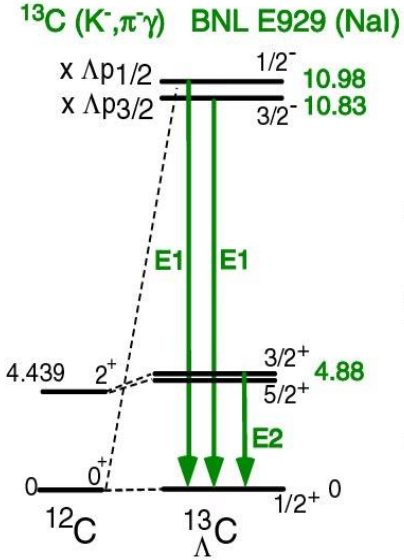
NPA 754 (2005) 58c



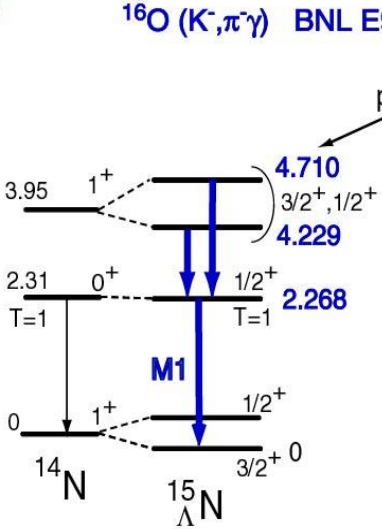
NPA 754 (2005) 58c



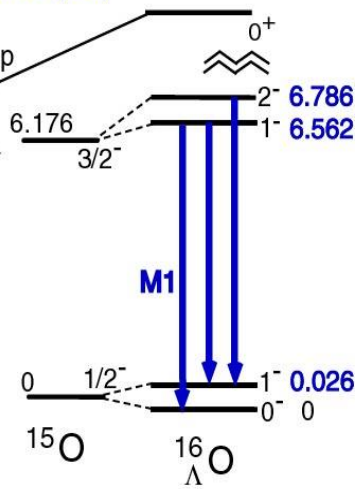
EPJ A33 (2007) 243



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



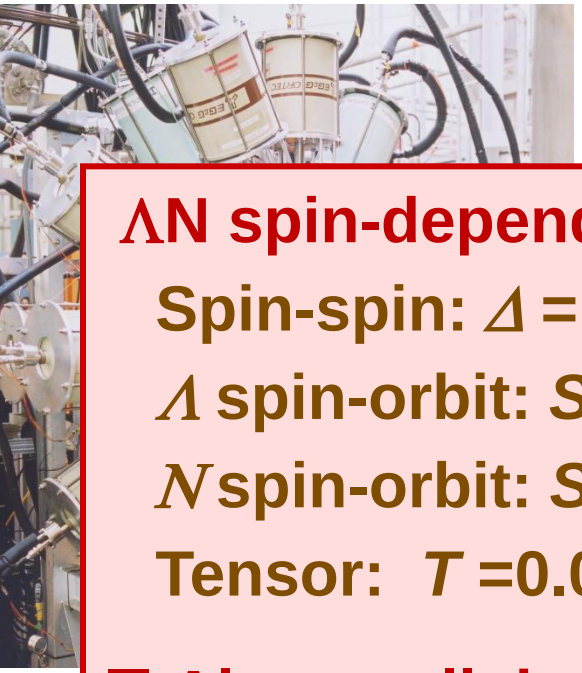
PRC 77 (2008) 054315

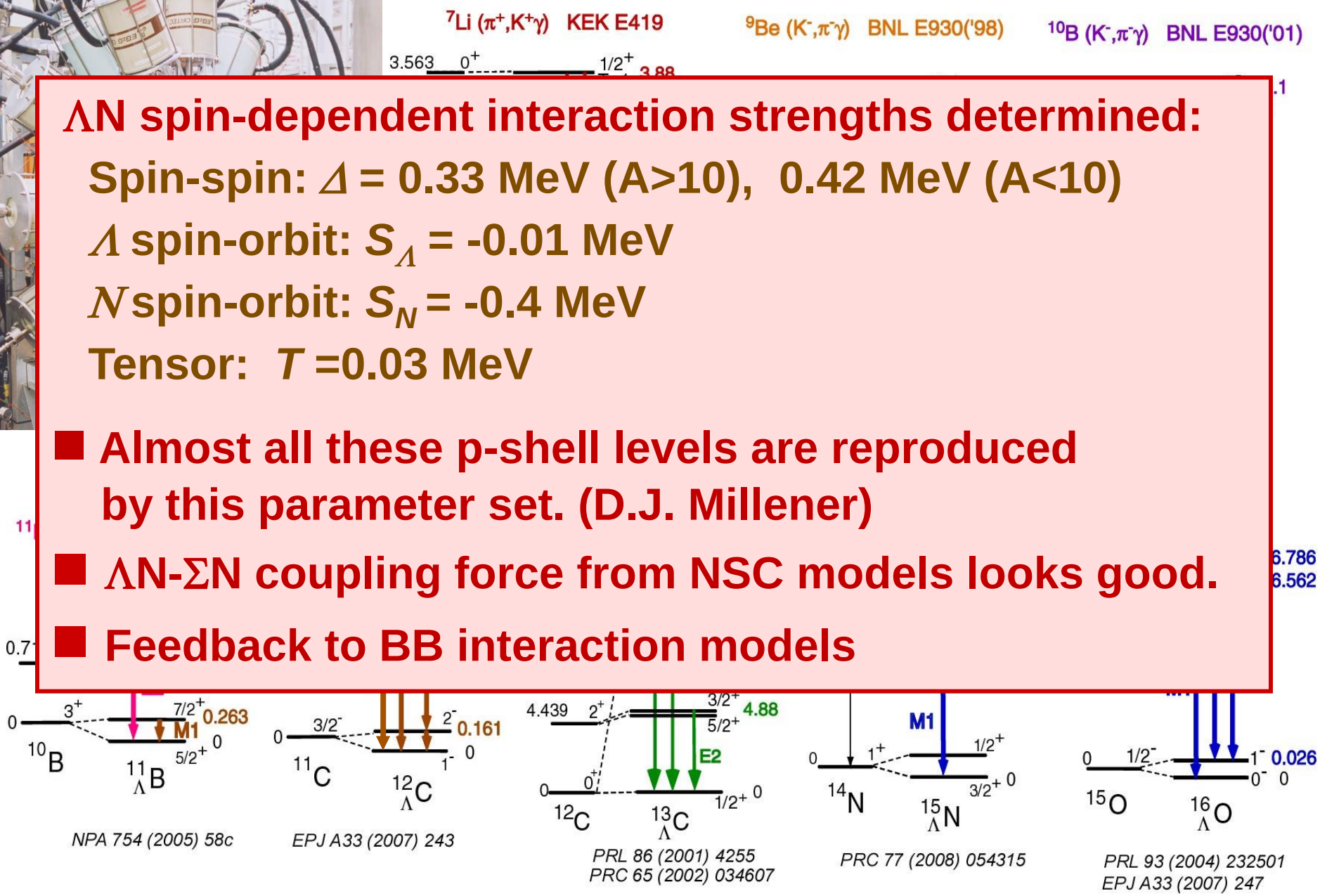


PRL 93 (2004) 232501
EPJ A33 (2007) 247

Hyperball

Hypernuclear γ-ray data





ΛN spin-dependent interaction strengths determined:

Spin-spin: Δ = 0.33 MeV (A>10), 0.42 MeV (A<10)

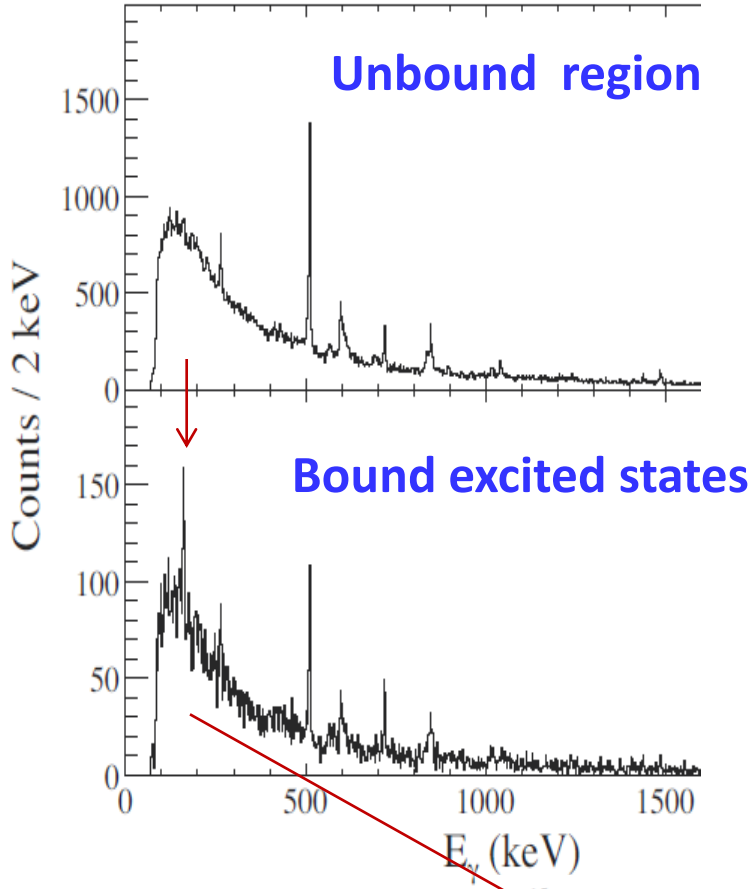
Λ spin-orbit: S_Λ = -0.01 MeV

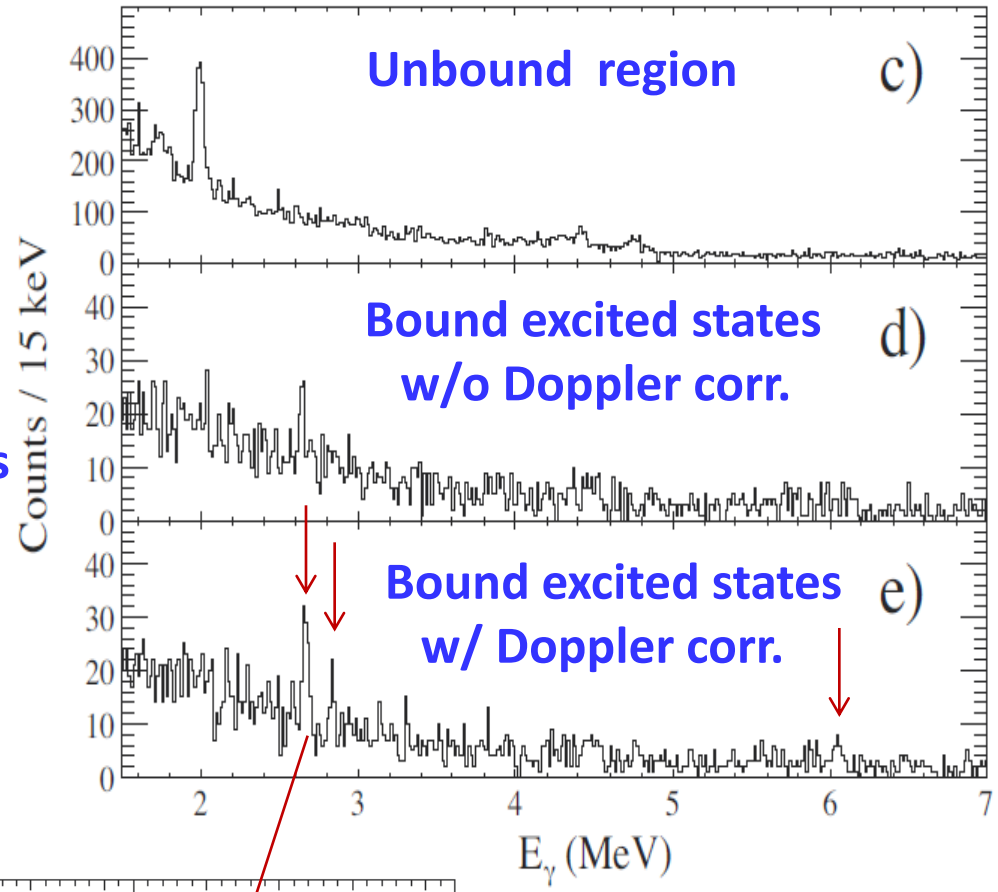
N spin-orbit: S_N = -0.4 MeV

Tensor: T =0.03 MeV

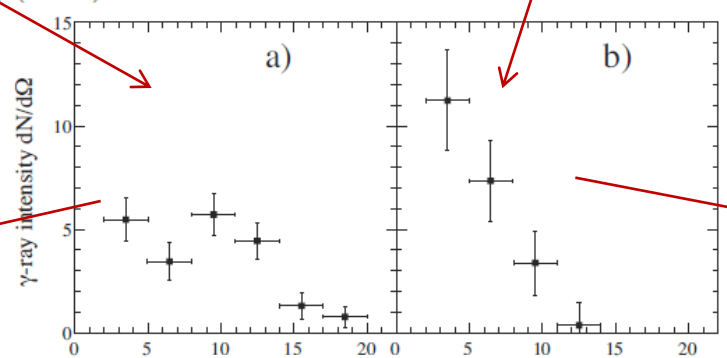
- **Almost all these p-shell levels are reproduced by this parameter set. (D.J. Millener)**
- **ΛN-ΣN coupling force from NSC models looks good.**
- **Feedback to BB interaction models**

An example of $^{12}C\ (\pi^+,K^+\gamma)^{12}{}_{\Lambda}C$ at KEK





Hosomi et al.
To be published

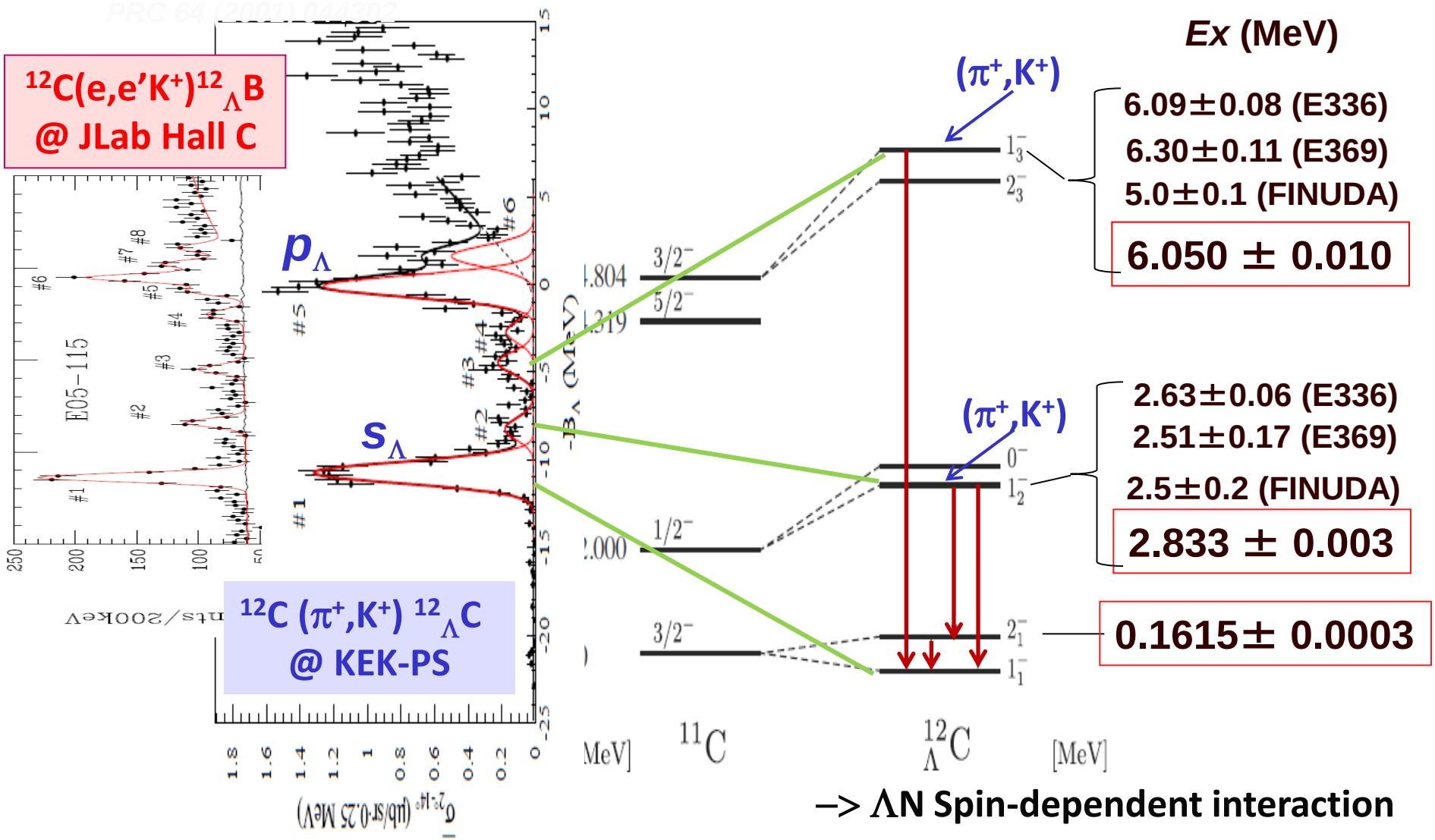


Spin-flip production

$\Delta L = 1$ non-spin-flip production

(π,K) Reaction angle

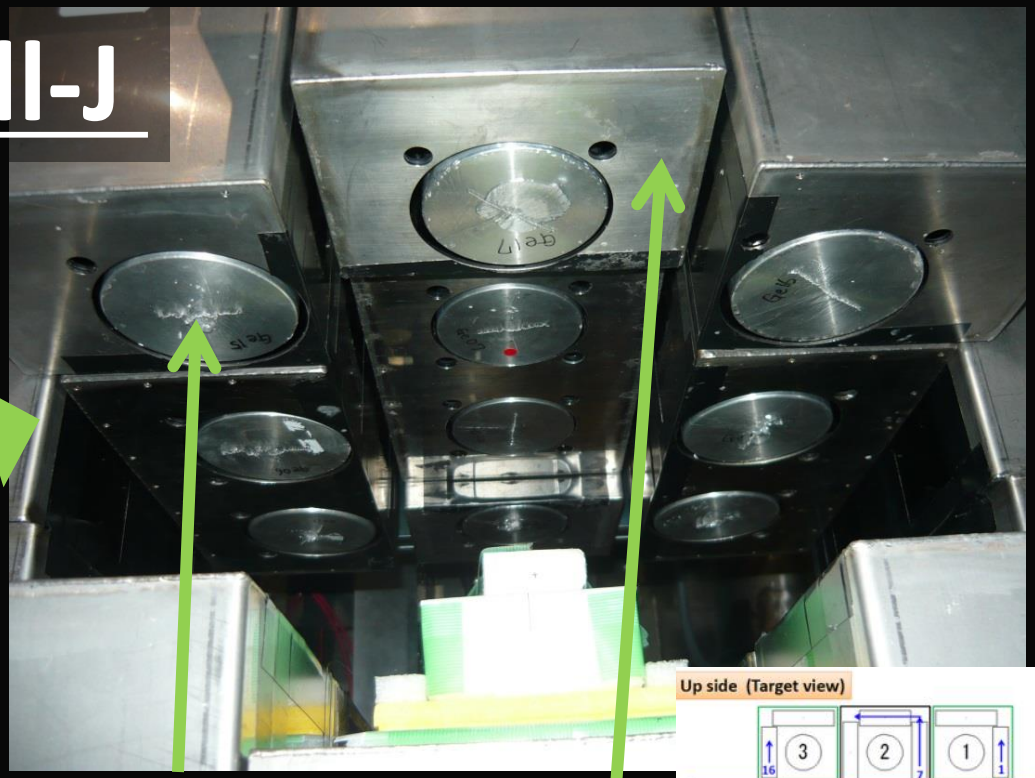
Level scheme of $^{12}_{\Lambda}C$ (Updated Analysis)



This precise $^{12}_{\Lambda}C$ level scheme is useful for testing new reactions and apparatus

2. E13: Purposes and Present Status

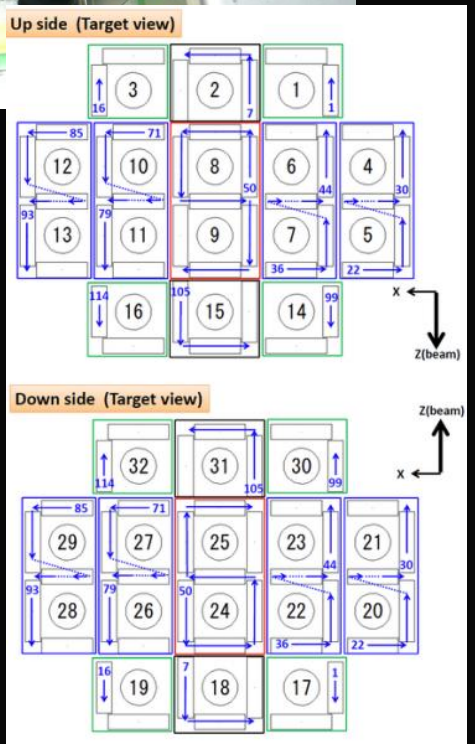
Hyperball-J



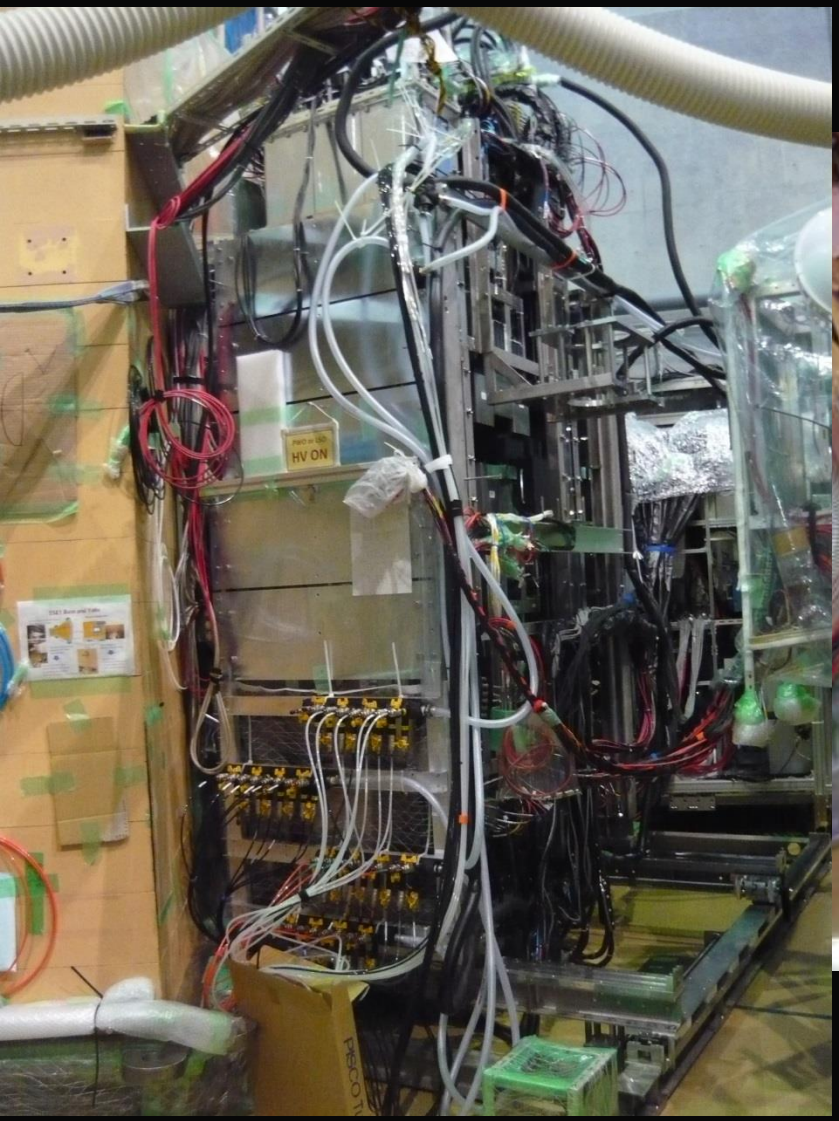
Ge cooled down to ~70K
by pulse-tube refrigerator
(c.f. 92K w/LN2)

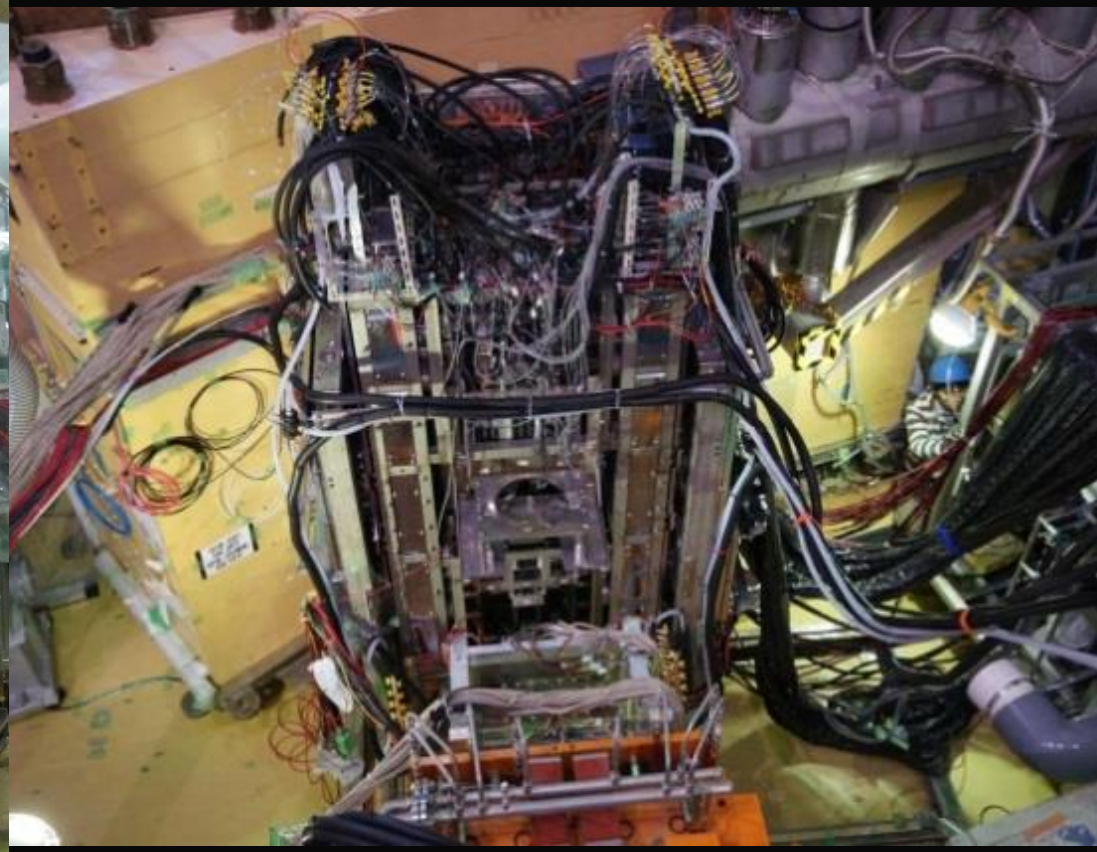
Fast background
suppressor made of PWO

Eff. ~ 6% @1 MeV
with 32 Ge(re=60%)

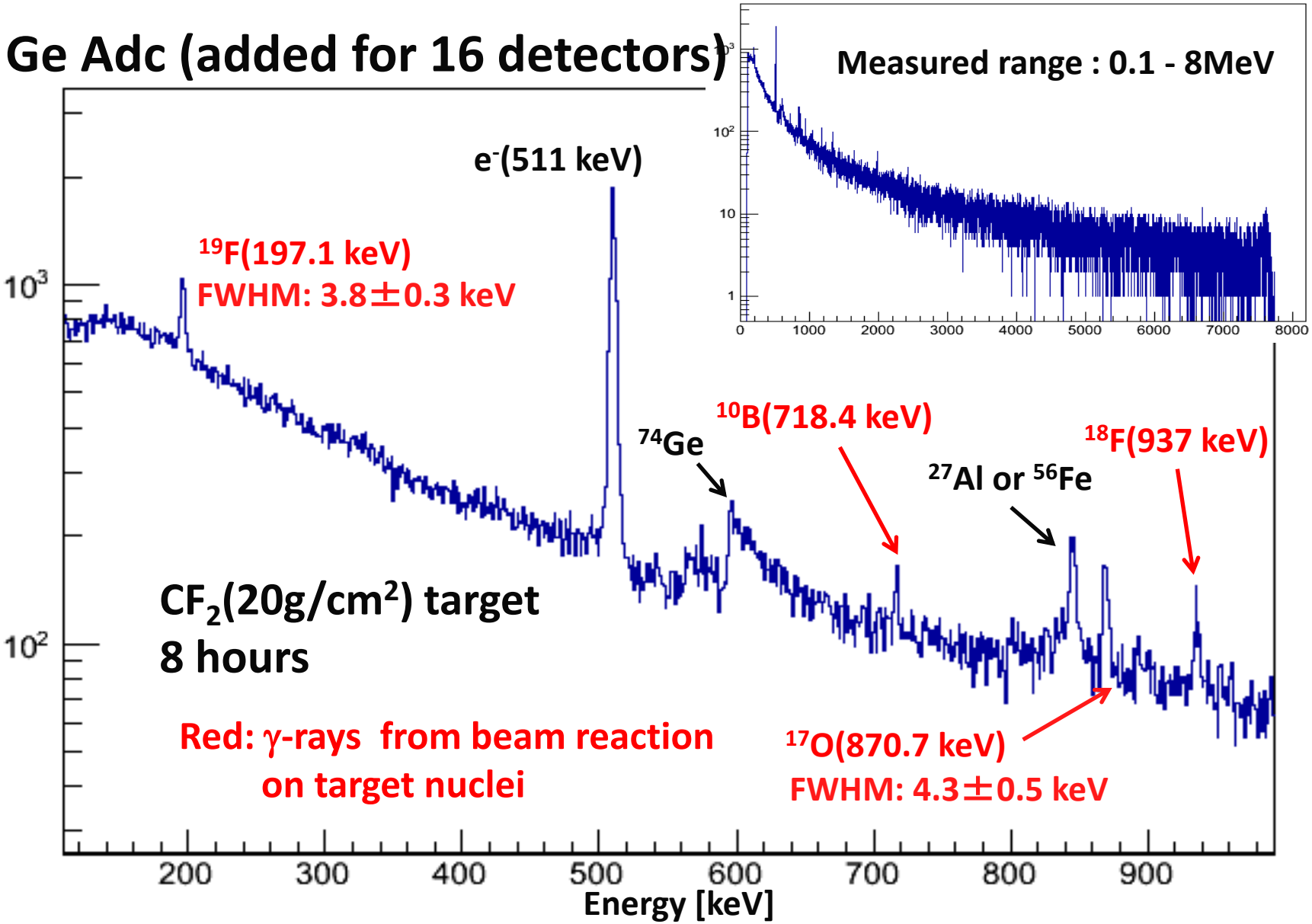


Hyperball-J
installed in front of SKS magnet at K1.8





Hyperball-J performance in beam



Purpose of E13 experiment

Approved as DAY1, Second priority

ΛN interaction

1st Part: 10--40kW, 2013.6 -> 2015.2~

(1) Charge symmetry breaking in ΛN interaction

$^{4}_{\Lambda}$He : Confirm (or deny) CSB effects suggested by old data

1.5,1.8 GeV/c (K^-,π^-) @K1.8

(2) Radial dependence of ΛN interaction

$^{19}_{\Lambda}$F : The first sd-shell hypernuclei

1.8 GeV/c (K^-,π^-) @K1.8

2nd Part: >50kW, after 2016?

(3) Study ΛN–ΣN coupling force

$^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B: Inconsistency in p-shell data.

1.1 GeV/c (K^-,π^-) @K1.1

g-factor of Λ in nucleus

(4) Spin-flip B(M1) measurement for g_Λ in a nucleus

$^{7}_{\Lambda}$Li : g_Λ measurement in ~3% accuracy

1.1 GeV/c (K^-,π^-) @K1.1

Experimental approaches to Charge Symmetry Breaking puzzle in A=4

Origin: ΛN-ΣN coupling?
But theoretically difficult

Experimental confirmation of CSB

J-PARC E13 (+ more)

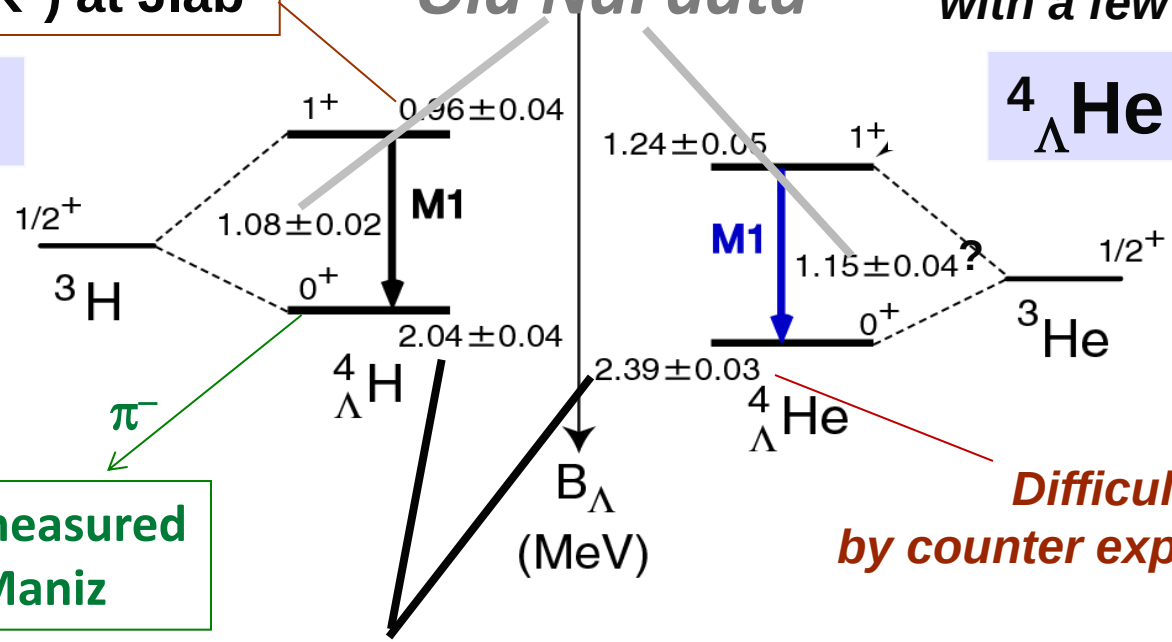
- ^{4}He(K^-,$\pi^-\gamma$) $^{4}_{\Lambda}$He(1^+->0^+)
- ^{4}He (K^-,$\pi^0\gamma$) $^{4}_{\Lambda}$H(1^+->0^+)

with a few keV accuracy

Will be measured via (e,eK$^+$) at Jlab

Will be measurd by Ge at J-PARC

Old NaI data

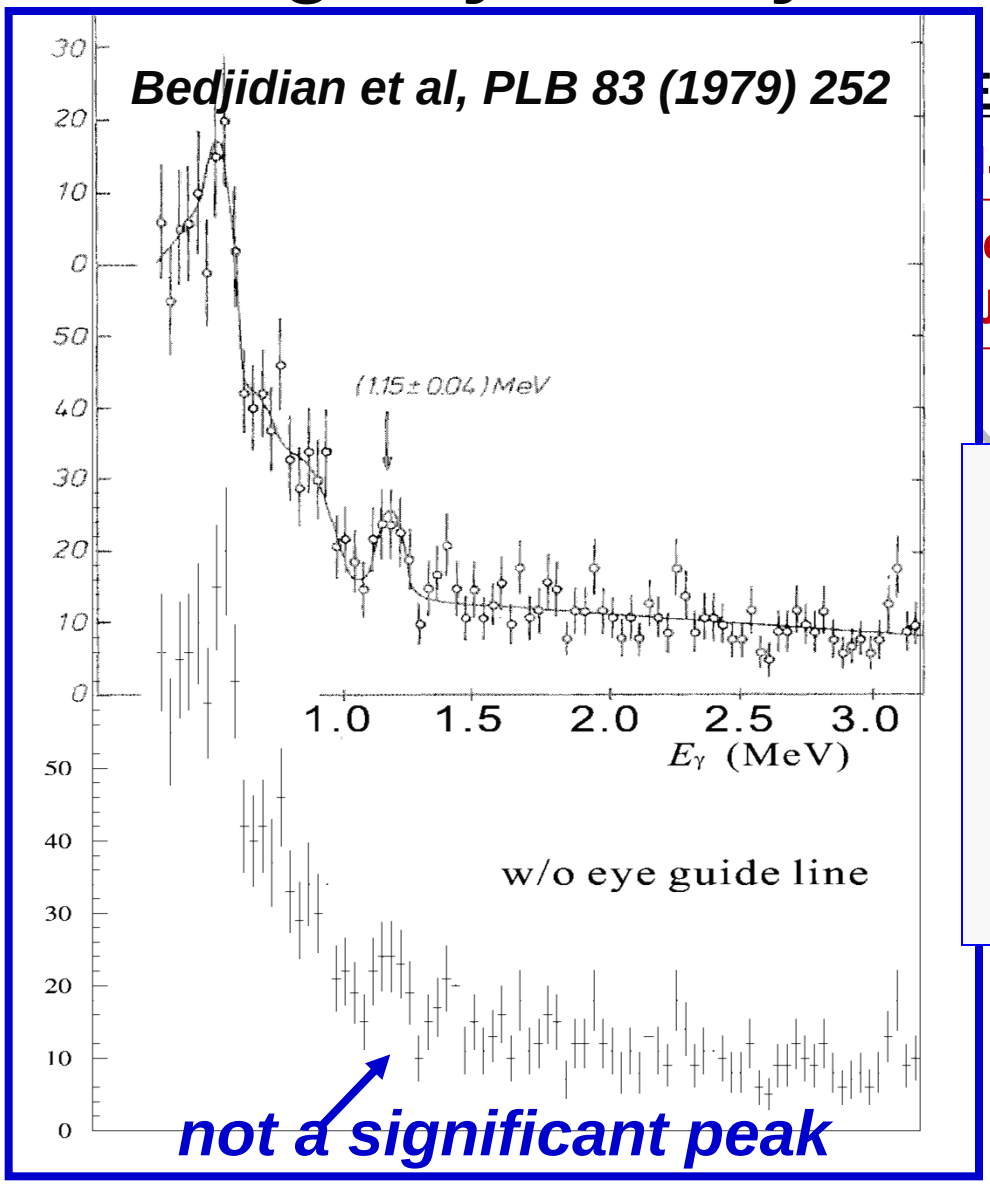


Being measured at Maniz

Difficult by counter experiments

Old emulsion data

Experimental approaches to Charge Symmetry Breaking puzzle in A=4



Experimental confirmation of CSB

J-PARC E13 (+ more)

Measurd J-PARC data

- ^{4}He(K^-,$\pi^-\gamma$) $^4_\Lambda$He(1^+->0^+)
- ^{4}He (K^-,$\pi^0\gamma$) $^4_\Lambda$H(1^+->0^+)

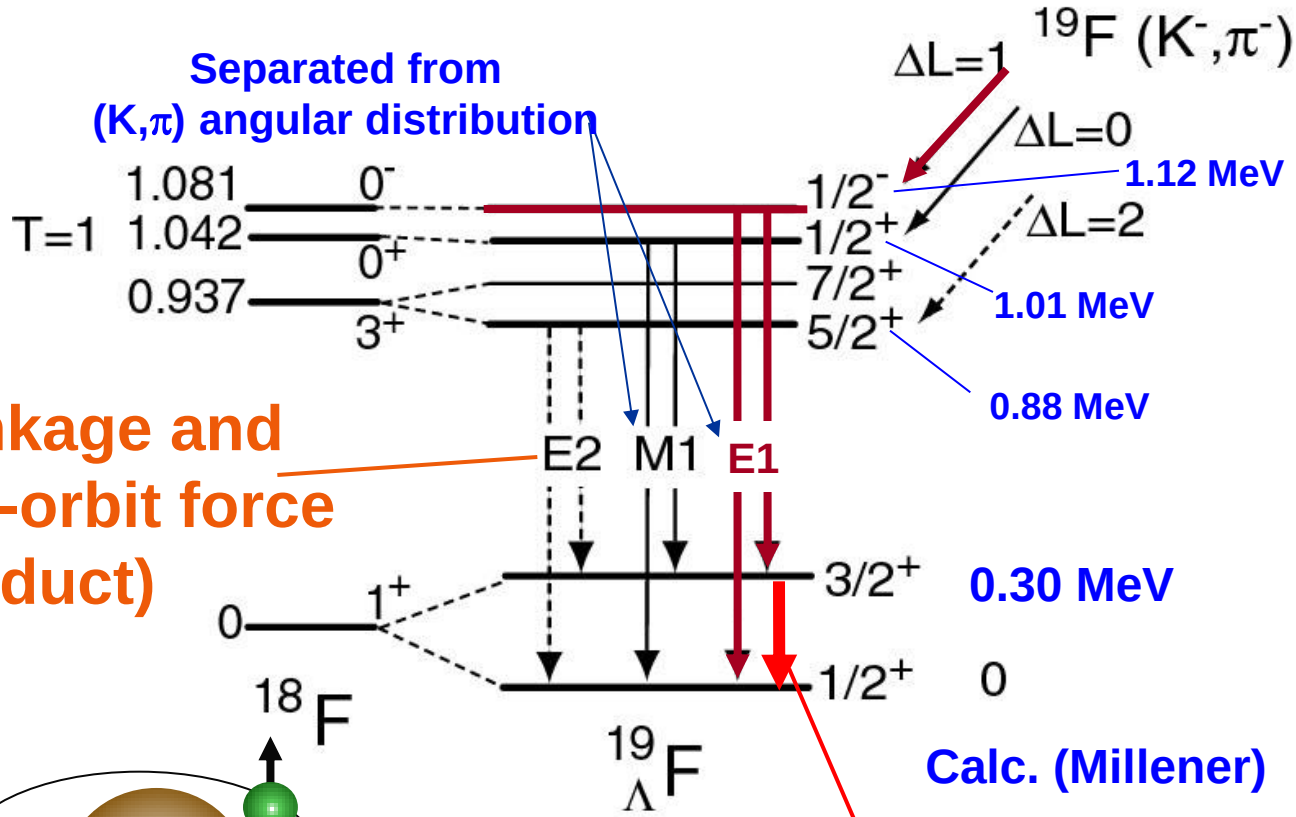
with a few keV accuracy

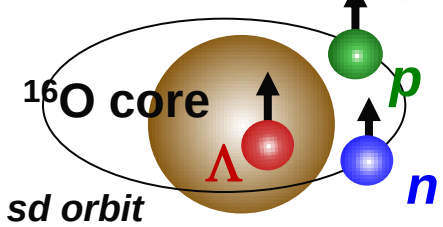
- $E\gamma[^4_\Lambda He] \neq E\gamma\,[^4_\Lambda H]$:
  Clear evidence of CSB.
  Spin dependence of CSB int.
- $E\gamma[^4_\Lambda He] = E\gamma\,[^4_\Lambda H]$:
  Strongly suggests CSB does not exist

by counter experiments

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

The first study of sd-shell hypernuclei





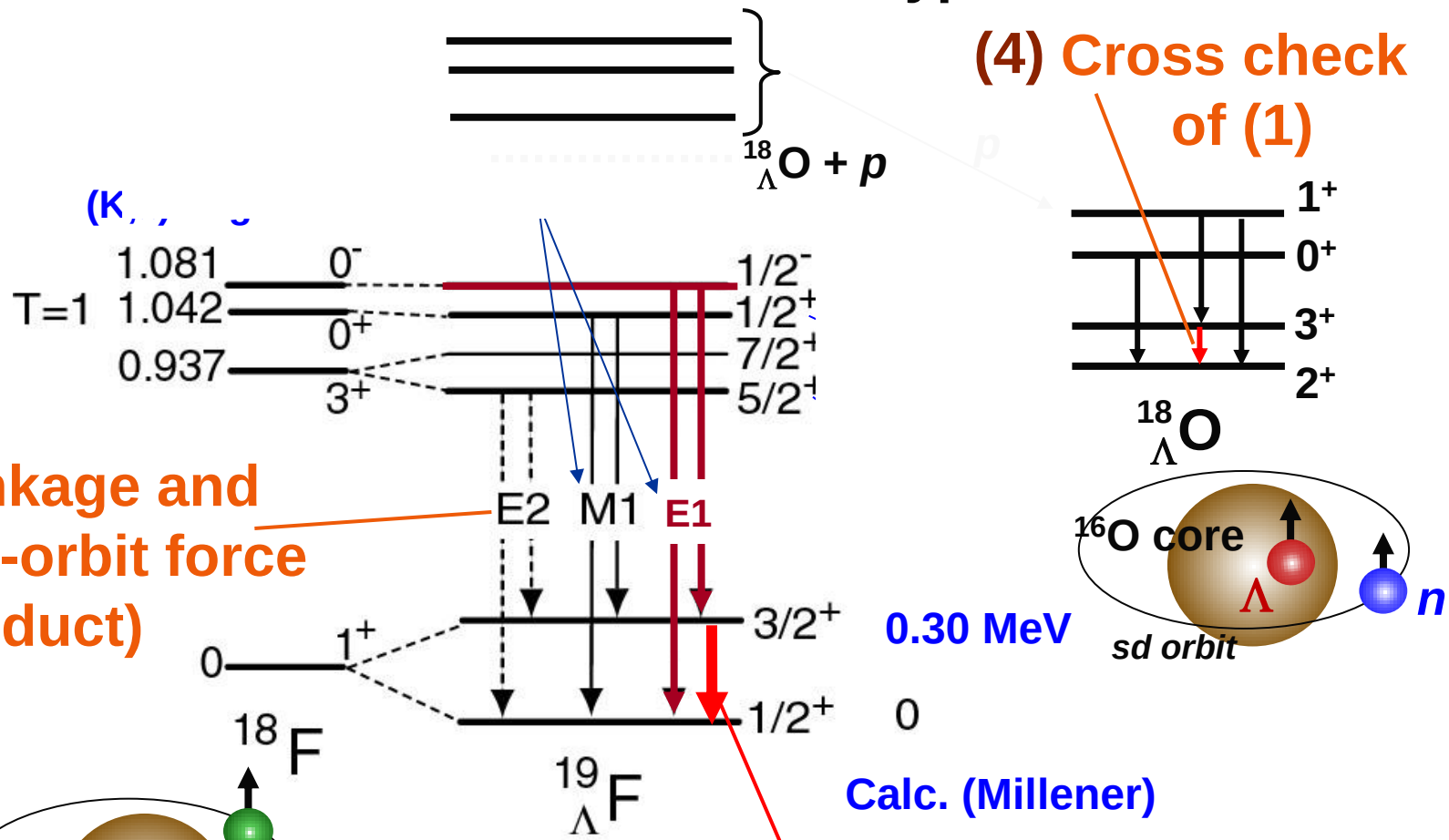
(3) shrinkage and N-spin-orbit force (byproduct)

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

(2) spin-flip B(M1) -> g_Λ (byproduct)

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

The first study of sd-shell hypernuclei

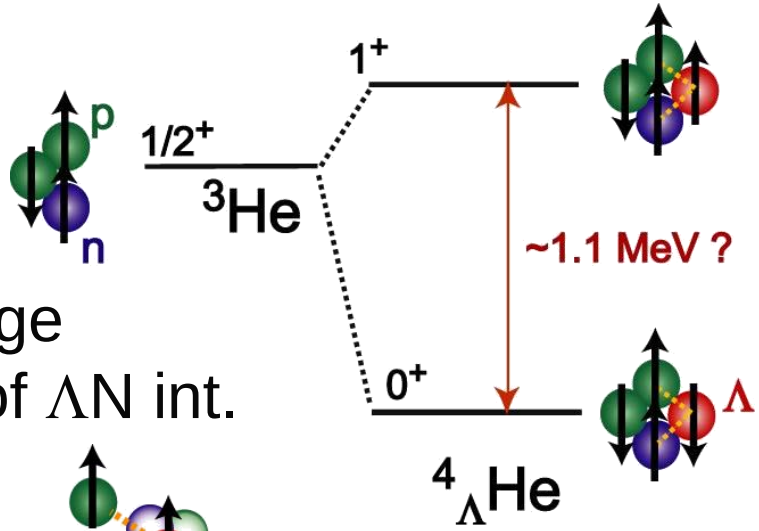


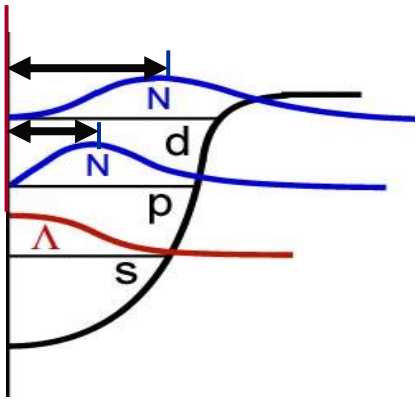
(1) ΛN spin-spin interaction in *sd* shell

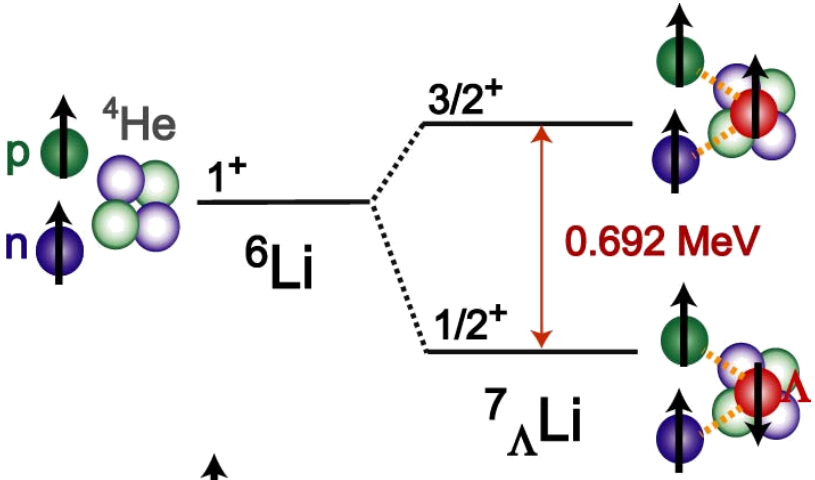
(2) spin-flip B(M1) -> g_{Λ} (byproduct)

A-dependence of ΛN spin-spin int. strength

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

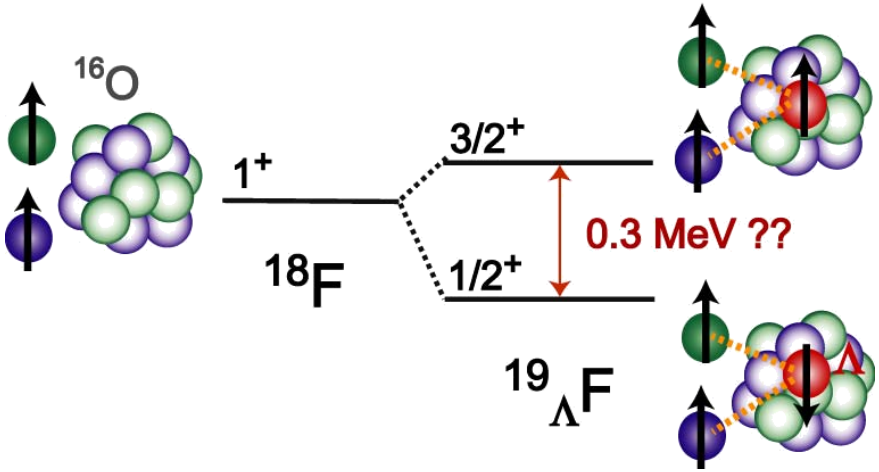






$s_\Lambda s_N$

$s_\Lambda p_N$



$s_\Lambda d_N$

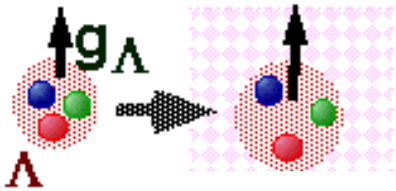
$\bar{r}\,(s_\Lambda\text{-}d_N) > \bar{r}\,(s_\Lambda\text{-}p_N) > \bar{r}\,(s_\Lambda\text{-}s_N)$

Magnetic moment of a Λ in a nucleus

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

m_q : Constituent quark mass

m_q decrease -> μ_q increase ?



Baryon magnetic moment in nucleus:

affected by partial restoration of chiral symmetry?

-> Origin of baryon spin and mass

Λ, free from Pauli effect, is a good probe.

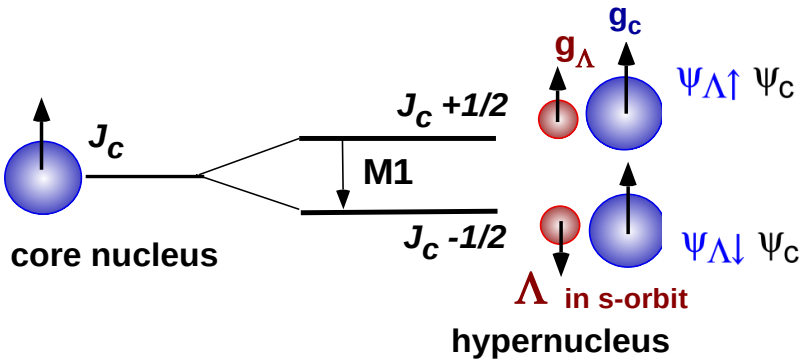
- **Direct measurement is difficult (τ ~ 0.1-- 0.2 ns)**

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

$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

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

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



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

~100% **Doppler Shift Attenuation Method**

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

Preliminary data on g_Λ

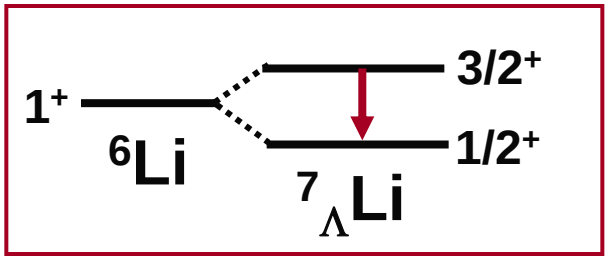
- **BNL E930** (M. Ukai)

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

τ from DSAM

$^{10}B\ (K^-, \pi^-)\ ^{10}{}_\Lambda B^*$

$\rightarrow\ ^{7}{}_\Lambda Li^* + {}^3He$



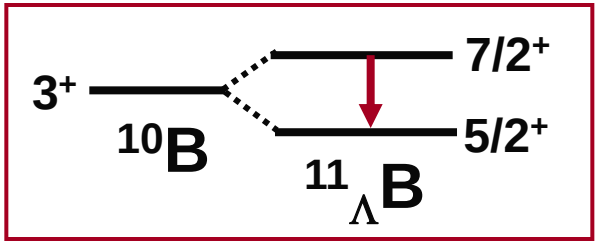
- **KEK E566** (Y. Ma)

$g_\Lambda > -1.76\ \mu_N$

τ from DSAM

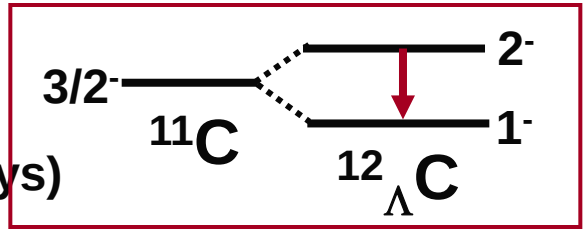
$^{12}C\ (K^-, \pi^-)\ ^{12}{}_\Lambda C^*$

$\rightarrow\ ^{11}{}_\Lambda B^* + p$



$g_\Lambda = -1.04 \pm 0.41\ \mu_N$

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



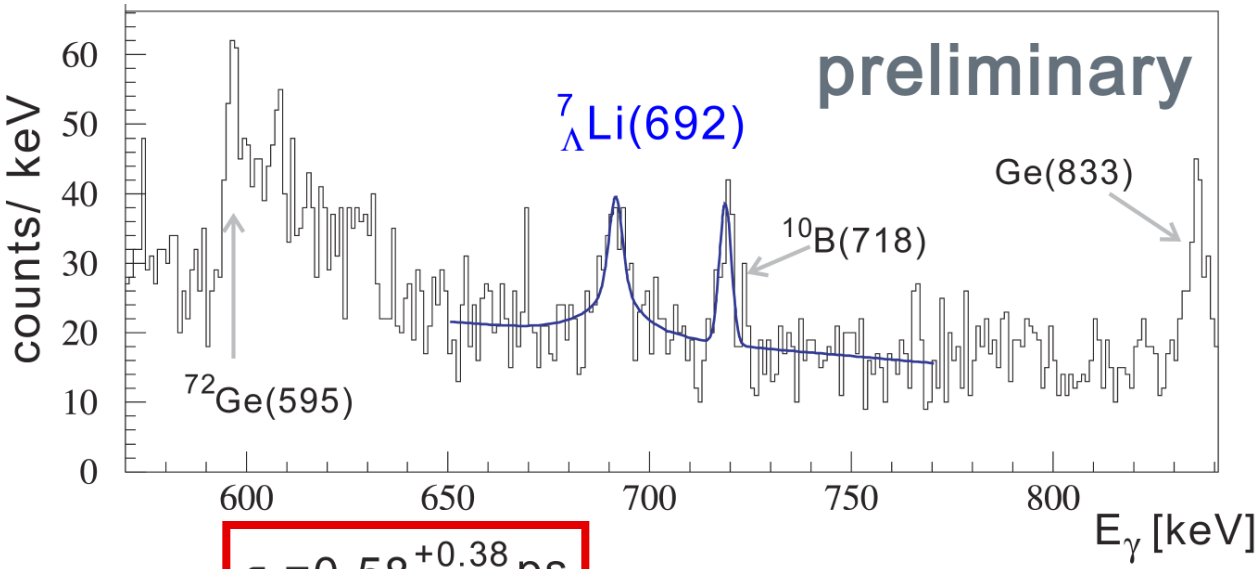
- Yield ratio for [$2^- \rightarrow 1^-$] / [$1^-_2 \rightarrow 2^-$] γ-rays
  -> Br($2^- \rightarrow 1^-$) = 0.19±0.12 (80% of 2^- weakly decays)
- Weak decay rate of 2^- and 1^- are <u>assumed</u> to be the same, Γ_{weak} = (lifetime 230.7±6.3 ps)$^{-1}$

=> $\Gamma_{M1} = Br/(1 - Br)\ \Gamma_{weak}$

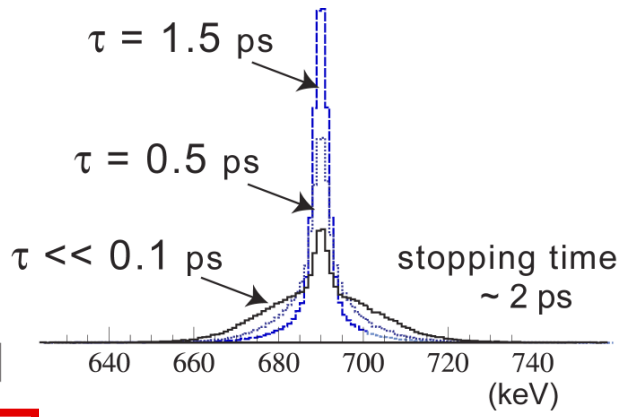
⇔ $g_\Lambda(free) = -1.226\ \mu_N$

Preliminary data on B(M1) in $^{7}_{\Lambda}$Li (BNL E930)

^{10}B (K^-, π^-) $^{10}_{\Lambda}$B*, $^{10}_{\Lambda}$B*(3^+) -> $^{7}_{\Lambda}$Li*($3/2^+$) + ^{3}He indirect population



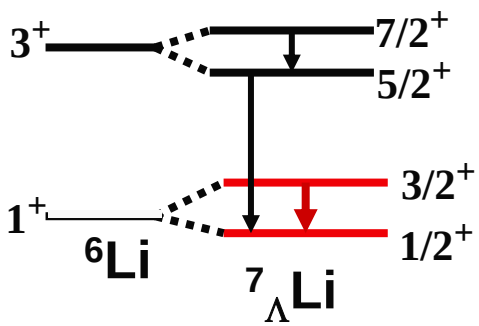
simulation



$\tau = 0.58^{+0.38}_{-0.20}$ ps

BR(M1)=100%

$B(M1) = 0.30^{+0.12}_{-0.16}$ [μ_N^2]



$- g_\Lambda = 1.1^{+0.4}_{-0.6}$ μ_N

preliminary
(statistical error only)

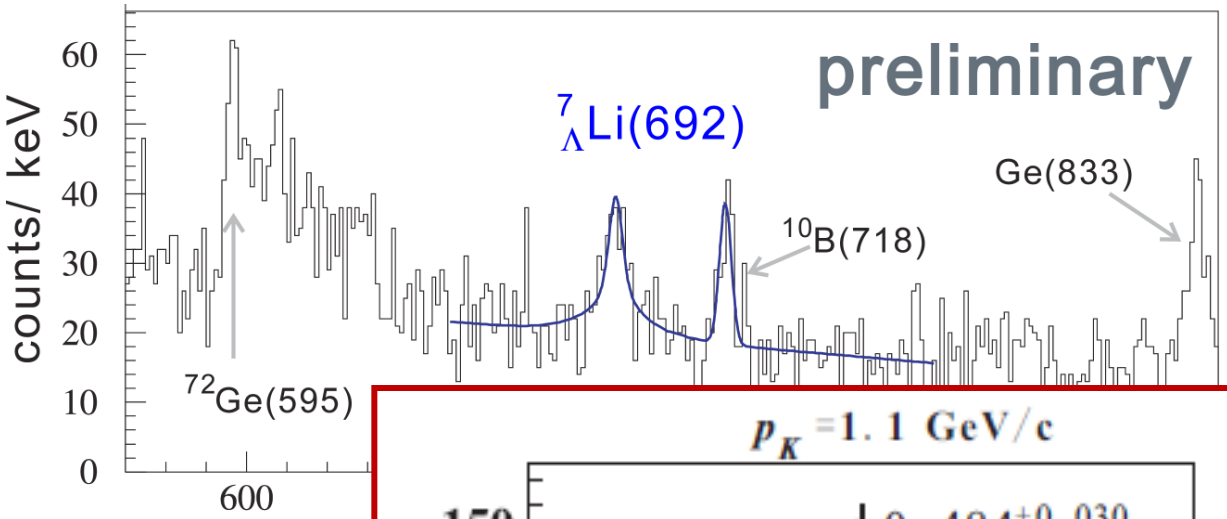
⬌ $- g_\Lambda$(free) = 1.226 μ_N

First data of g_Λ in nucleus

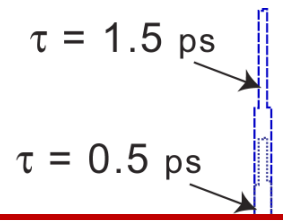
-> Precise(~5%) B(M1) measurement of $^{7}_{\Lambda}$Li at J-PARC E13

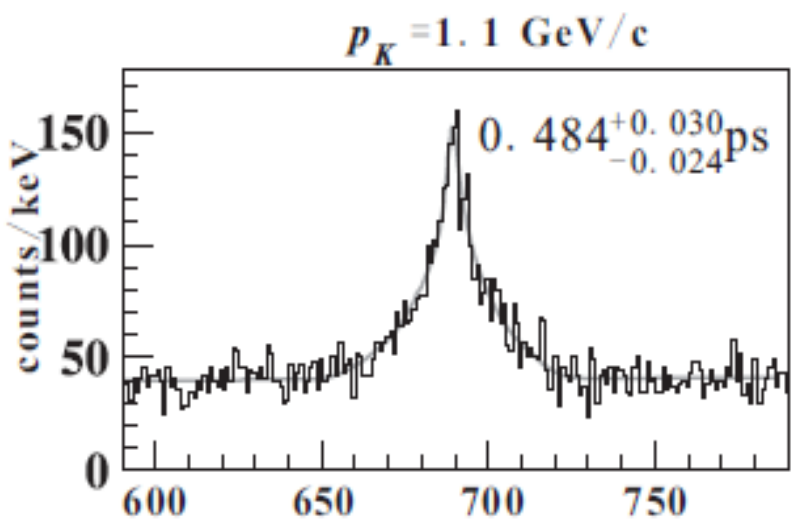
Preliminary data on B(M1) in $^{7}_{\Lambda}$Li (BNL E930)

^{10}B (K^-, π^-) $^{10}_{\Lambda}$B*, $^{10}_{\Lambda}$B*(3^+) -> $^{7}_{\Lambda}$Li*($3/2^+$) + ^{3}He indirect population



simulation



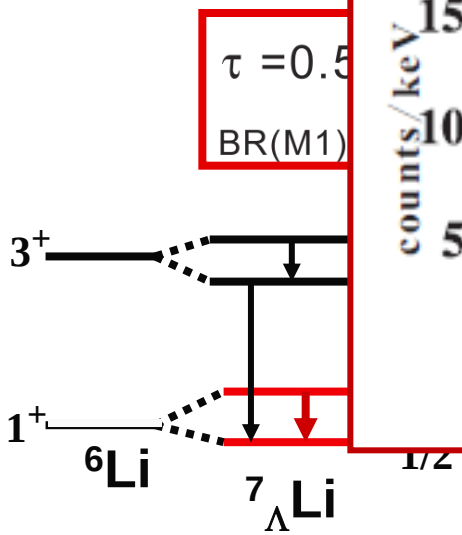


E13 (2nd): Simulation

Nucl.Phys. A881 (2012) 310

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

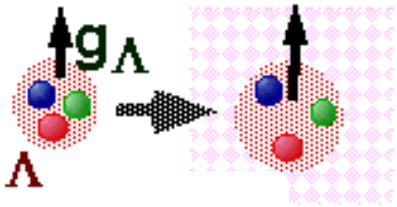
=> $\frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|}$ ~ 3%



-> Precise(~5%) B(M1) measurement of $^{7}_{\Lambda}$Li at J-PARC E13

3. Beyond E13

Future Plans



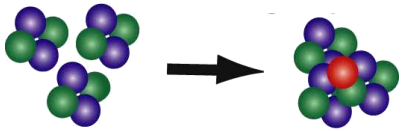
- Systematic study of g_Λ ($^{7}_{\Lambda}$Li, $^{12}_{\Lambda}$C, $^{19}_{\Lambda}$F, …)
  - ρ dependence -> chiral symmetry restoration
  - Isospin dependence -> effect of Σ mixing

  Doppler shift attenuation method

  + Weak-gamma coincidence method

- Impurity effects in *p* and *sd* shell hypernuclei

  - Shrinkage/ deformation change ($^{9}_{\Lambda}$Be, $^{13}_{\Lambda}$C, $^{20}_{\Lambda}$Ne,...)
  - Disappearance of neutron halo ($^{7}_{\Lambda}$He)
  - Study structure of normal nuclei using a Λ

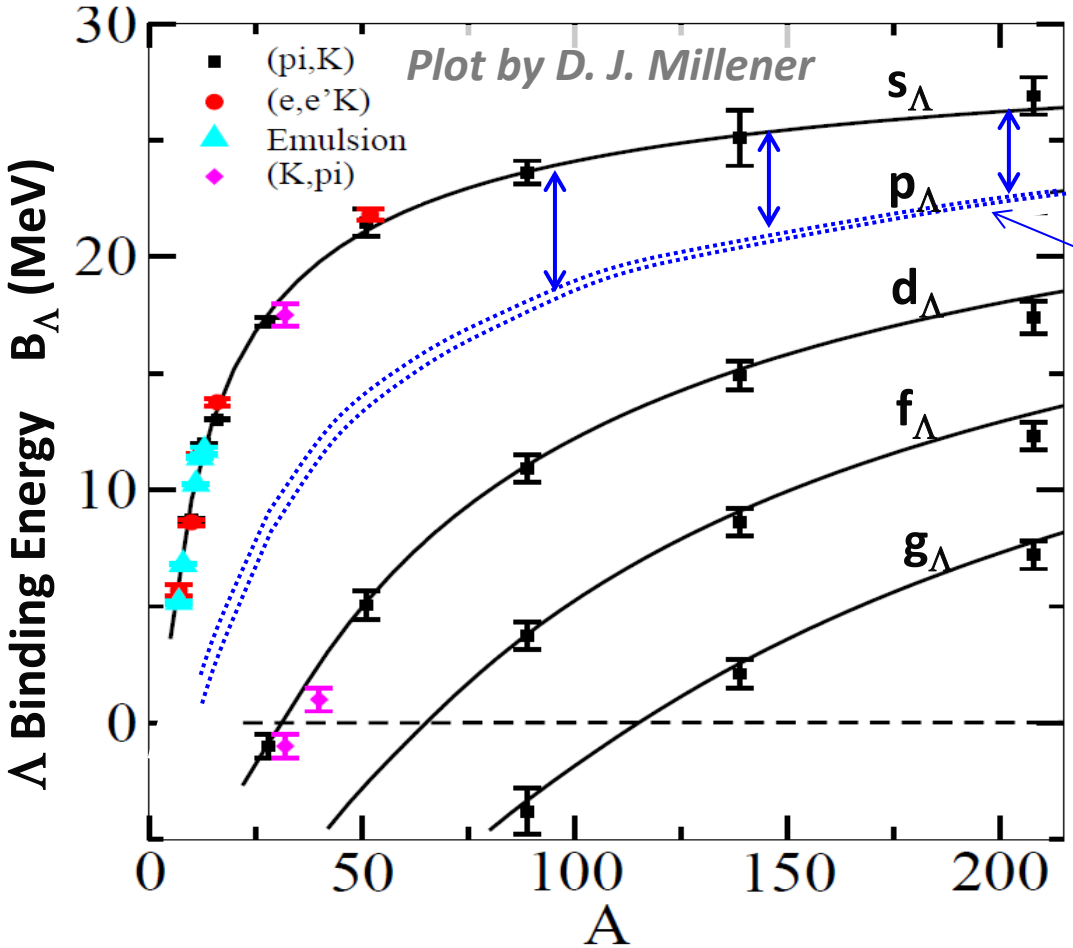


    Triaxial deformation ($^{25}_{\Lambda}$Mg), α-cluster gas (^{12}C(0^+_2)+ Λ)

- Λ's single particle energies for a wide range of A
  - *1ħω* energy
  - LS splitting

    from *E1:* ($p_{1/2}^{\Lambda}$->s^{Λ}, $p_{3/2}^{\Lambda}$->s^{Λ}) for a wide mass range

Λ's single particle energy



E1 γ-ray error ~ 1 keV

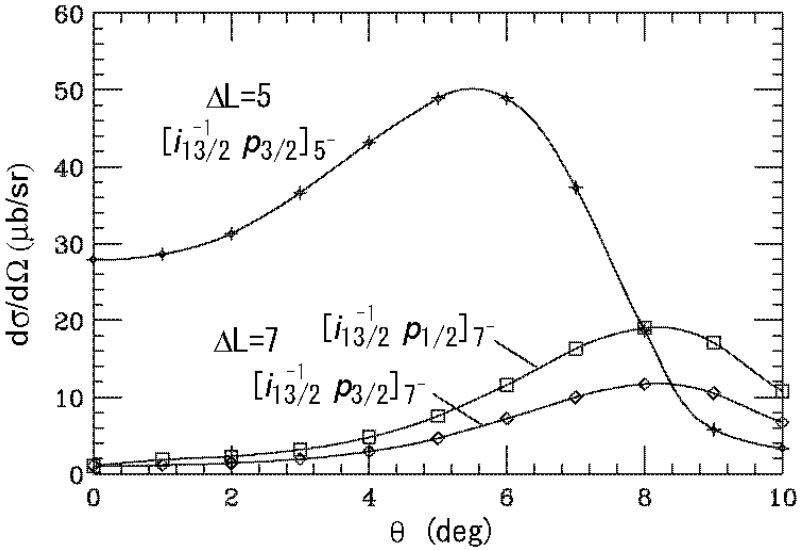
LS splitting

- ***Density dependence of ΛN interaction -> EOS and hyperon puzzle (Y.Yamamoto's talk)***
- ***Origin of LS splitting (2B-LS force, tensor force, many body effects)***

(K^-,π^-), (π^+,K^+) -> ΔE~200 keV @J-PARC Ext-HH

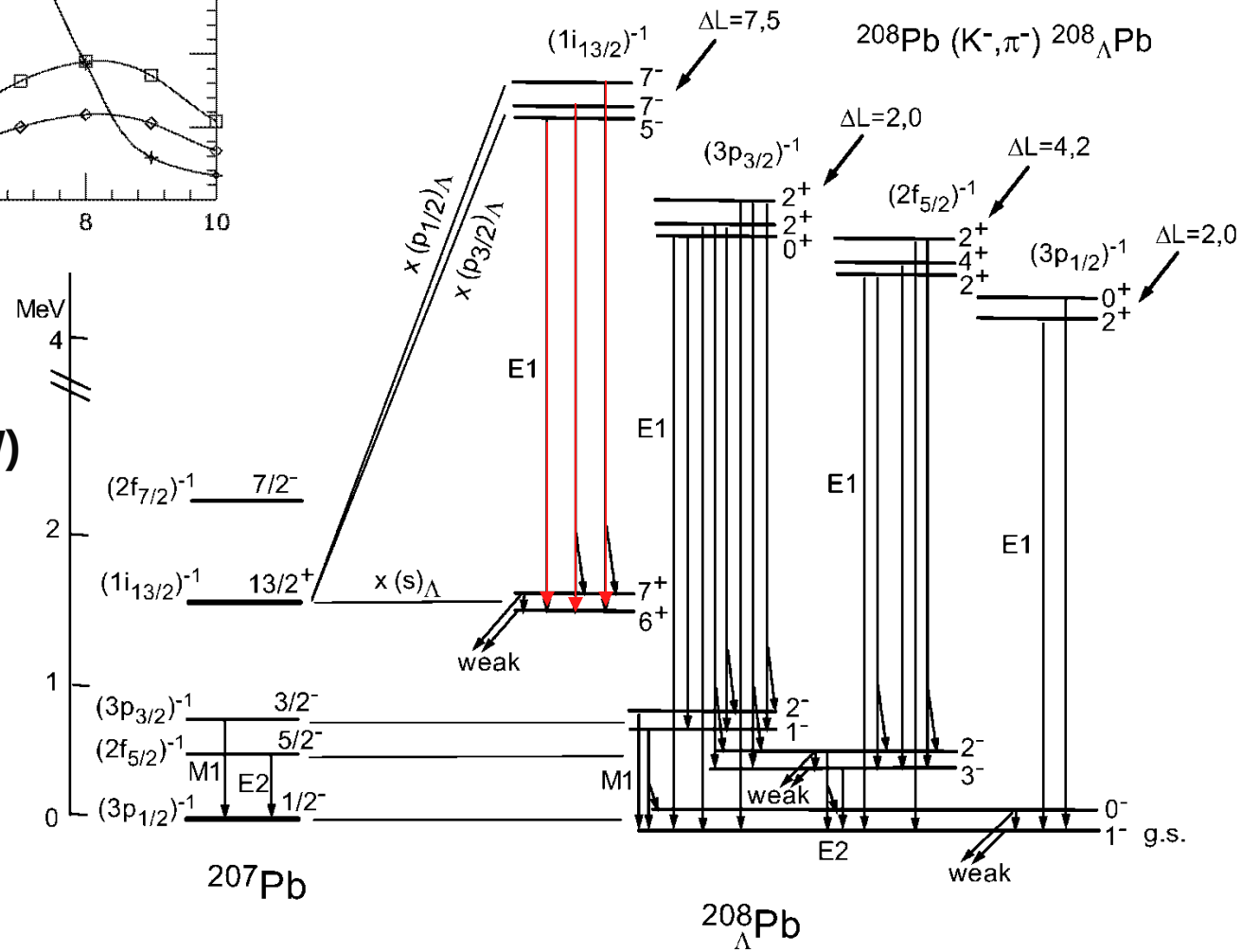
$(e,e'K^+)$ ΔE~500 keV, syst.err. ~100 keV@Jlab Hall-A (HKS+HRS)

E1 measurement for heavy hypernuclei



γ-spectroscopy of $^{208}{}_{\Lambda}$Pb

H.Tamura et al., J-PARC LOI



(K$^-$,π$^-$) at 1.8 GeV/c

10 g target

3x10^{6}K$^-$/4s (~270 kW)

500 h

***p*3/2(5-) ~500 events**

***p*1/2(7-) ~200 events**

***p*3/2(7-) ~130 events**

Higher intensity is necessary!

4. Summary

- **E13-1st will study $^{4}_{\Lambda}$He and $^{19}_{\Lambda}$F for CSB and ΛN interaction in sd-shell hypernucleus.**
- **Hyperball-J is ready and commissioning has been done.**
- **E13-2nd will study g_{Λ} in nucleus from B(M1) measurement.**
- **Beyond E13, we plan E1 (p_{Λ}->s_{Λ}) measurement for heavy hypernuclei, as well as systematic study of g_{Λ} and impurity effects.**