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Gamma-ray Spectroscopy of Hypernuclei

Department of Physics, Tohoku University

Advanced Science Research Center, JAEA

H. Tamura

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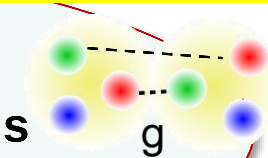
Present Status of

γ-ray spectroscopy

Motivations of hypernuclear studies

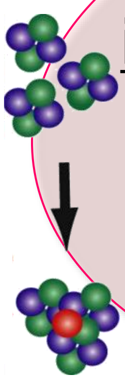
Hypernuclei ➡ Scattering exp. for free YN int.
Hypernuclei for YN int. in nuclear matter

BB interactions



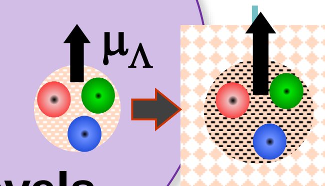
Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures
Test lattice QCD calculations

Impurity effect in nuclear structure



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

Properties and behavior of baryons in nuclei

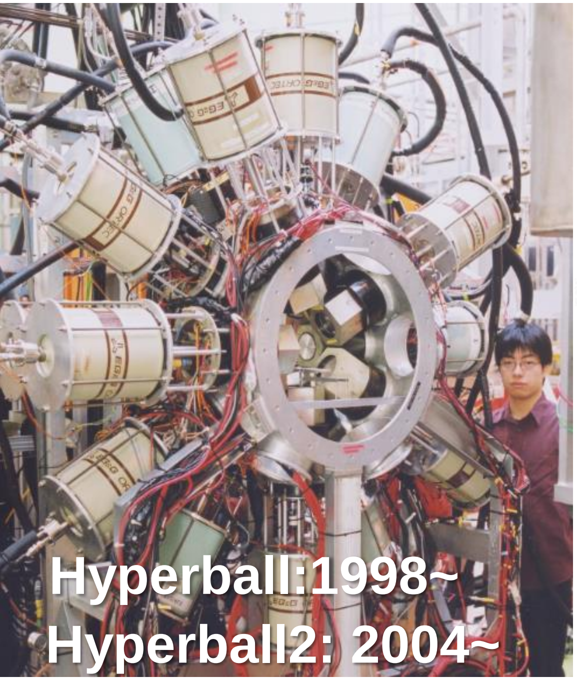


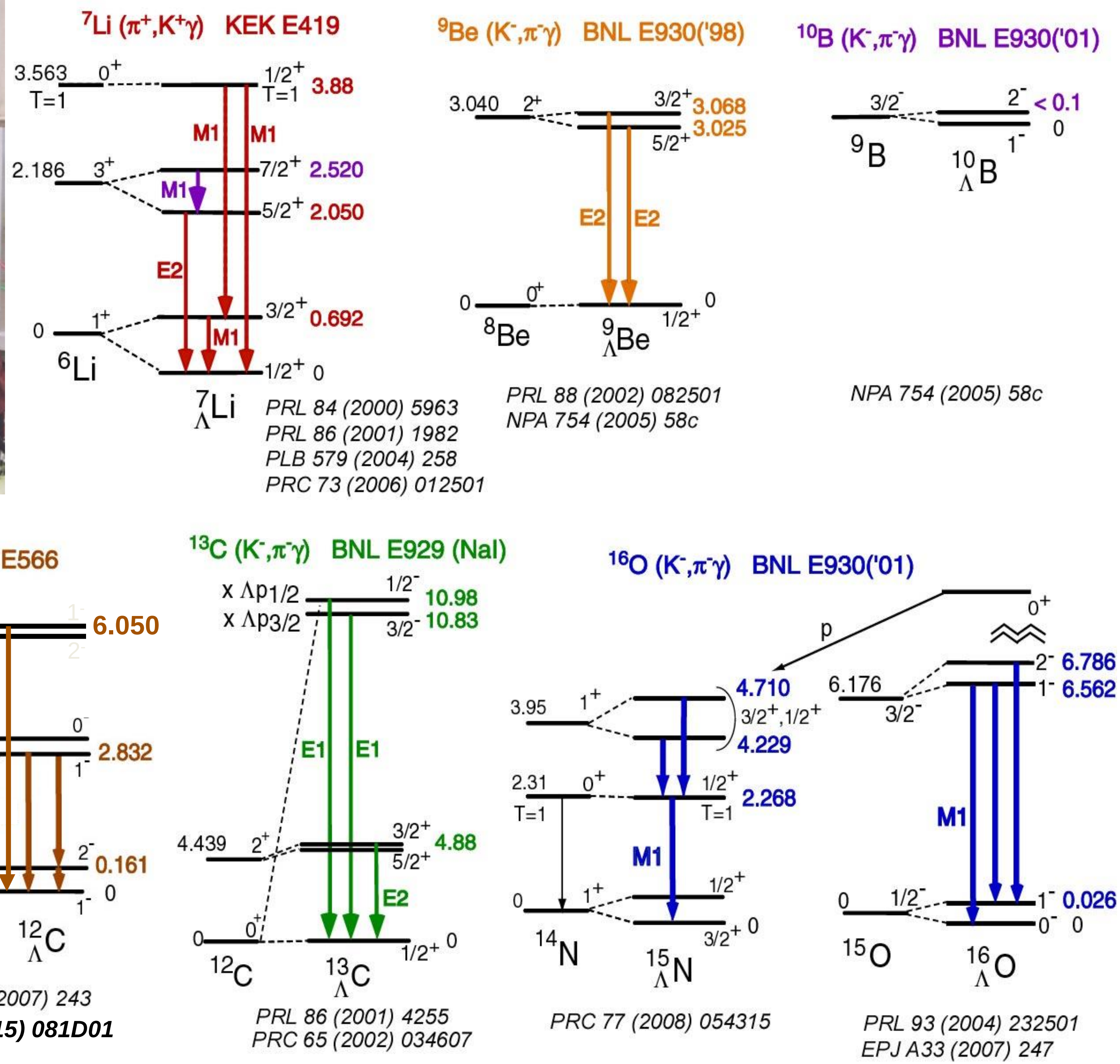
μ_Λ in a nucleus
Λ's single particle levels
Weak decays of Λ in nuclei

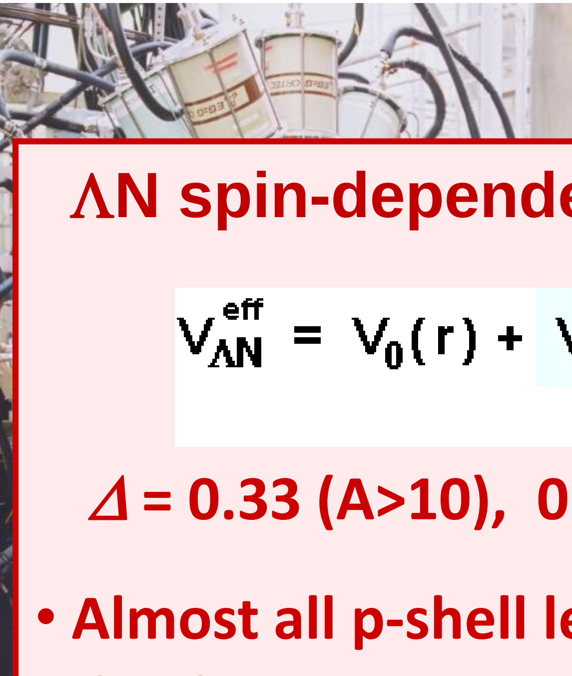
Clues to understand hadrons and nuclei from quarks

Cold and dense nuclear matter with strangeness

Hypernuclear γ-ray data (2015)







Hypernuclear γ-ray data (2015)

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

ΛN spin-dependent interaction strengths determined:

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

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 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 for ΛN.
- Next step

  ΛN-ΣN force and CSB not undefrstood => s-shell hypernuclei

  ΛN force in dense nuclear matter? => sd-shell (heavier) hypernuclei

NPA 754 (2005) 58c

EPJ A33 (2007) 243

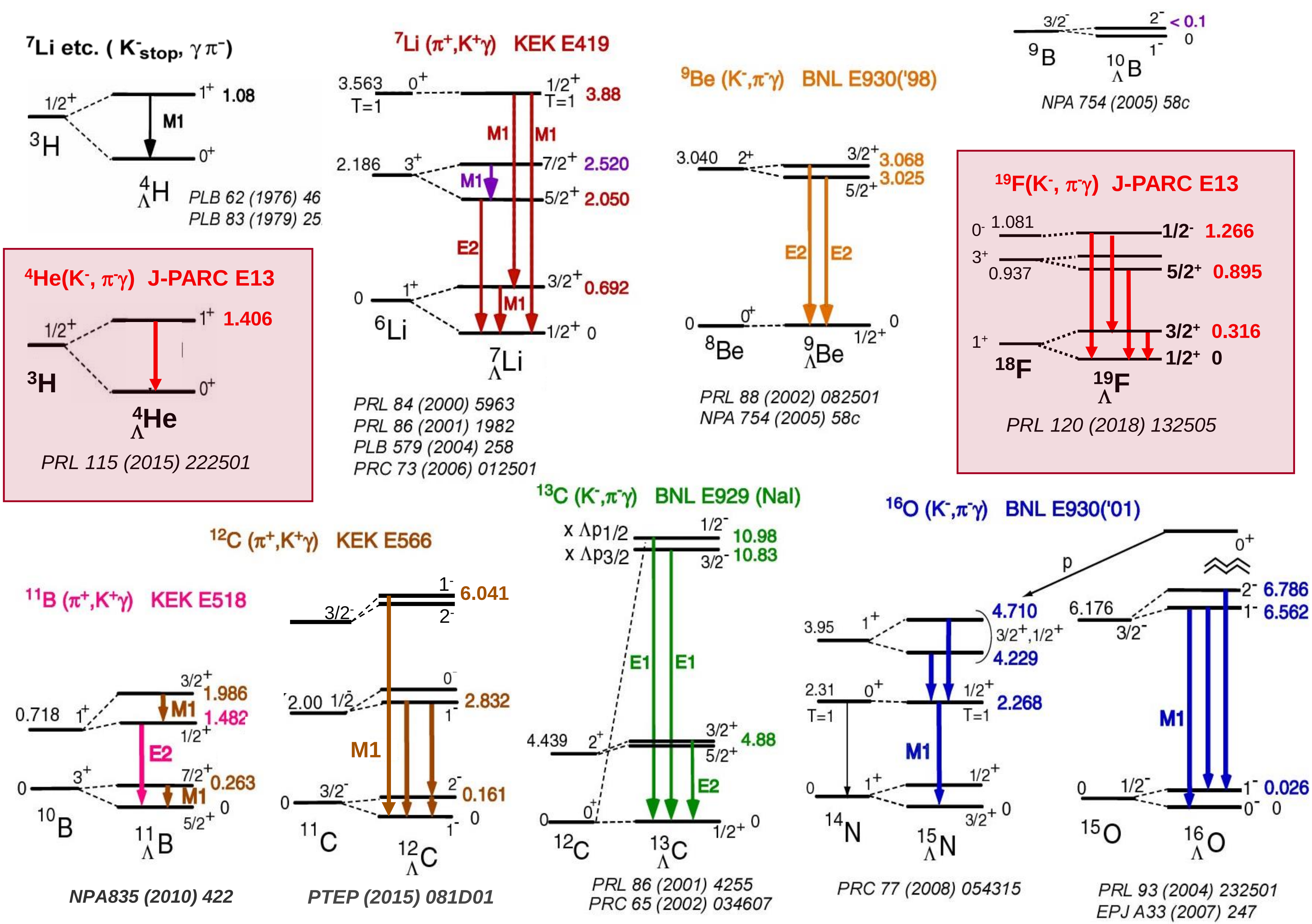
PTEP (2015) 081D01

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

PRC 77 (2008) 054315

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

Hypernuclear γ-ray data (2019)



Plans of γ spectroscopy experiments

- Further study of CSB
  - Re-measure $^{4}_{\Lambda}$H(1^{+}->0^{+})
  - p-shell hypernuclei via (π^{-},K^{0}) reaction
- Search for $^{3}_{\Lambda}$H γ-rays
- B(M1) measurement for g_{Λ} of a Λ in medium
- Medium to heavy hypernuclei
  - E1(p_{Λ}->s_{Λ}) for density dependent ΛN interaction and origin of spin-orbit splitting
  - Impurity effects in deformed hypernuclei

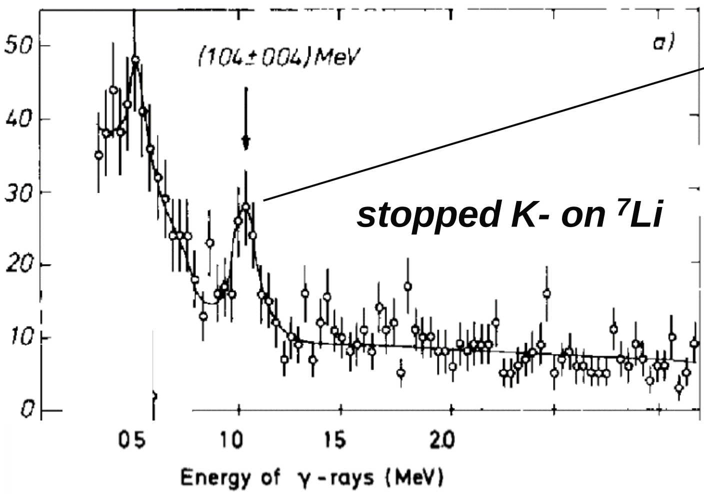
E63 (approved)

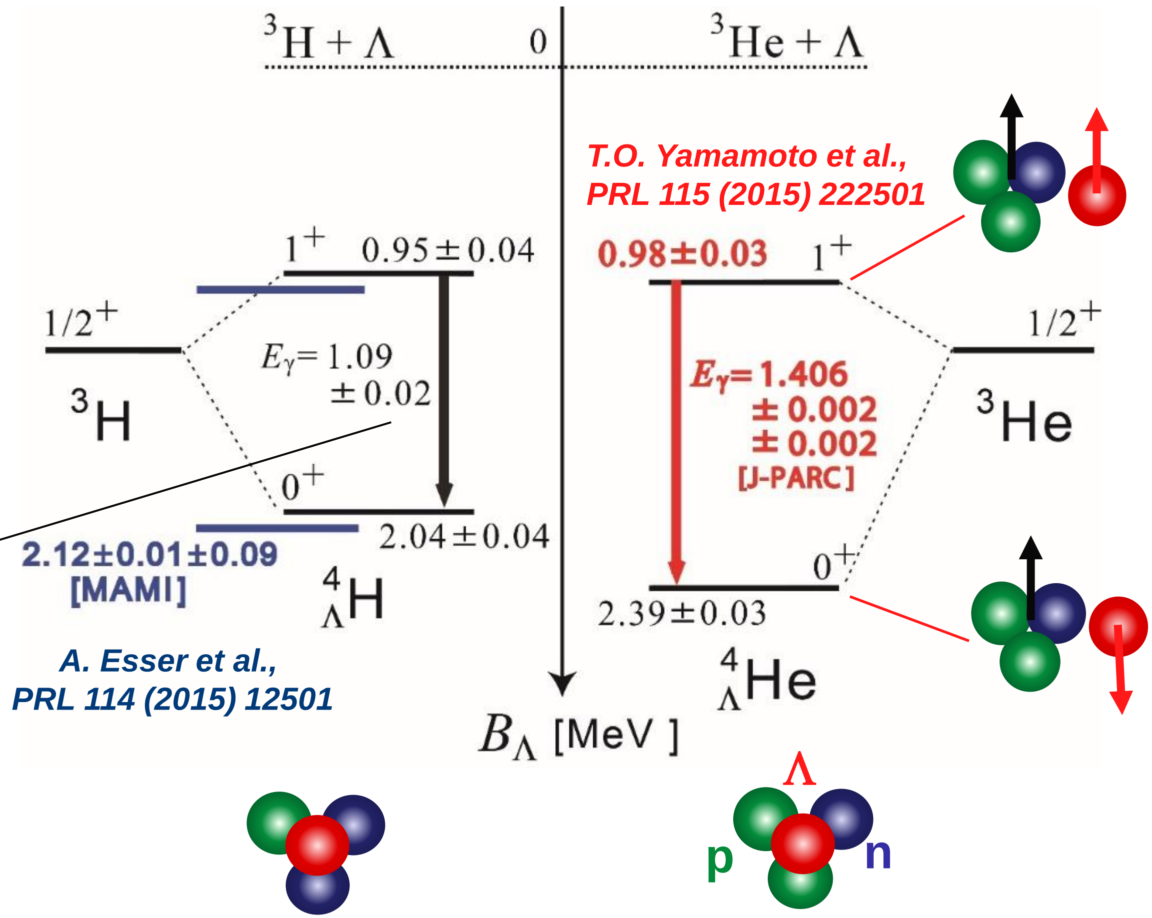
ΛΣ mixing and CSB

Energy levels of A=4 mirror hypernuclei

M. Bedjidian et al.
Phys. Lett. B 83, 252 (1979).

NaI counters (bad resolution)
a large Doppler broadening





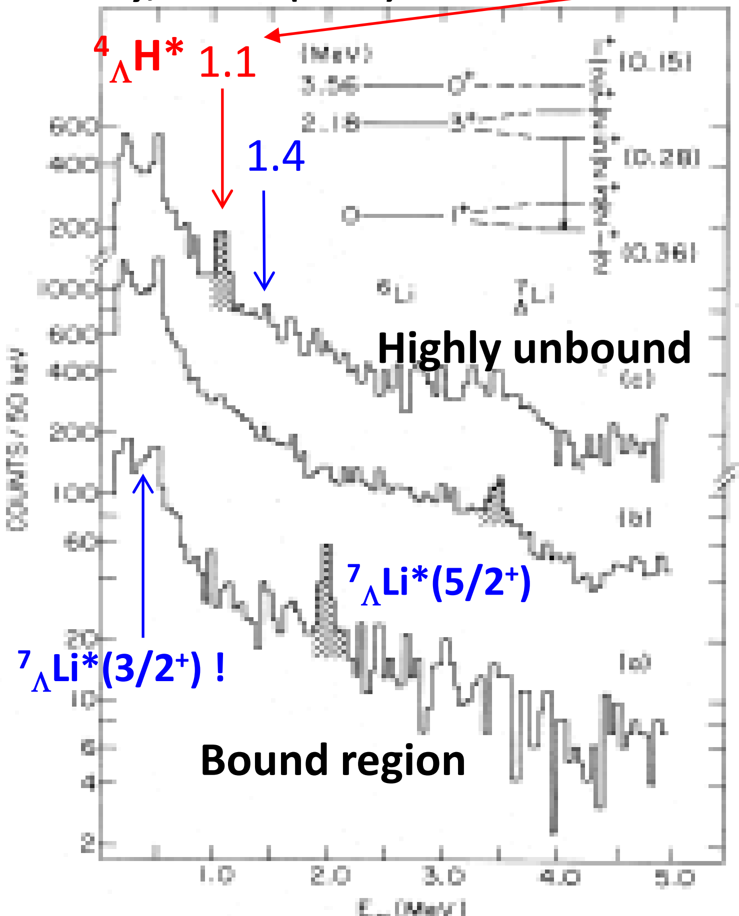
$^4_\Lambda$H γ-ray should be precisely measured (E63).

Production of ${}^{4}_{\Lambda}H^*$ and ${}^{3}_{\Lambda}H^*$ via in-flight ${}^{7}Li\ (K^-,\pi^-)$

M. Ukai

Gating highly unbound region of the missing mass
-> a peak at **1.108 ± 0.010 MeV** with systematic error
It should be ${}^{4}_{\Lambda}H$ γ-ray

M. May, PRL 51(1983)2085



NaI: 74 keV (FWHM) at 1 MeV

Possible reaction process

$Ex({}^{7}_{\Lambda}Li^*) > 19.3$ MeV

${}^{7}Li$

$K^- + (\alpha + t) \to (\Lambda + {}^{3}He) + \pi^- + t$

$\Lambda + {}^{3}He \to {}^{4}_{\Lambda}He$ (0^+ only non-spin-flip)

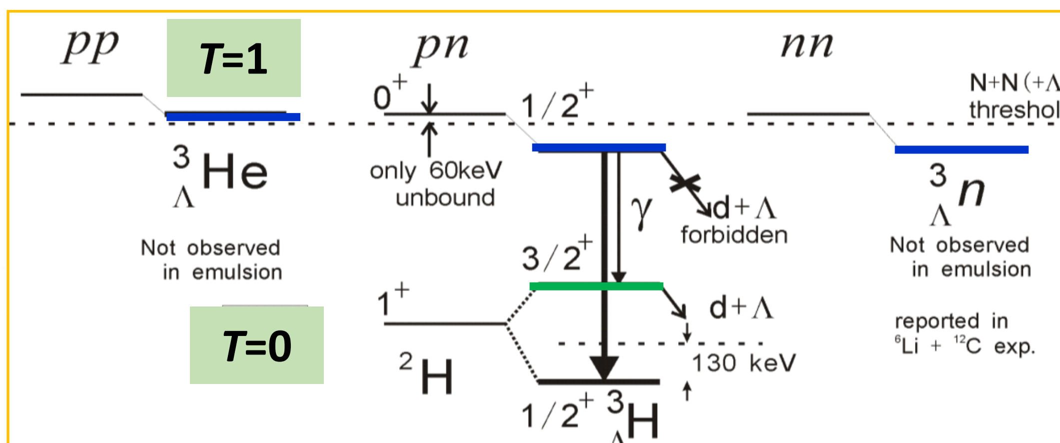
$\Lambda + t \to {}^{4}_{\Lambda}H$ (Both 0+/1+ ratio =1:3 expected)

Byproduct

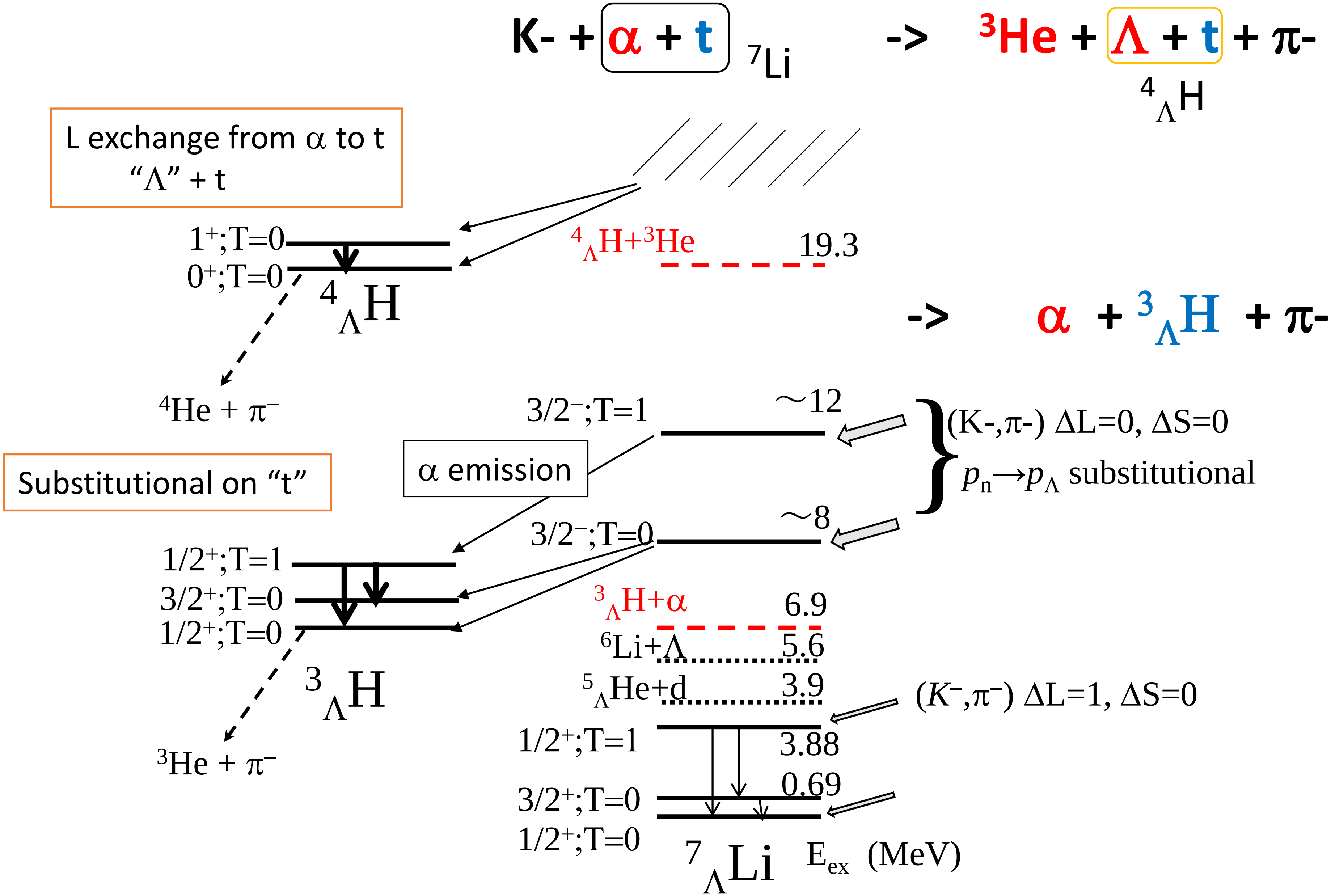
${}^{7}_{\Lambda}Li^*$ ($p_n p_\Lambda$ substitutional state)

$Ex({}^{7}_{\Lambda}Li^*) = 12$ MeV

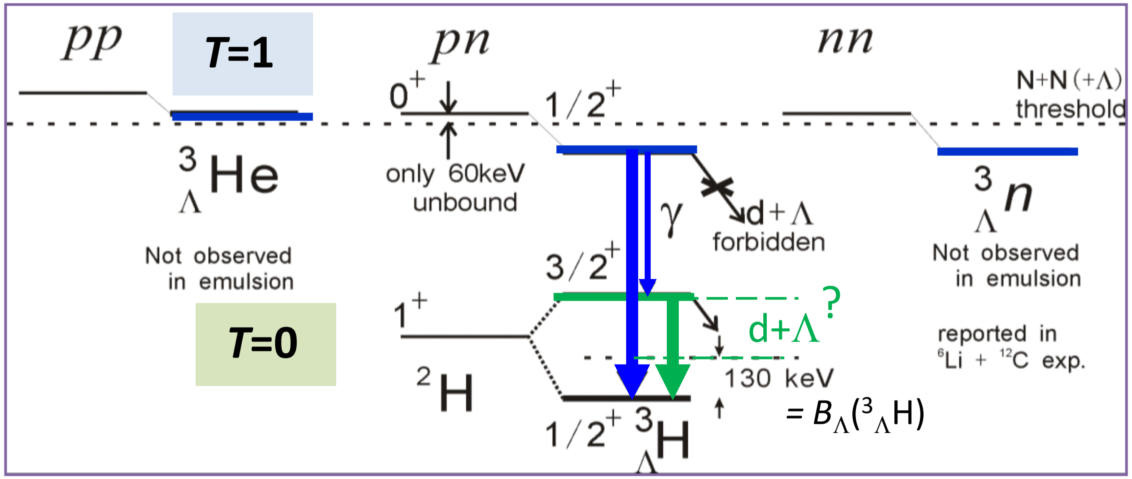
$K^- + (\alpha + t) \to (\alpha + {}^{3}_{\Lambda}H^*) + \pi^-$

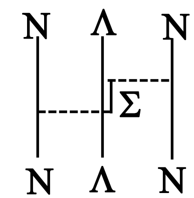


$^{7}_{\Lambda}$Li level structure and particle emission thresholds

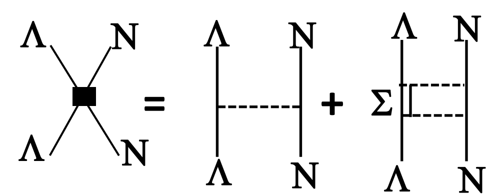


Physics Motivation





T=1 level γ transitions from $^3_\Lambda$H*(T=1, 1/2+) -> Precise energy for Λnn (T=1) interaction



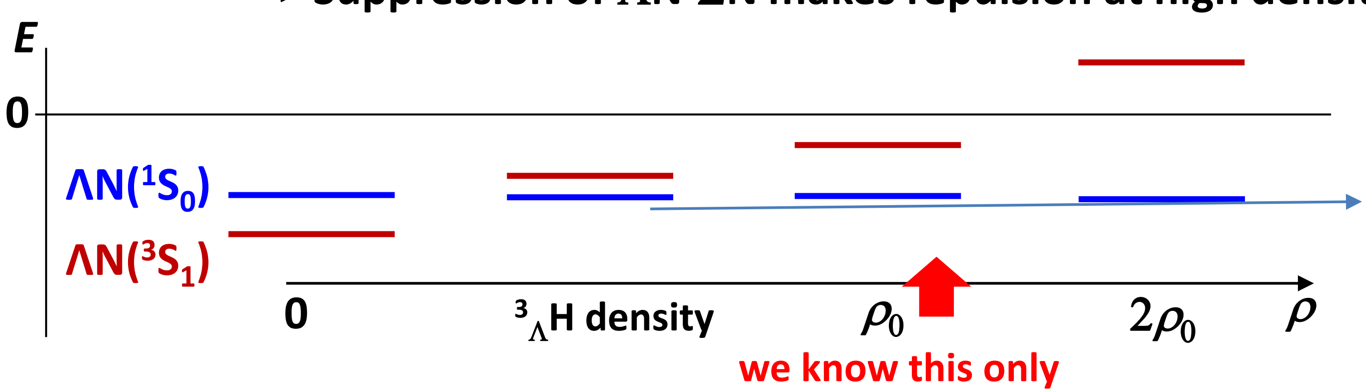
T=0 level γ transitions from $^3_\Lambda$H*(T=0, 3/2+)

-> Attractive effect of ΛN-ΣN in ΛN($^3S_1$)

NLO13, HALQCD predict a large attraction in ΛN($^3S_1$) due to ΛN-ΣN

-> $^3S_1$ is less attractive than $^1S_0$ in nuclear matter due to Pauli effect

-> Suppression of ΛN-ΣN makes repulsion at high density -> solution of hyperon puzzle ?



$^3_\Lambda$H (3/2,1/2) splitting can be smaller than B_Λ

Emulsion: 0.13±0.05 MeV

STAR: 0.41±0.12 MeV

Range counters for E63

F. Oura

- J-PARC E63 実験を計画中 [1]

beam line: J-PARC K1.1

reaction: $^{7}\mathrm{Li}(K^{-},\pi^{-})$反応の後,

生成される$^{7}_{\Lambda}\mathrm{Li}^{*}$が,

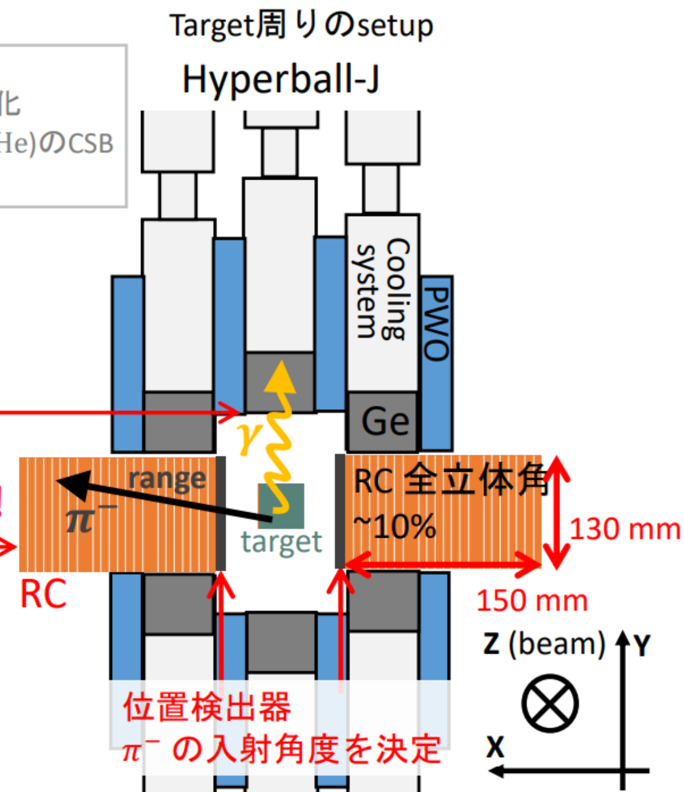
$^{4}_{\Lambda}\mathrm{H}$や$^{3}_{\Lambda}\mathrm{H}$などのハイパー核に崩壊

[1] H. Tamura, J-PARC E63 proposal.

E63実験 physics motivations
- 核内でのΛのg因子の変化
- 4体系ハイパー核($^{4}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{He}$)のCSB
- $^{3}_{\Lambda}\mathrm{H}$のエネルギー構造

ガンマ線測定 (Ge検出器群: Hyperball-J)
+
核種を完全に決定するために,
二体弱崩壊πの飛程測定 (Range counter)

γ-weak coincidence!

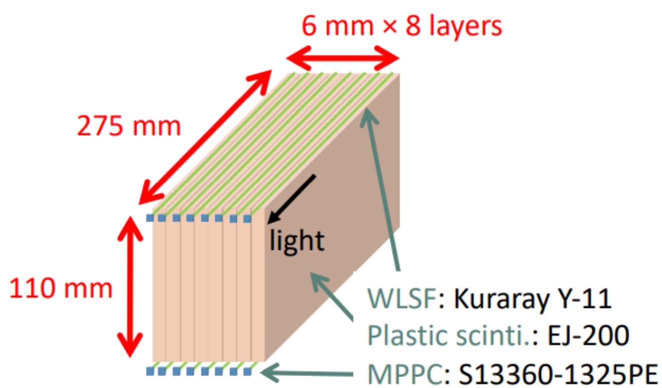


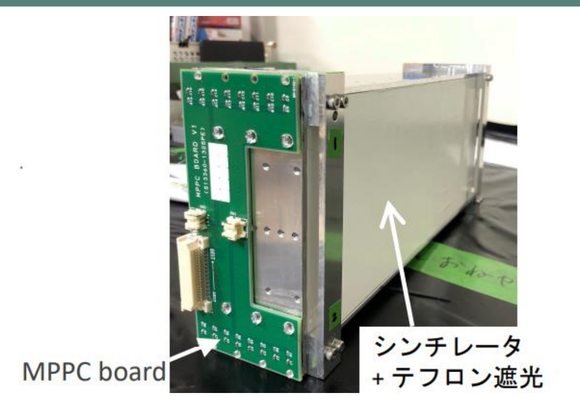
$^{4}_{\Lambda}\mathrm{H}\rightarrow {}^{4}\mathrm{He}+\pi^{-}$ (133 MeV/c, range in pla.scinti.=99.5 mm)

$^{3}_{\Lambda}\mathrm{H}\rightarrow {}^{3}\mathrm{He}+\pi^{-}$ (114 MeV/c, range = 64.6 mm)

(要求) →これらの π^{-} をRCで識別したい。

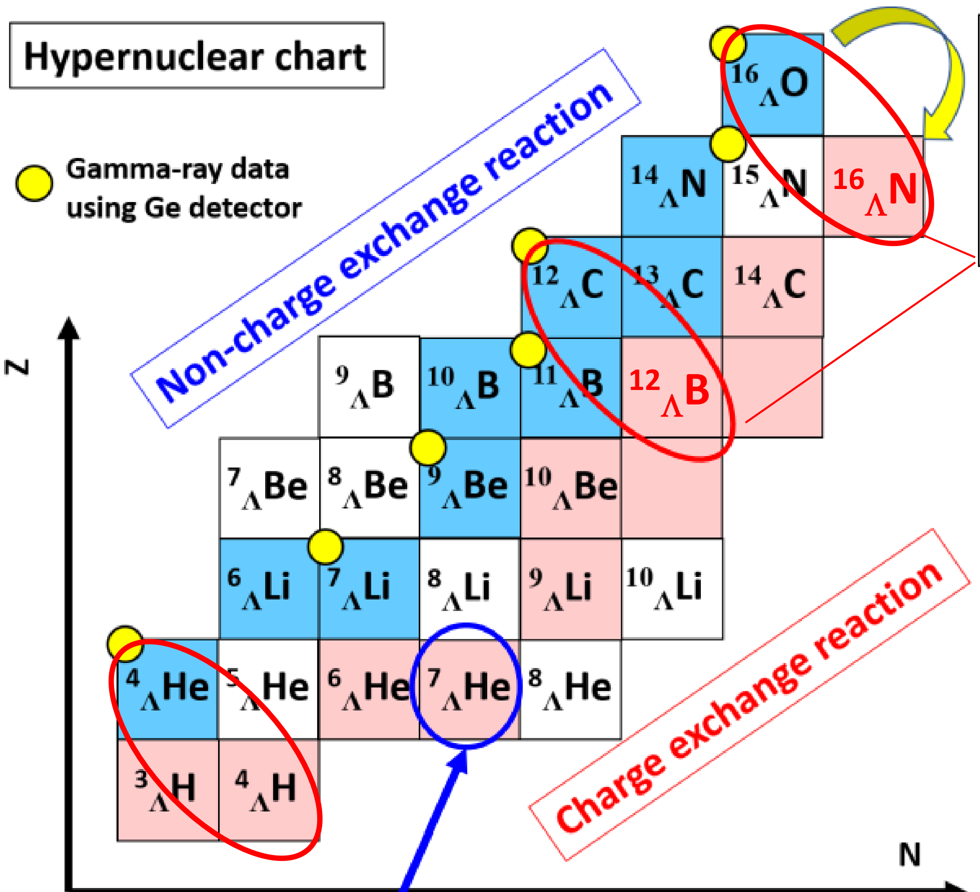
↔これらの π^{-} (range差: 34.9 mm)を 3σで分けたい。





CSB and n-rich p-shell hypernuclei

T.O. Yamamoto



How strongly CSB effect apereas for A>4 hypernuclei?

-> may help to understand the origin

We only have precise data for **proton rich** hypernuclei produced by **“n→Λ reaction”**

Need to approach mirror pair **(neutron rich)** hypernuclei by introducing **“p→Λ reaction”**

Other neutron rich hypernuclei can be accessed

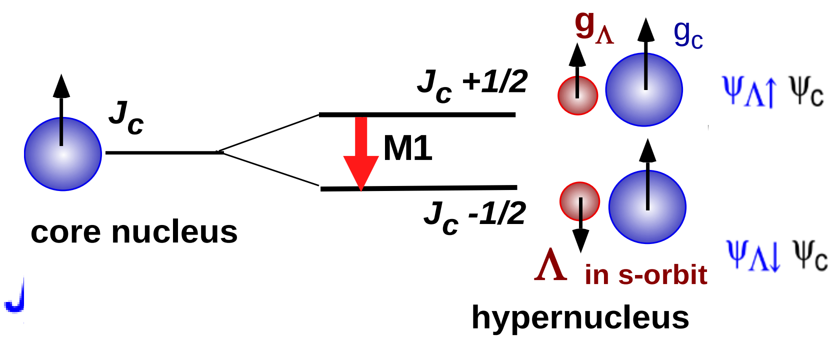
→ ΛΣ mixing effect

Shrinkage (Drastic change of B(E2))

Baryon modification
in nuclear medium

g_Λ in a nucleus

B(M1) of Λ-spin-flip M1 transition



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

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

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

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

: assuming "weak coupling" between a Λ and the core.

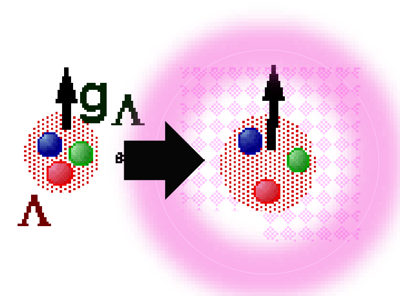
R.H. Dalitz and A. Gal, Annals of Phys. 116 (1978) 167.

$^7_\Lambda$Li ~100%

Doppler Shift Attenuation Method: eg) B(E2): Tanida et al. *PRL 86 (2001) 1982*

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

Modification of g_Λ in nuclear medium?



- Λ–Σ mixing: *C.B. Dover, H. Feshbacj, A. Gal, PRC 51 (1995) 541.*
  +2--5 % for $^4_\Lambda$He, small for T=0 hypernuclei
- K, 2π exchange current: *K. Saito, M. Oka, T. Suzuki, NPA 625 (1997) 95.*
  -7% for $^7_\Lambda$Li
- "Quark exchange current" in QCM *T. Takeuchi, K. Shimizu, K. Yazaki, NPA 481 (1988) 693.*

Experiment at J-PARC

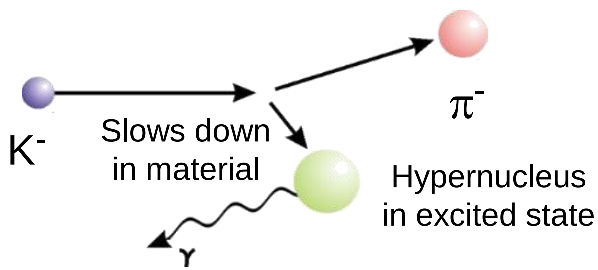
Approved as E13 -> E63

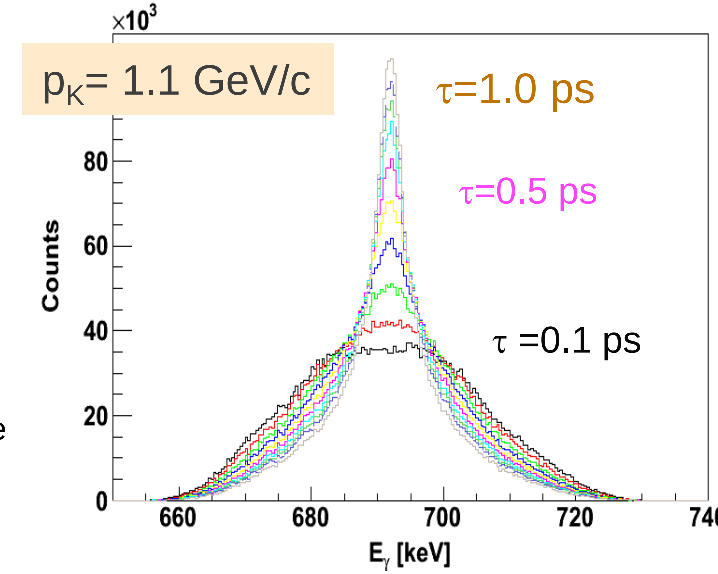
DSAM (Doppler Shift Attenuation Method)

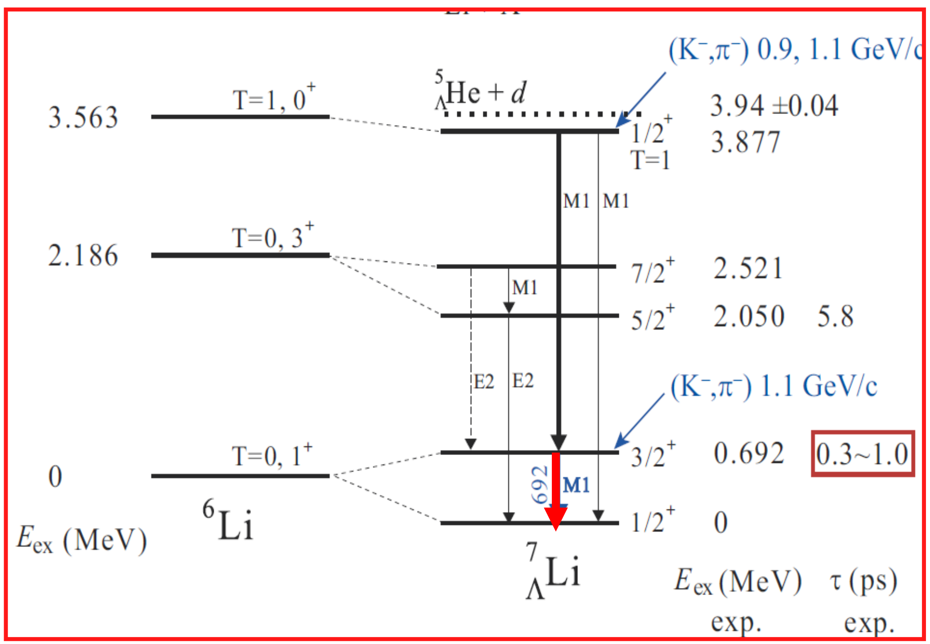
τ ~ **0.5 ps**

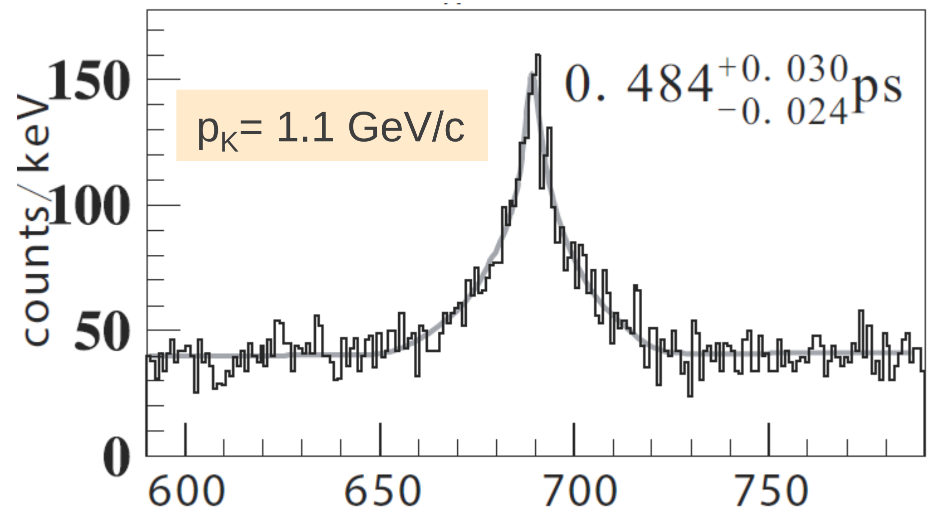
t_{stop} **~ 2 ps**

in Li_2O (2.01 g/cm^3)









H. Tamura et al., Nucl.Phys. A881 (2012) 310

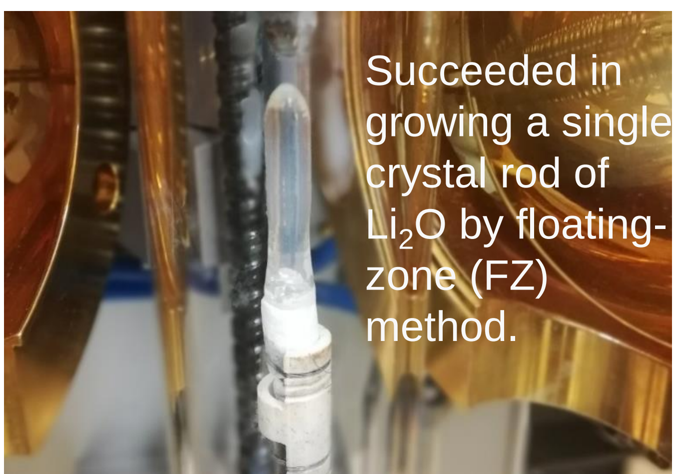
For 35 days for 50kW
Assuming 56k K⁻/spill for 0.9 GeV/c
176k K⁻/spill for 1.1 GeV/c

Stat. error
$\Delta\tau/\tau = 6\%$ => $\frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|}$ ~ 3%

E63 setup

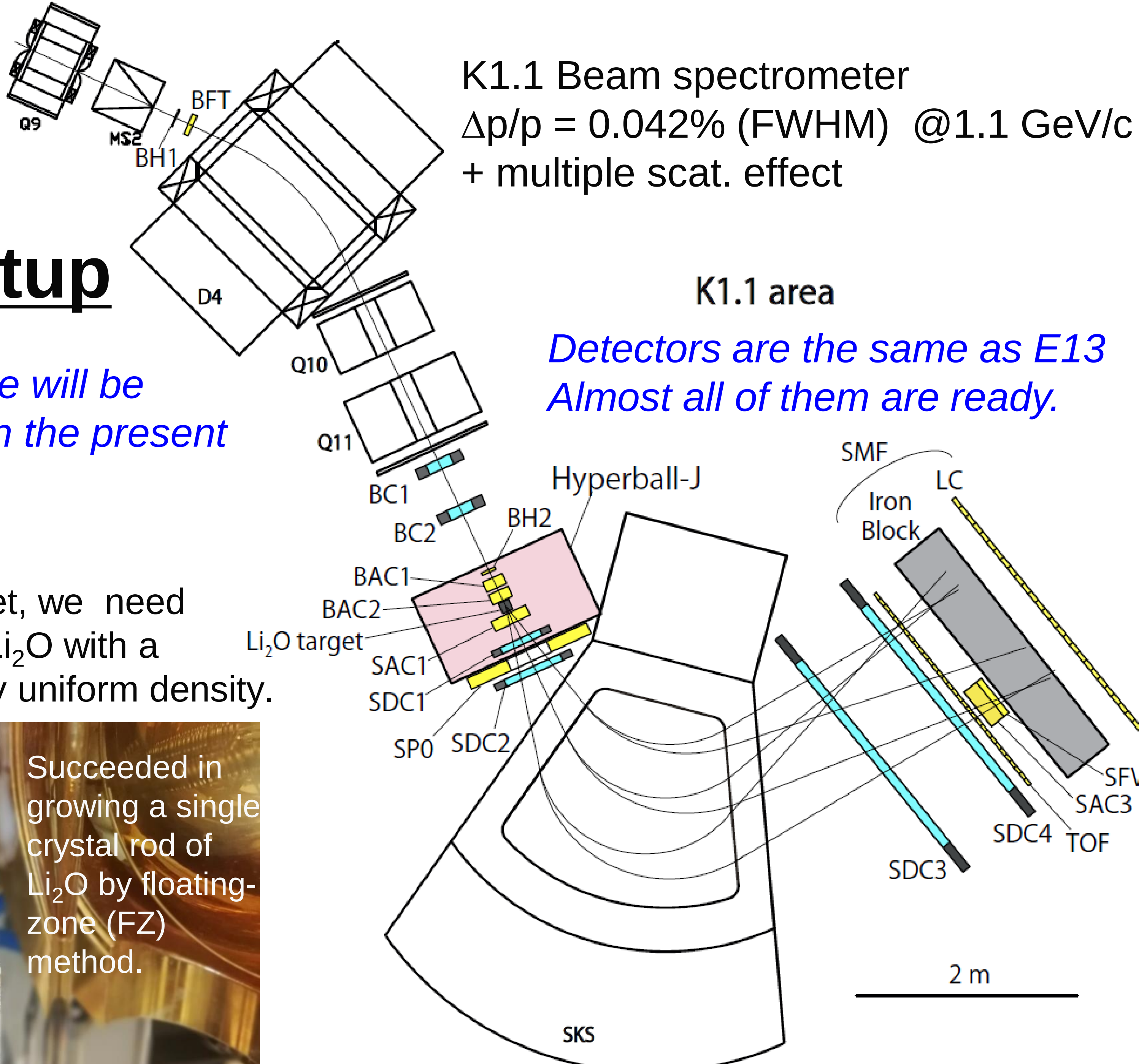
K1.1 beamline will be constructed in the present hadron hall.

For the Li target, we need single-crystal Li_2O with a microscopically uniform density.



K1.1 Beam spectrometer
$\Delta p/p$ = 0.042% (FWHM) @1.1 GeV/c
+ multiple scat. effect

Detectors are the same as E13
Almost all of them are ready.



B(M1) value expected in "ordinary" nuclear physics

Experimental values:

^{6}Li: $g_c = 0.822047 \mu_N$

Λ: g_Λ (free) = $-1.226 \pm 0.008\ \mu_N$

=> If weak coupling is OK, $^7_\Lambda$Li B(M1) = $0.334 \pm 0.003\ \mu_N^2$

Calculations

	$J_i, T_i \rightarrow J_j, T_f$	$B(M1)\ (\mu_N^2)$	
$^7_\Lambda$Li	$3/2^+, 0 \rightarrow 1/2^+, 0$	0.322	$^5_\Lambda$He+p+n cluster (Hiyama et al.) [a]
		0.352	^{4}He+d+Λ cluster (Motoba-Bando-Ikeda) [b]
		0.364	Shell model (Dalitz-Gal) [c]

-3.5% from weak coupling

<+5.5% from weak coupling

[a] H. Hiyama et al., PRC 59 (1999) 2351.

[b] T. Motoba, H. Bando, K. Ikeda, T. Yamada, PTP Suppl. 81 (1985) 42.

[c] R.H. Dalitz and A. Gal, Annals of Phys. 116 (1978) 167.

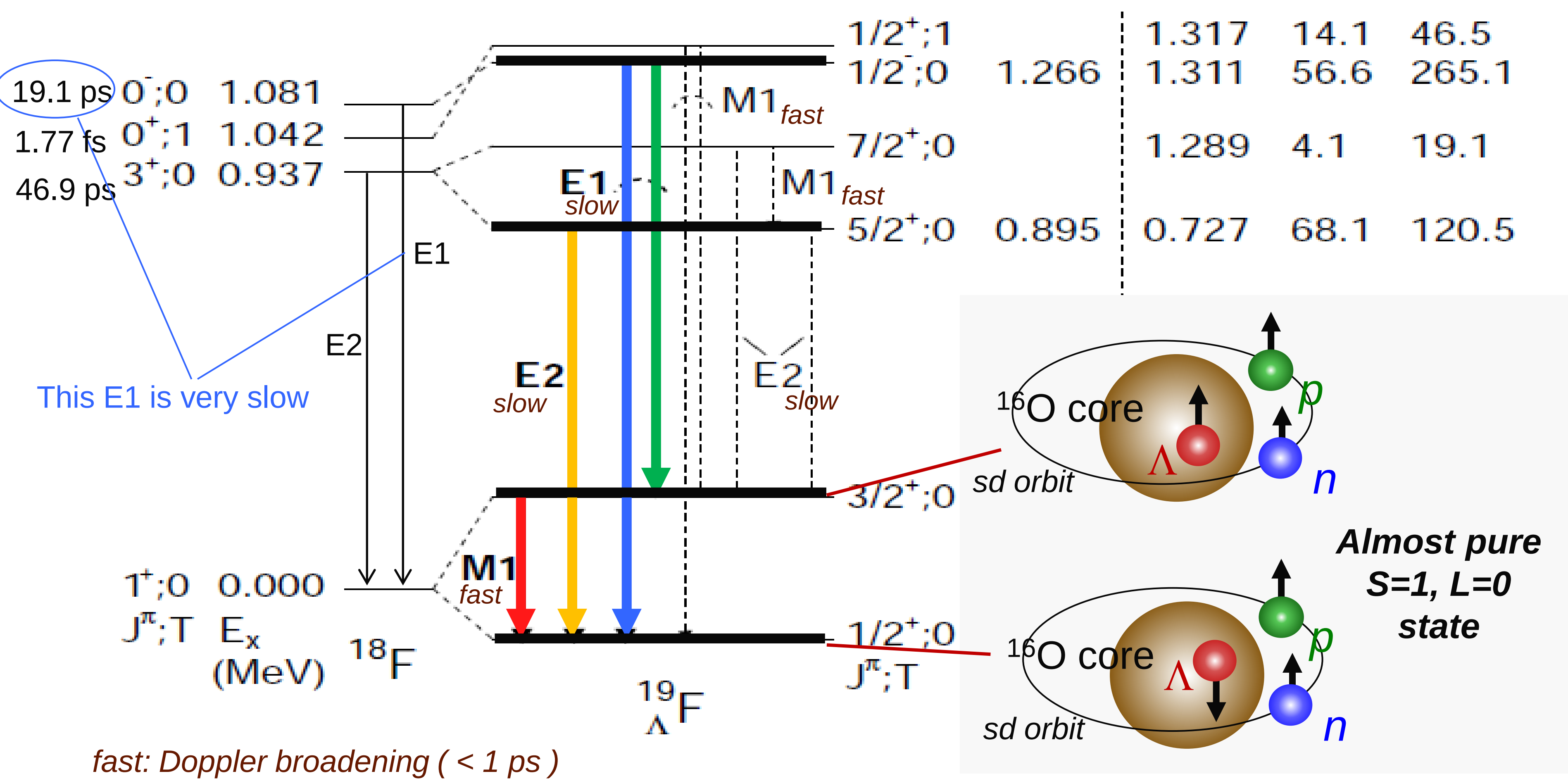
- Suggesting that the weak coupling hypothesis holds well.
- Better calculation by Hiyama is going on.
  ^{4}He+p+n+Λ cluster model with and without Λ–Σ coupling
- Ab-initio 7-body calculations in future (after the measurement is done)

Medium/heavy hypernuclei and the hyperon puzzle

S.B. Yang et al., PRL 120 (2018) 132505

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

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

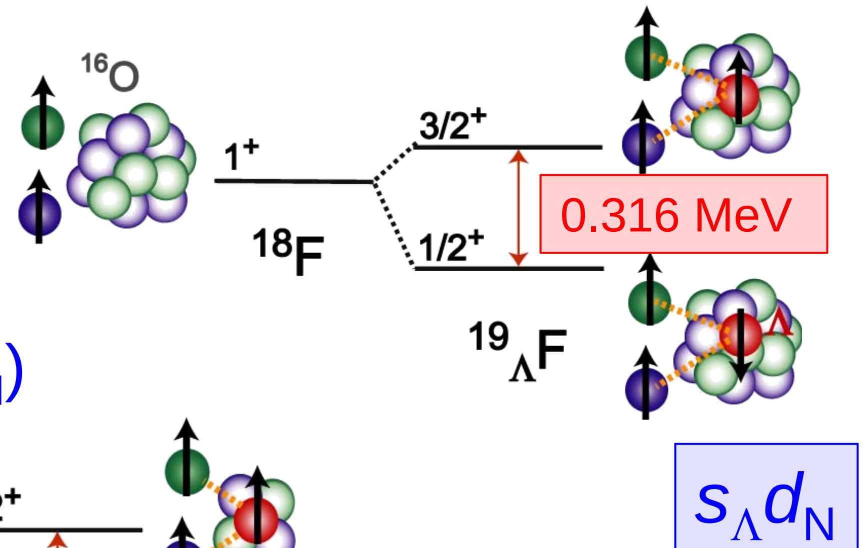


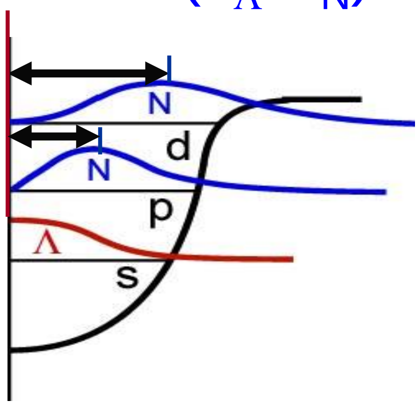
fast: Doppler broadening (< 1 ps)
slow: No Doppler broadening (> 1 ps)

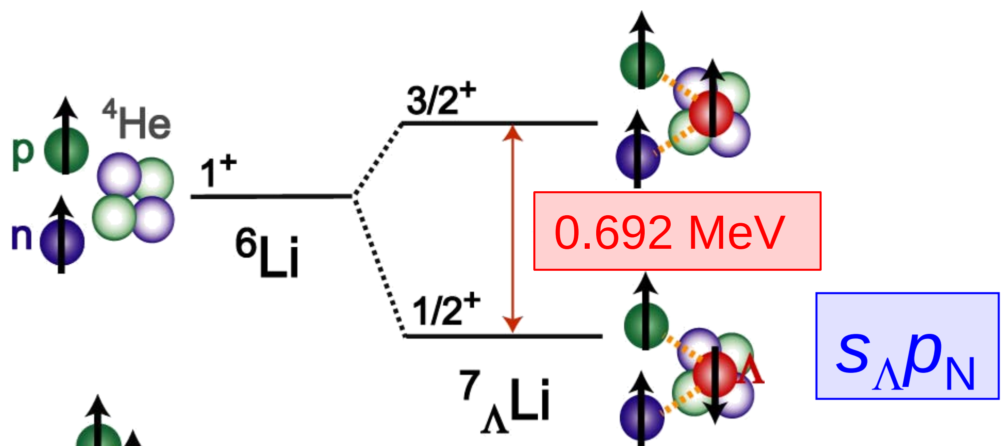
∗ *A. Umeya and T. Motoba, Nucl. Phys. A954 (2016) 242. Shell model calculation with NSC97f interaction*

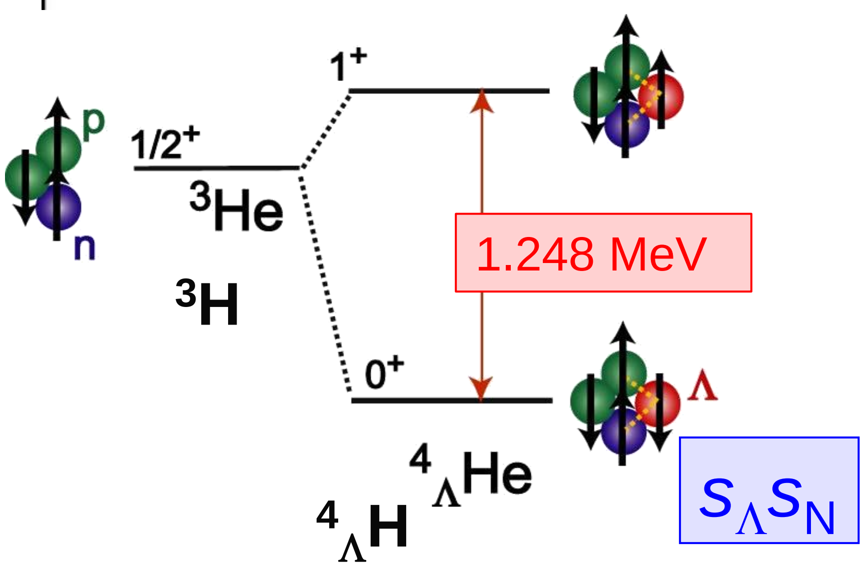
A-dependence of ΛN interaction strength

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







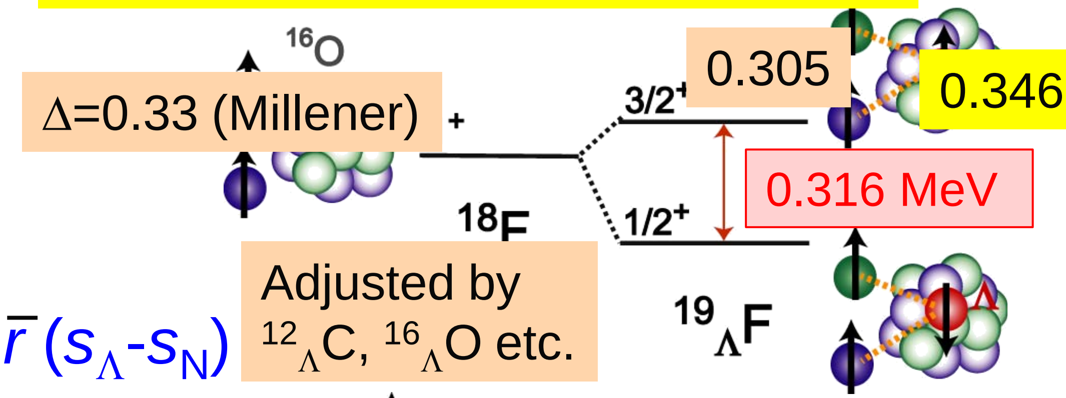


Effective interaction between two baryons in different shells is consistently understood by theories

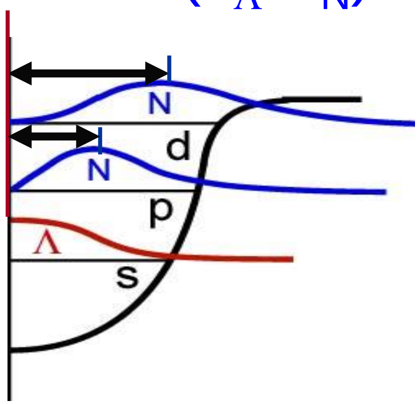
⇒ Level structure of hypernuclei in a wide range of A can be reproduced.
=> Density dependence of ΛN int. may be able to be studied

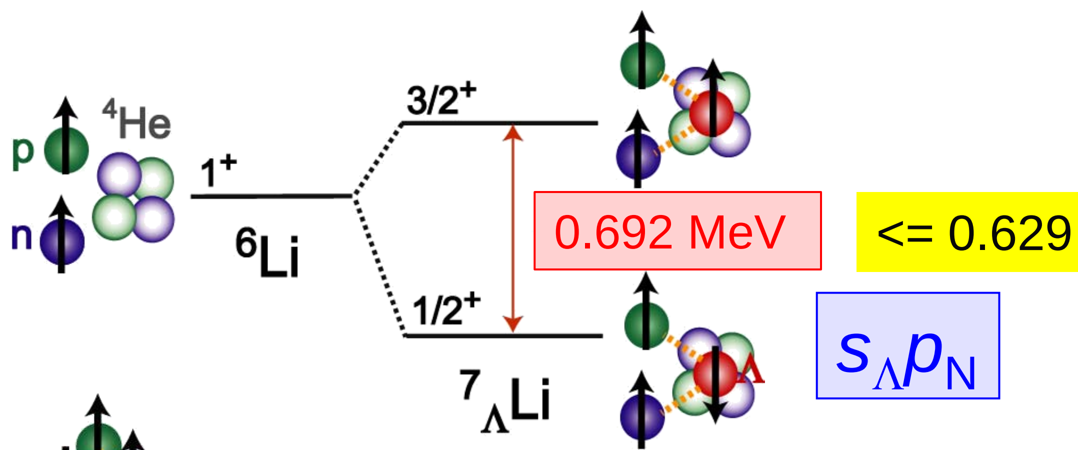
A-dependence of ΛN interaction strength

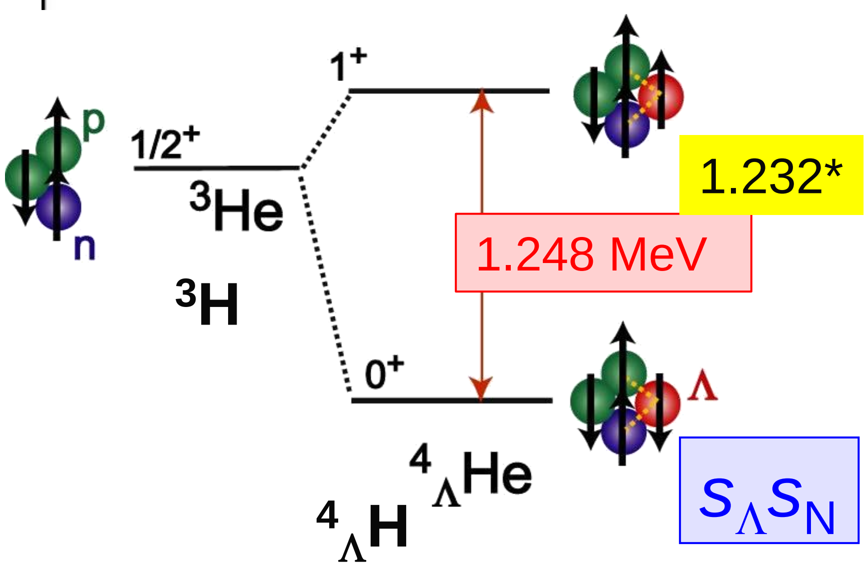
NSC97e+f (Motoba, Umeya, Akaishi*)



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







Effective interaction between two baryons in different shells is consistently understood by theories

⇒ **Level structure of hypernuclei in a wide range of A can be reproduced.**
=> Density dependence of ΛN int. may be able to be studied

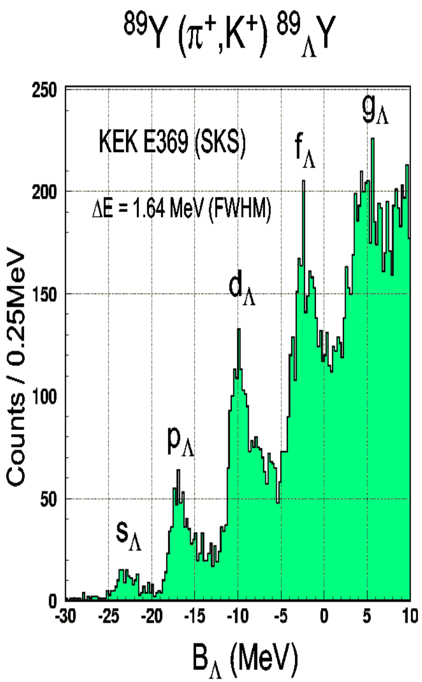
How to study density dependence of ΛN inteaction in matter?

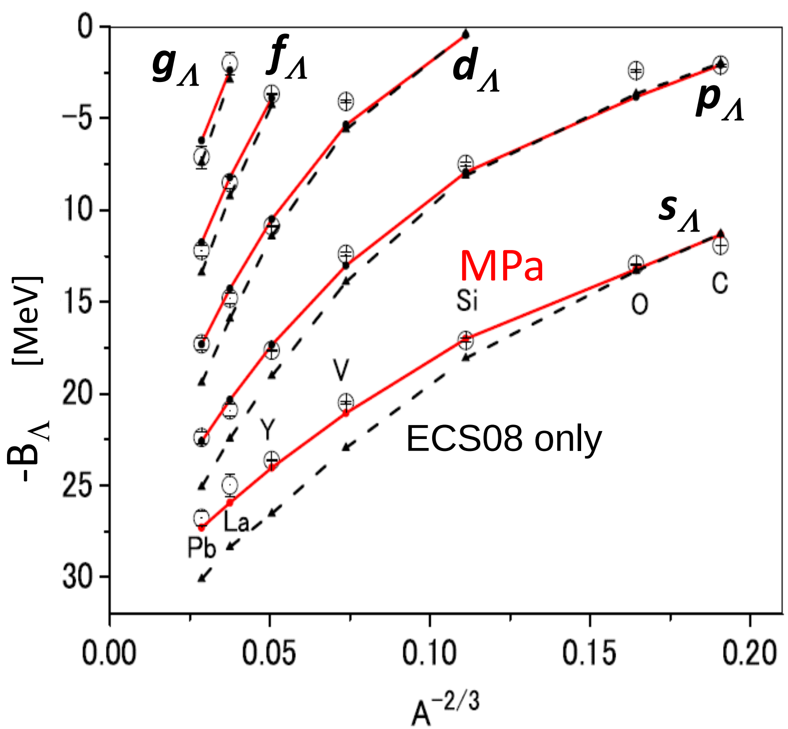
Ab-initio calc. of nuclear masses from NN force => NNN repulsion necessary
Similar YNN (YYN, YYY) repulsive forces?
--- Lack of precise YN scattering /hypernuclear data!

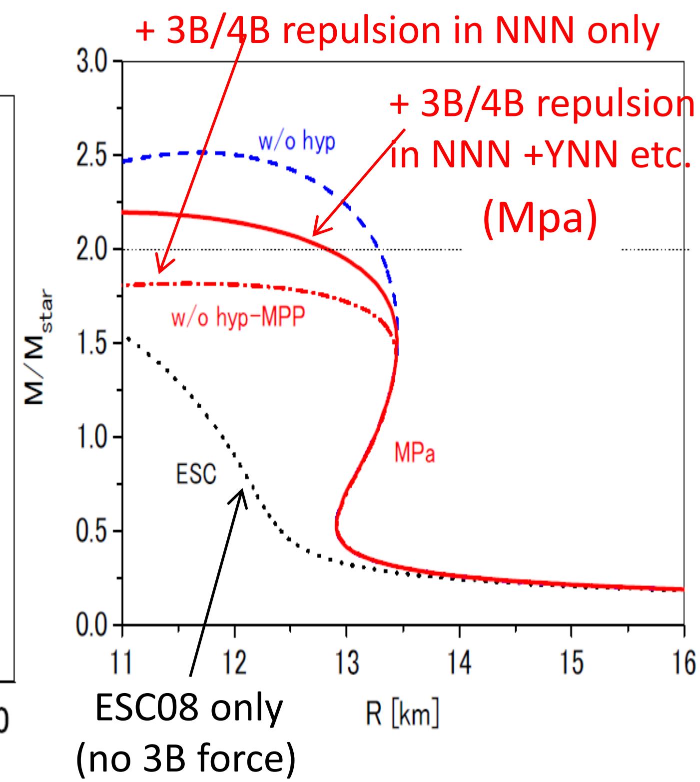
Precise B_Λ data for wide A of Λ hypernuclei in < 0.1 MeV accuracy is necessary
=> HIHR at Ext-HD

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

NNN determined from HI collision data



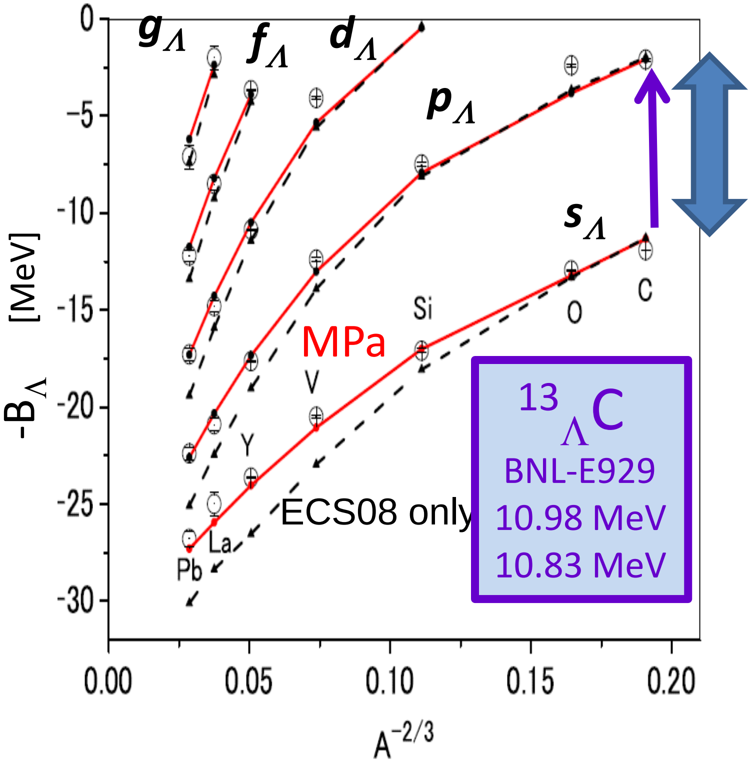


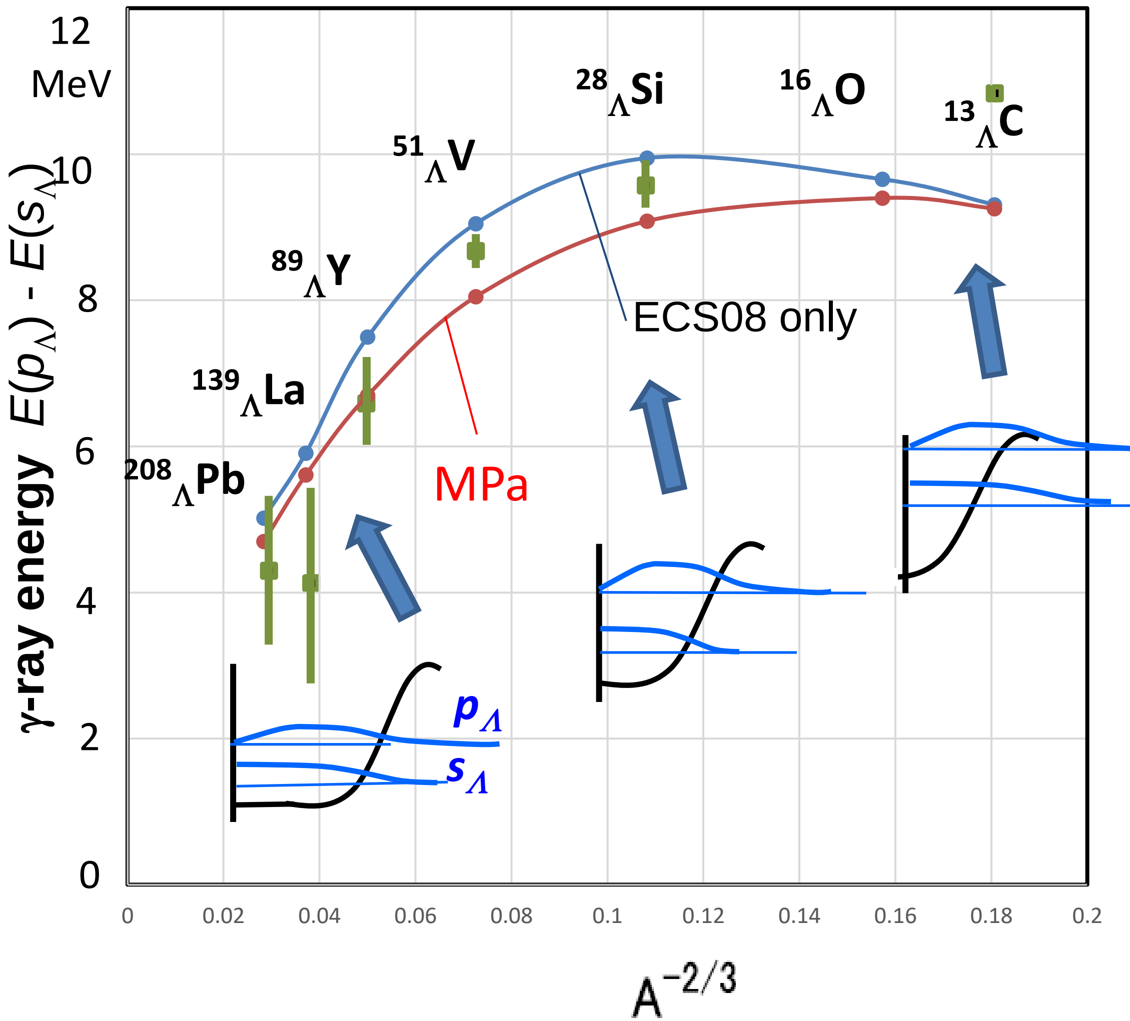


Another approach using γ-rays

p_Λ-s_Λ spacing is affected by density dep. of ΛN interaction

It can be precisely (~keV) measured with E1 γ-transitions.





Λ spin-orbit splitting in $^{13}_{\Lambda}C$

^{13}C (K^-, π^- γ)

BNL E929

w/ NaI array

$p_{1/2}$, $p_{3/2}$ single-particle level splitting

E($1/2^-$)-E($3/2^-$) =152±54±36 keV

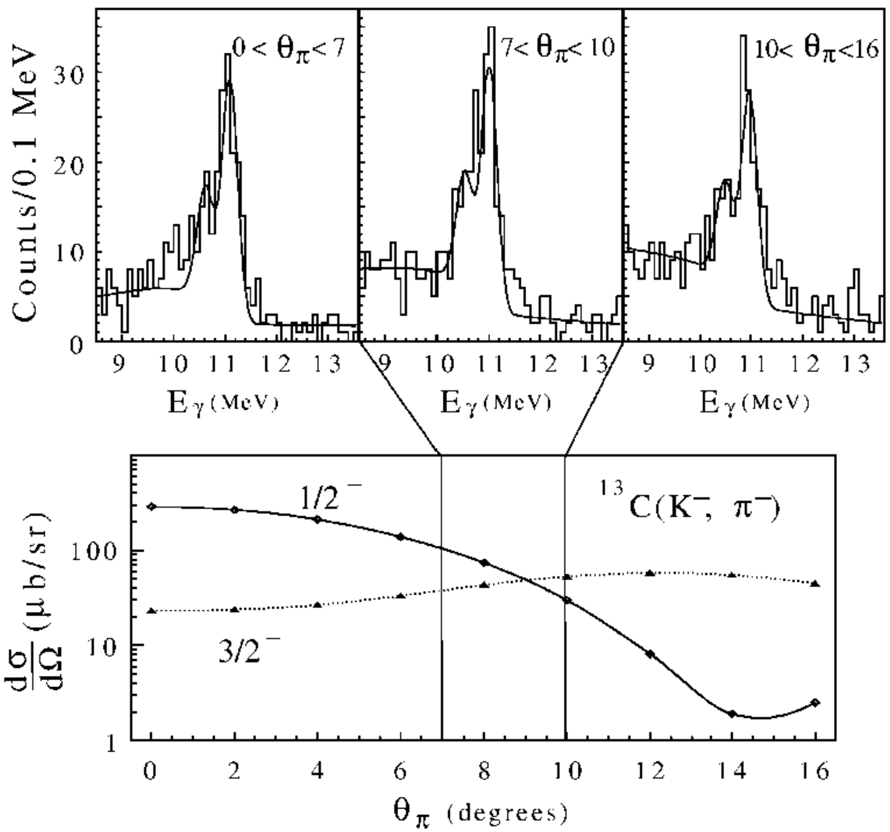
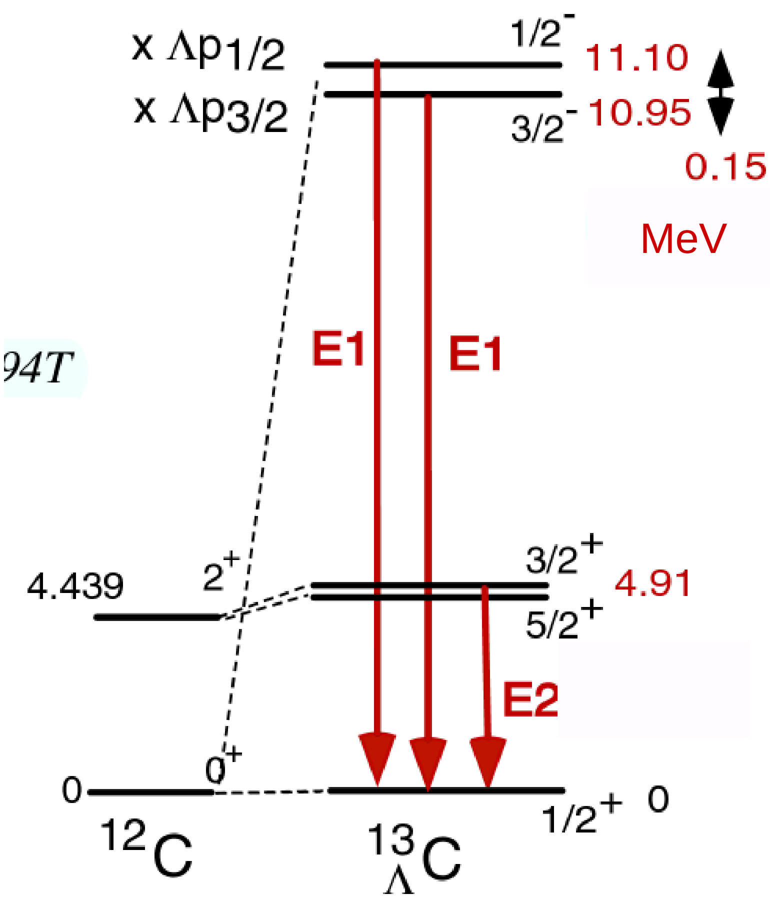


FIG. 2. γ ray spectra taken in coincidence with scattered π^-'s (upper panel) and differential cross section of $1/2^-$ and $3/2^-$ states calculated by Motoba [18] (lower panel) are shown.



Ajimura et al., PRL 86 (2001) 4255

E1 (p_Λ->s_Λ) measurement for a wide A range

$^{29}_{\Lambda}$Si, $^{52}_{\Lambda}$Cr, $^{89}_{\Lambda}$Y, $^{135}_{\Lambda}$La, $^{208}_{\Lambda}$Pb

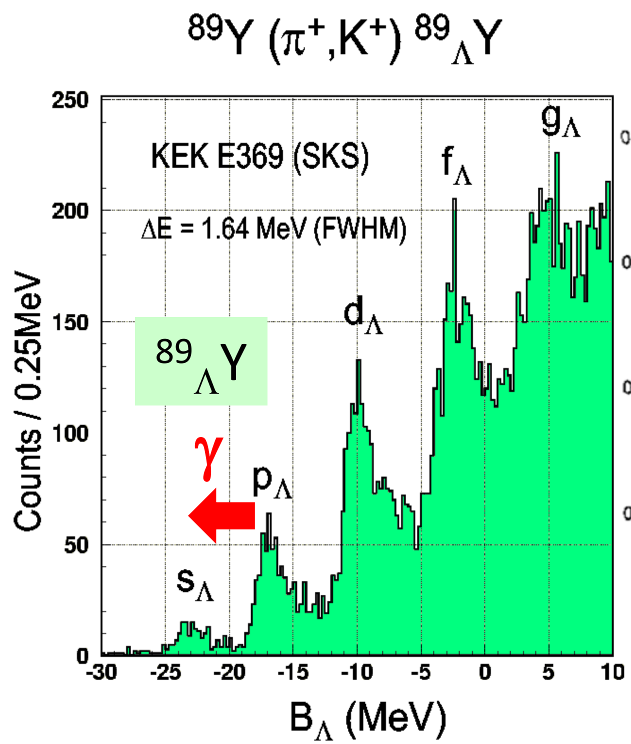
	$^{13}_{\Lambda}$C	$^{16}_{\Lambda}$O	$^{28}_{\Lambda}$Si	$^{29}_{\Lambda}$Si	$^{40}_{\Lambda}$Ca	$^{51}_{\Lambda}$V	$^{52}_{\Lambda}$Cr	$^{89}_{\Lambda}$Y	$^{139}_{\Lambda}$La	$^{208}_{\Lambda}$Pb
ΔE (p_Λ-s_Λ)	11.10 10.95	10.6	9.6	~9	~9	8.8 (8.1)	~8	6.6 (6.0)	4.1	4.4
Sp (core)	16.0	7.3	7.5	11.6	5.8	7.9	9.5	6.7	6.1	7.5
Sn (core)	18.7	13.2	13.3	17.2	13.3	9.3	9.3	9.4	7.5	6.7
Target (%)	^{13}C 1.1%	^{16}O 100%	^{28}Si 92%	^{29}Si 4.7%	^{40}Ca 97%	^{51}V 100%	^{52}Cr 84%	^{89}Y 100%	^{139}La 100%	^{208}Pb 52%

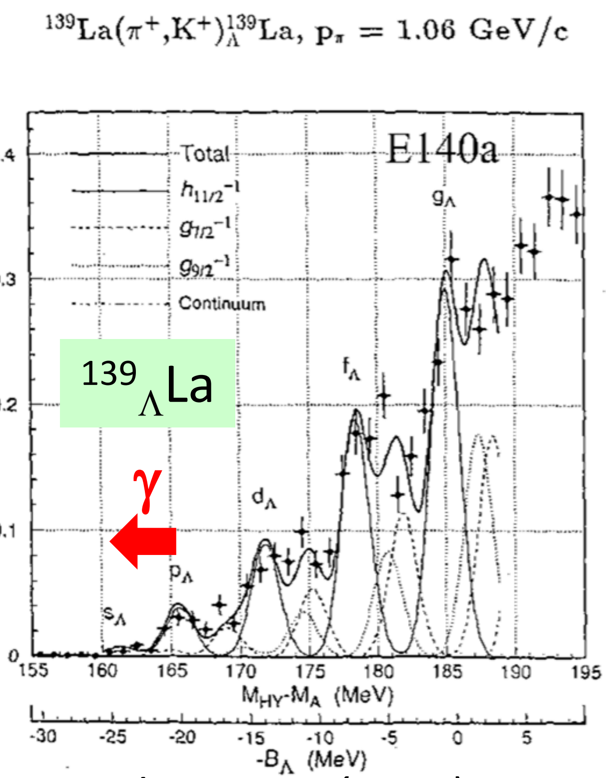
(K^-,π^-) 1.1 GeV/c @K1.1 line, 100 kW, Total ~ 7 weeks

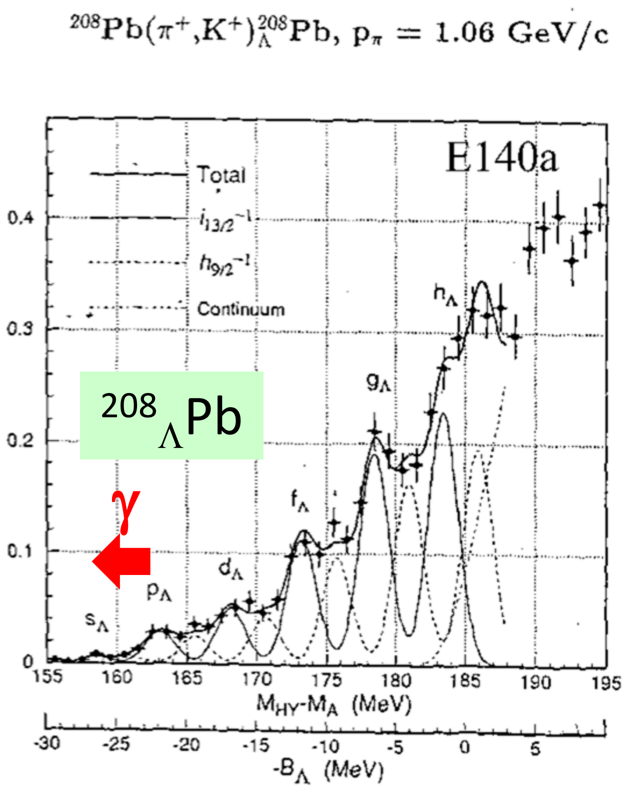
- **Density dependence of ΛN interaction**
- **Origin of nuclear LS splitting** -> "Nuclear structure without pion"

- 2-body LS force ---Very small due to cancellation between a large SLS and a large ALS
- Tensor force ---No one pion exchange -> small, no isospin dependence.
- Many-body correlation ---No one pion exchange ->Small ?

Heavy hypernuclei



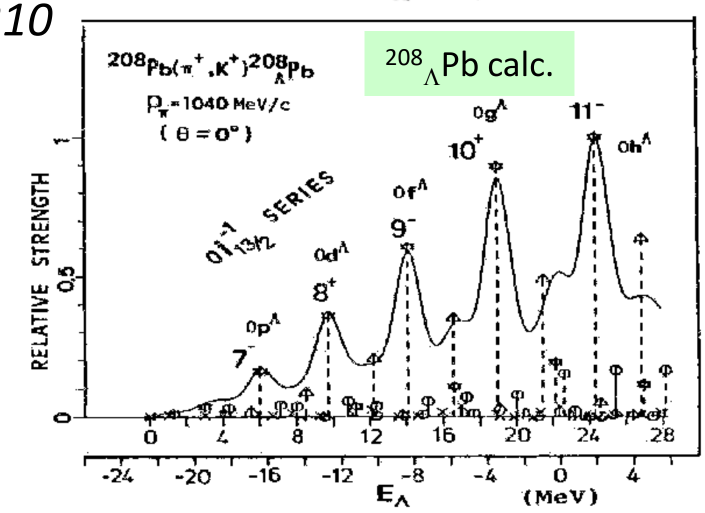




Hasegawa et al., PRC 53 (1996) 1210

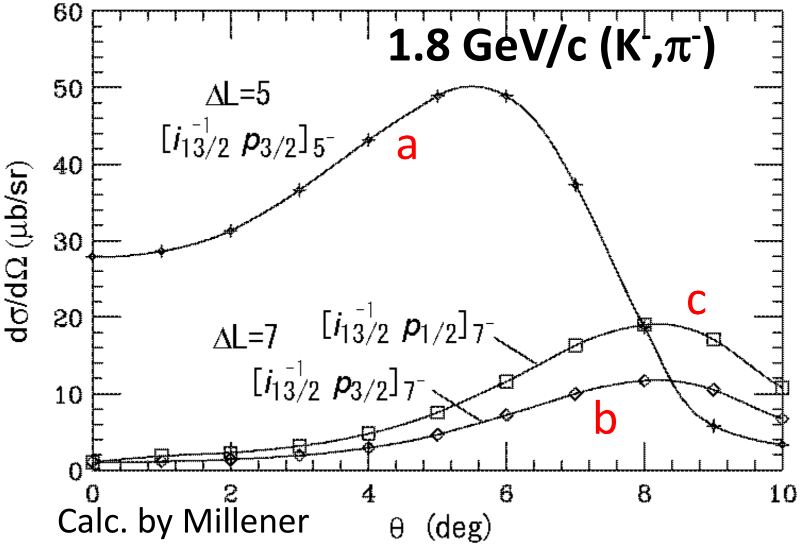
(π^+,K^+) reaction

KEK E140a, K6+SKS



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

Split into several transitions



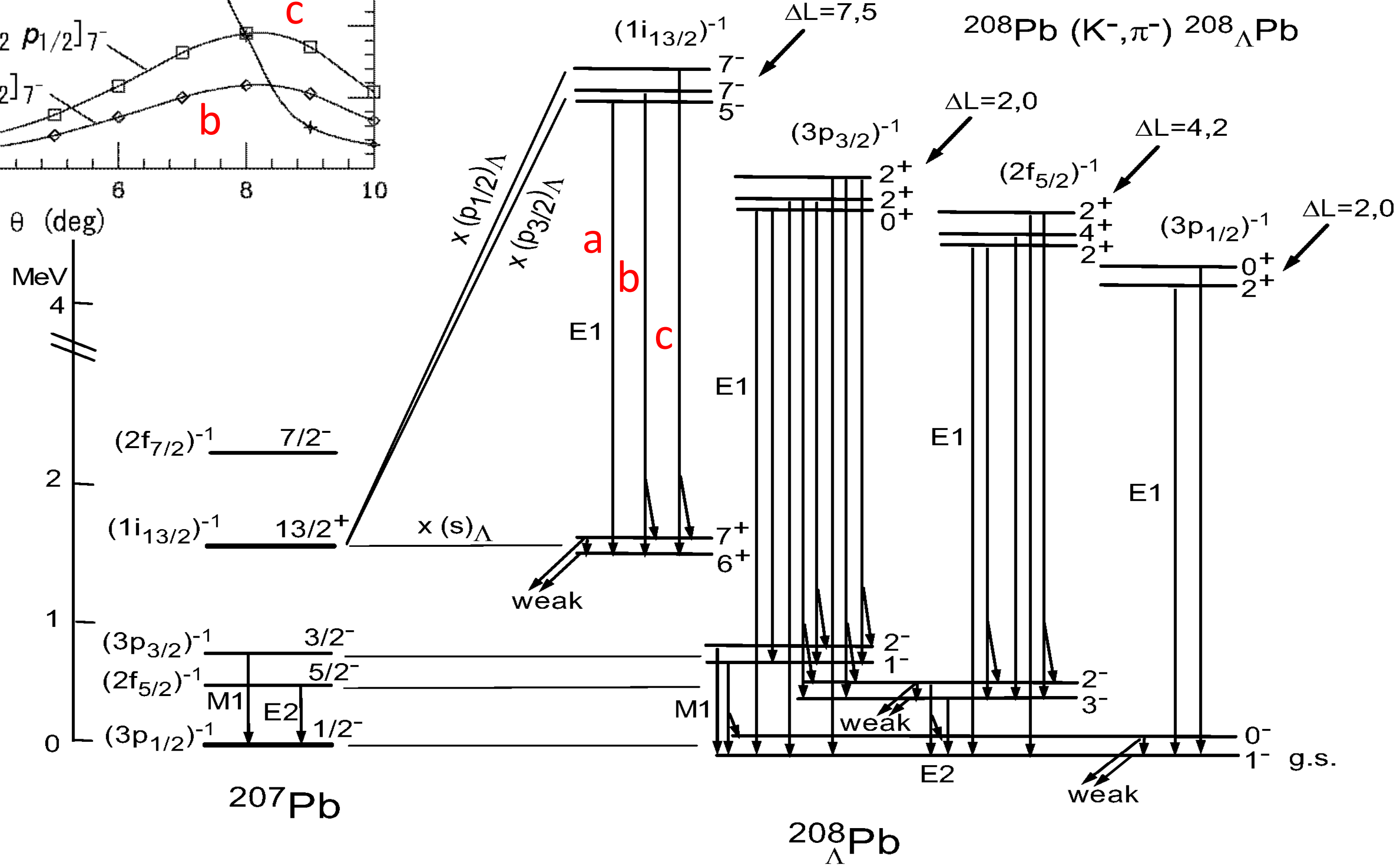
from J-PARC LOI

15 days at K1.1 @120 kW

a: ~300 ev

b: ~200 ev

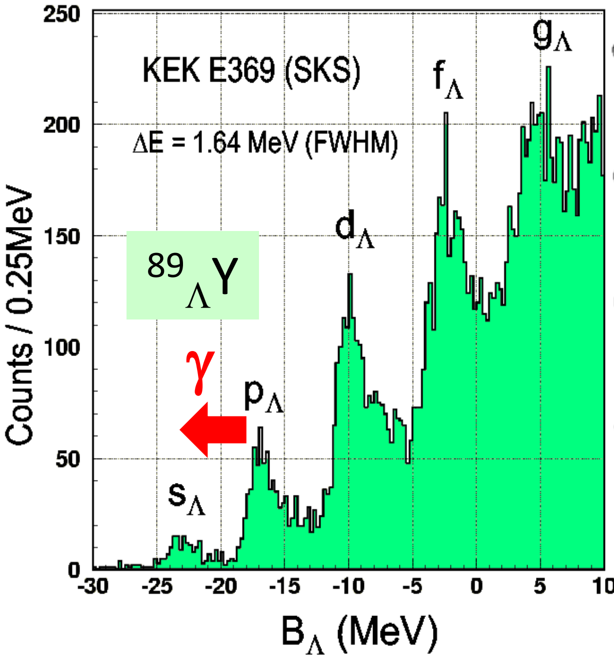
c: ~700 ev

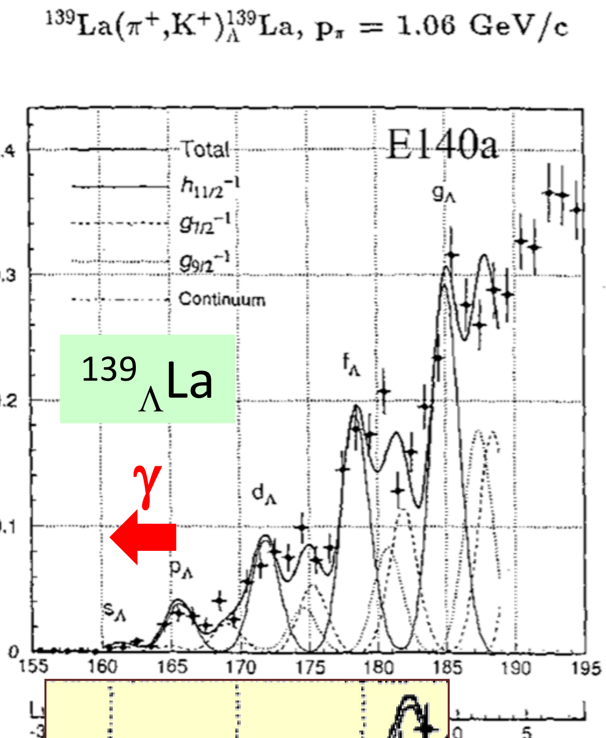


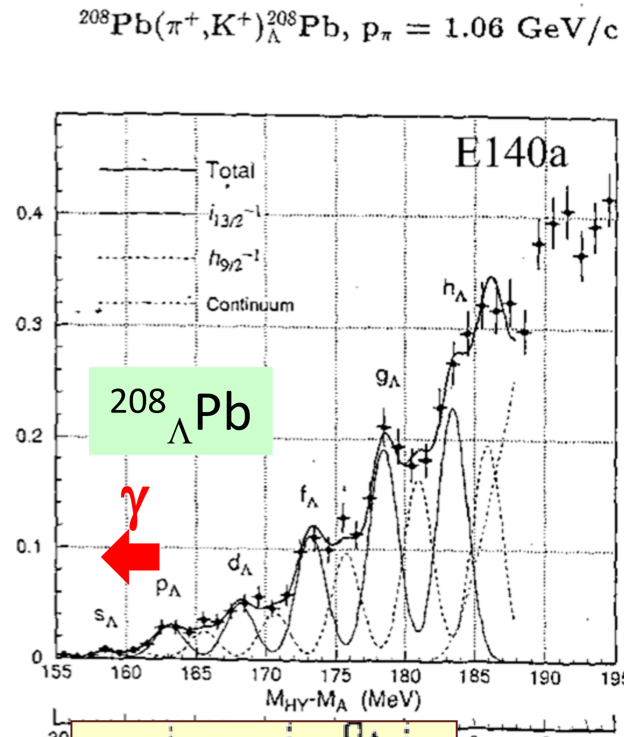
Probably, we can clearly assign transitions, even when several peaks are observed, from angular distribution and intensity combined with reliable calculations of hypernuclear structure and reactions.

Heavy hypernuclei

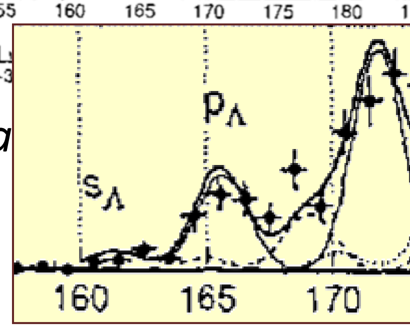
$^{89}Y\ (\pi^+,K^+)\ ^{89}{}_{\Lambda}Y$

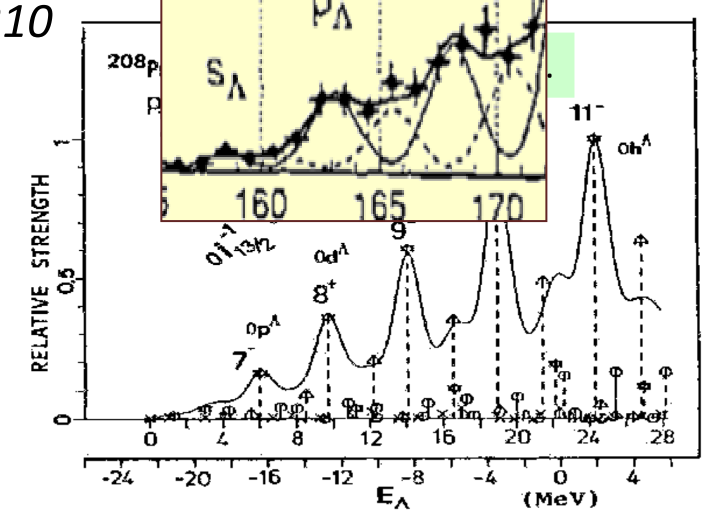






Hasegawa ...) 1210



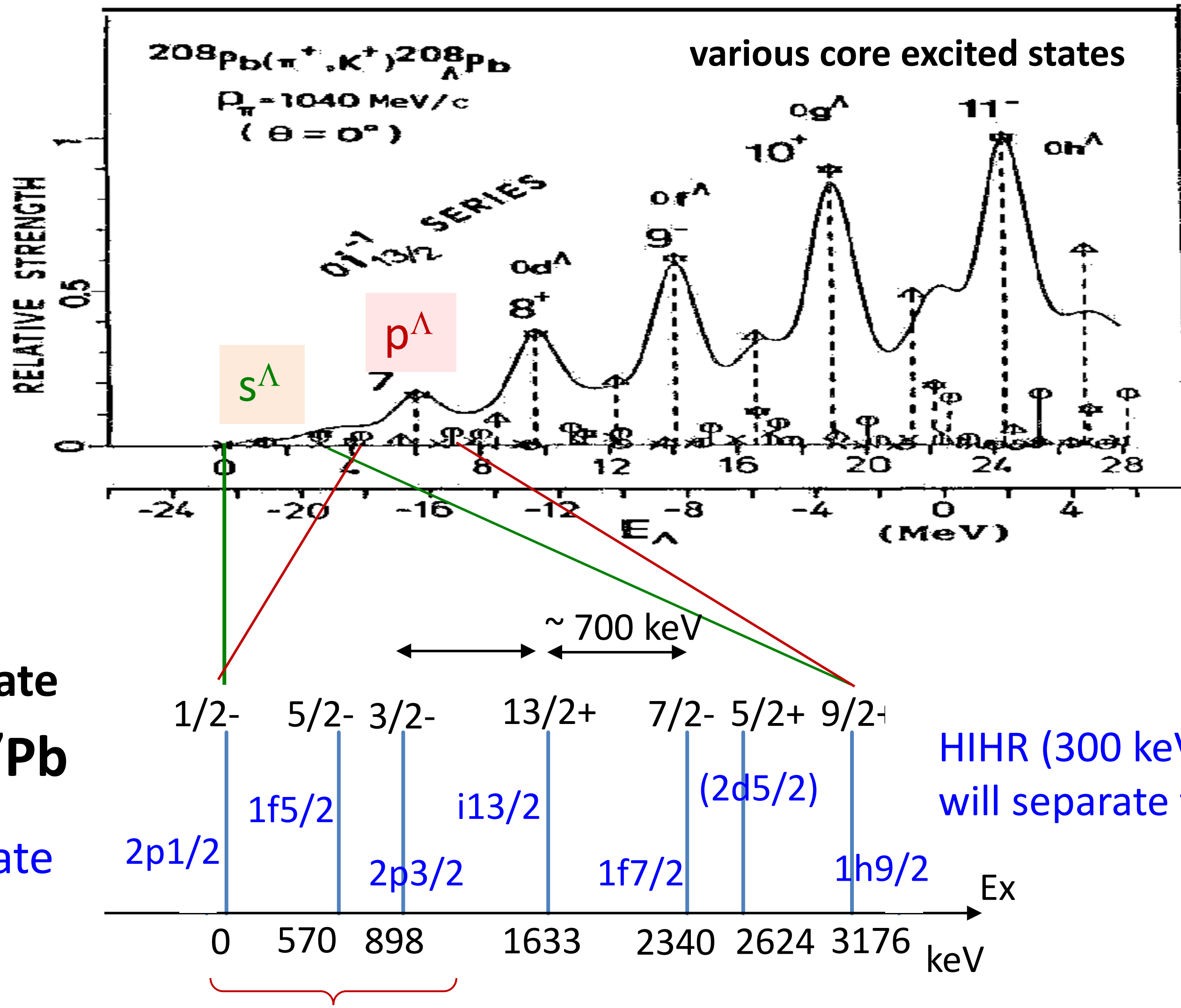


(π^+,K^+) reaction

KEK E140a, K6+SKS

Detailed low-lying level schemes are important for measurement of Λ's single particle energies with HIHR.

In the case of $^{208}{}_{\Lambda}Pb$



HIHR (300 keV resolution) will separate these peaks.

Gamma-ray data is desired to decompose the doublet and assign these low-lying levels

What to be studied for a proposal

- K1.1(SKS) or K1.8(S-2S)?
  1.8 GeV/c (K-,pi-) may be better for higher momentum transfer
- Realistic estimates of gamma-ray yields

Request to the theorists

- How reliably the density dependence of ΛN force (ΛNN force) can be derived from p_Λ-s_Λ spacings?
  Effects of nuclear deformation and level structure?
- What we can extract from spin-orbit splitting of various heavy Λ hypernuclei?
- Realistic calculations of level schemes and cross sections of medium/heavy hypernuclei necessary.