Gamma-ray spectroscopy of Λ hypernuclei at the HIHR/K1.1 beamlines

2021/7/8

T.O. Yamamoto
JAEA ASRC (Japan)

Contents

- **Present status of gamma-ray spectroscopy of Λ hypernuclei**
- **Prospect of future measurement**
  - **A=3 hypernuclei**

    study of ΛN-ΣN mixing effect
  - **s~p-shell neutron rich hypernuclei**

    study of charge symmetry breaking effect + ΛN-ΛΣ mixing
  - **Medium-hevy hypernuclei**

    study of density dependence of ΛN interaction
- **Summary**

Gamma-ray spectroscopy to study nuclear structure

What's we can obtain from gamma-ray spectroscopy

- Transition energy and coincidence (or branching) relationship
  → Level structure
- Transition rate
  → Lifetimes, electric/magnetic moment, …
- Angular correlations and liner polarizations
  → Spin, Parity

Precise gamma-ray spectroscopy have a important roll to study nucleus

○ Good energy resolution!

○ Prove without large perturbations in the nuclear medium.

○ Gamma-rays penetrate target material and reach detector.

× Can not apply for un-bound (or short lifetime) state

only low-lying (or long lifetime) state will emit gamma-ray

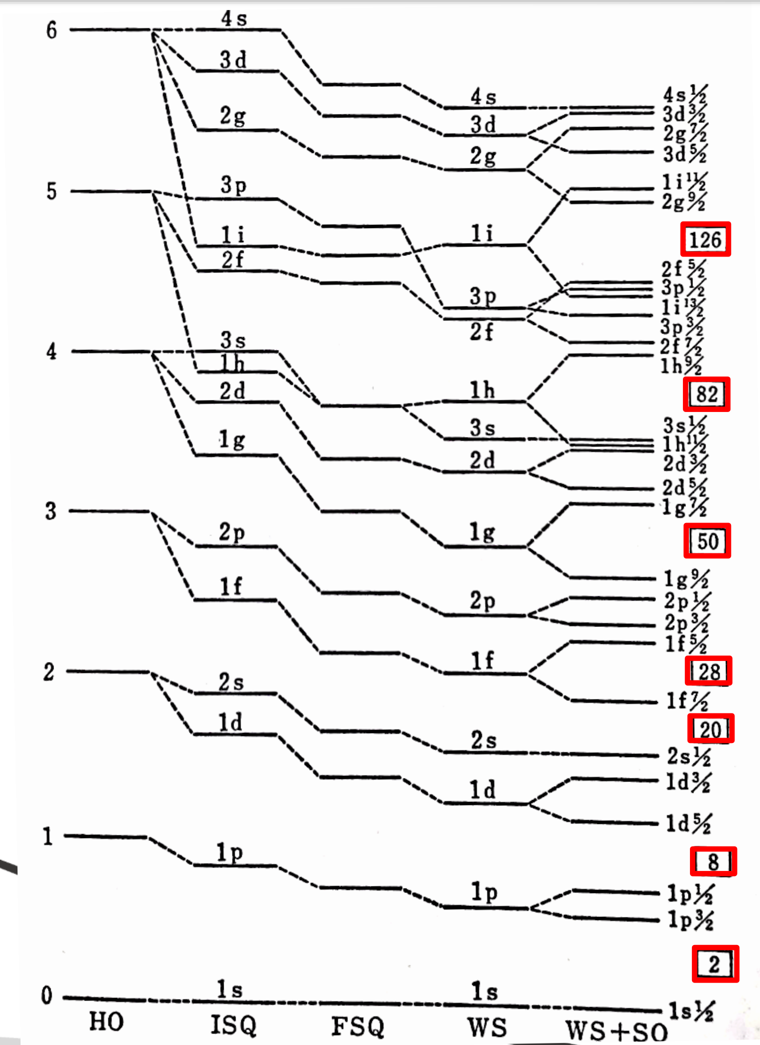
× No absolute mass information

energy spacing between nuclear state can be measured

Complementary to reaction spectroscopy

Nuclear structure and gamma-ray spectroscopy

Level scheme of single particle potential



朝倉書店　基礎物理化学シリーズ4
原子核物理　八木浩輔

w/ LS force

Existence of magic number

Large LS force ⇒ "Shell structure"

Studied (at near closed shell):
- Excitation and separation energy
- (Single) particle/hole state
- Spin and parity

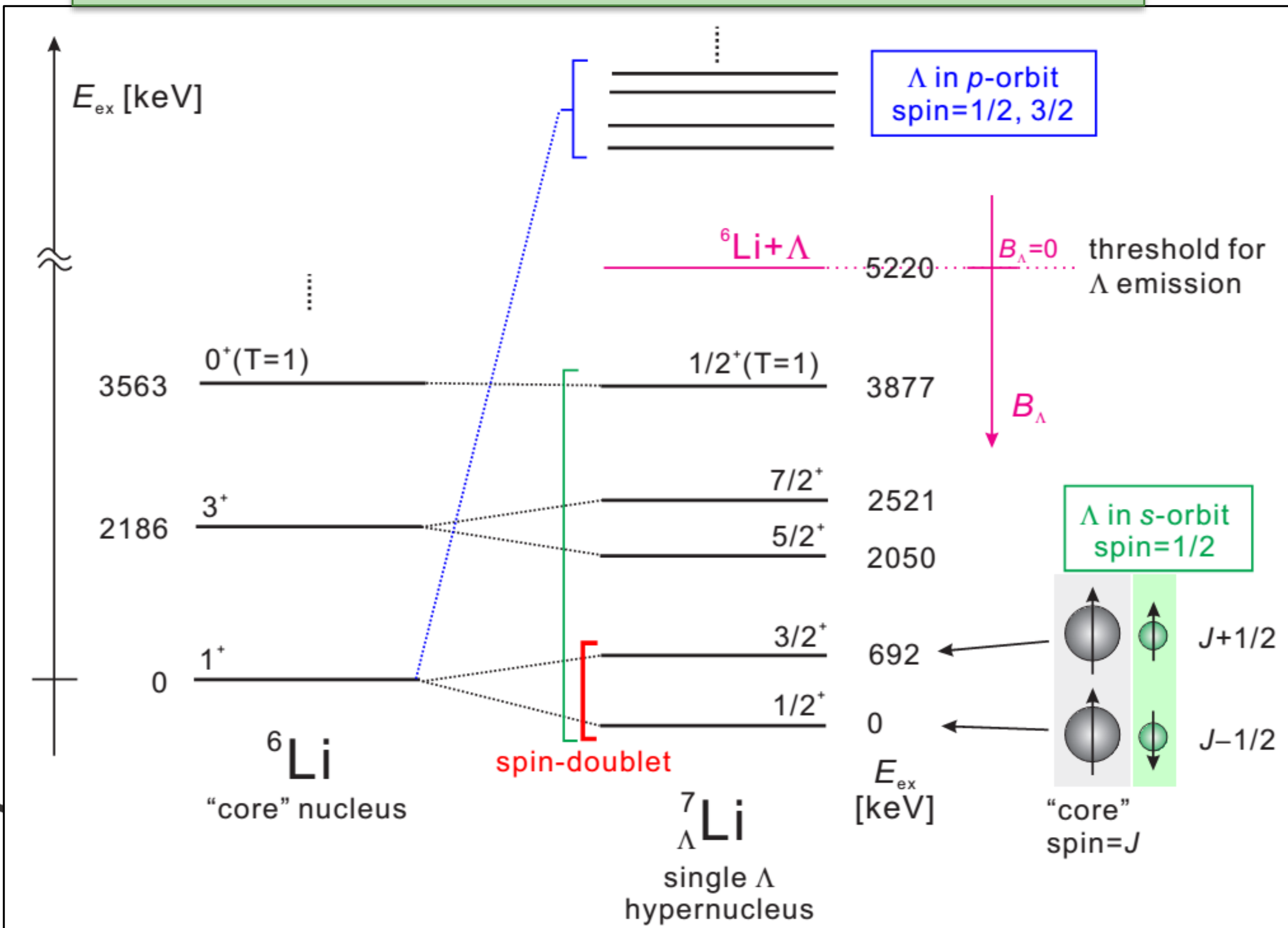
We introduce strangeness
to understand nucleon force
as baryon-baryon interaction

LS force in ΛN interaction (↔NN case)

- Asymmetric LS force
  (not exist in NN case)
- Forbidden ρ meson exchange
  (in meson exchange picture)

Hypernuclear structure and ΛN interaction

Level schema of $^{7}_{\Lambda}$Li and "core" nuclei



Spin-dependent
ΛN interaction
+
Combination of $S_{core} \cdot S_{\Lambda}$

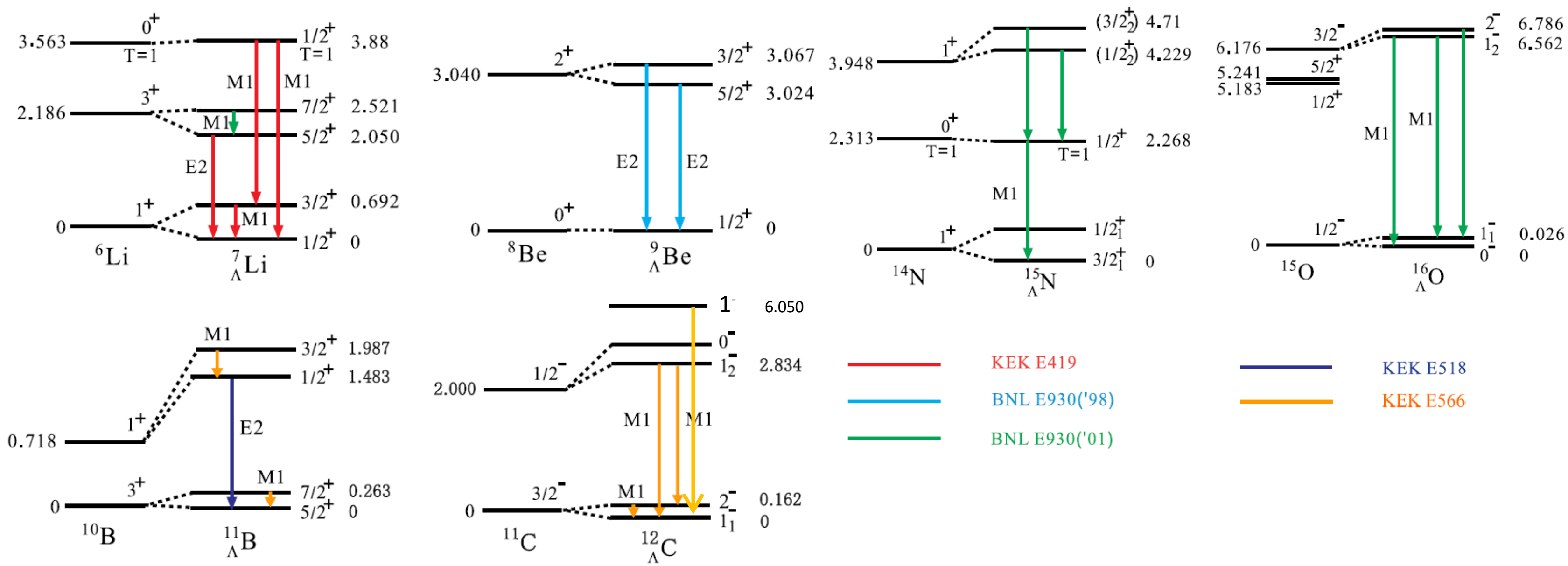
Spin-doublet structure
(energy spacing
: 10~1000 keV)

Precise gamma-ray spectroscopy using Ge detector
(2 keV energy resolution)

Hyperball project

Level scheme of *p*-shell hypernuclei

determined by Hyperball project @KEK, BNL



Strength of ΛN spin-dependent terms in *p*-shell

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\boldsymbol{s}_N \cdot \boldsymbol{s}_\Lambda + V_\Lambda(r)\boldsymbol{l}_{N\Lambda} \cdot \boldsymbol{s}_\Lambda + V_N(r)\boldsymbol{l}_{N\Lambda} \cdot \boldsymbol{s}_N + V_T(r)\boldsymbol{S}_{12}$$

< First step @J-PARC > → Done in J-PARC E13 [2013-2015]

- **Spin dependent-term in *s*-shell, *sd*-shell**
- **Charge symmetry breaking (CSB) effect in A=4 mirror hypernuclei**

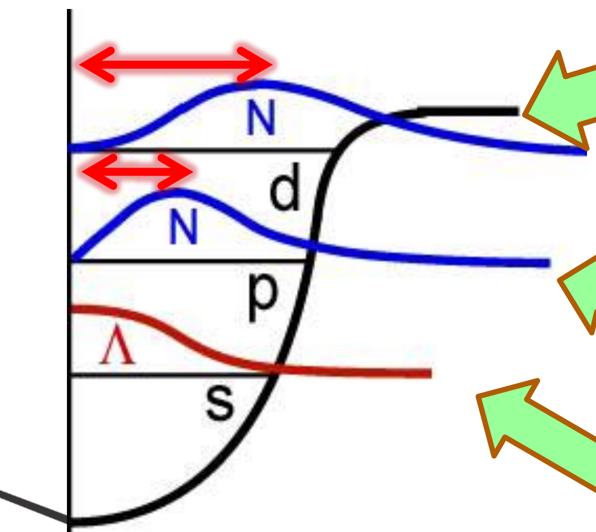
Study of spin-spin term in *s*-shell, *sd*-shell hypernuclei (J-PARC E13)

p-shell data [KEK, BNL]

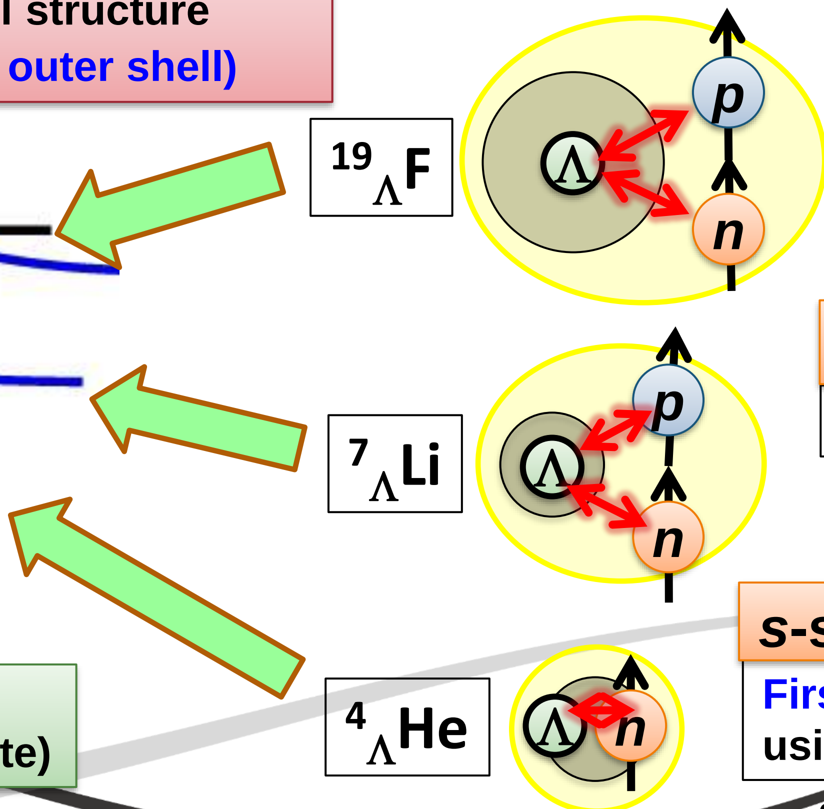
\+ *s*-shell, *sd*-shell data [J-PARC E13]

→**Radial dependence** of spin dependent interaction

Effect of spin-dependent interaction on hypernuclear level structure
Λ(s-shell) ↔ N(most outer shell)



Wave functions of Nucleon and Λ(s-state)



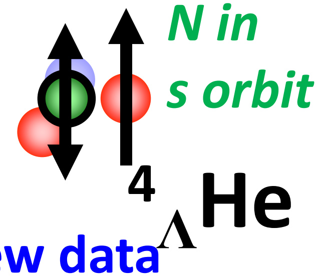
***sd*-shell**
First measurement in sd-shell hypernuclei
~0.3 MeV
E13

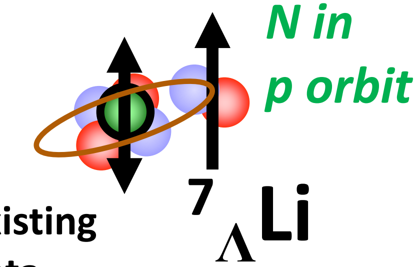
***p*-shell**
Studied in KEK exp.
~0.7 MeV

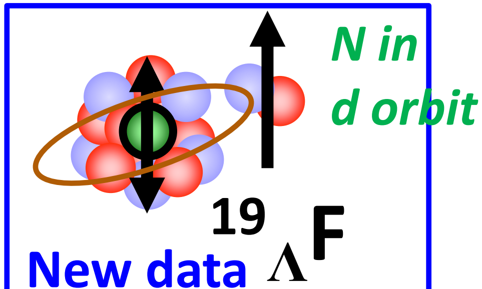
***s*-shell**
First precise measurement using Ge detector
~1 MeV
including large ΛΣ mixing effect
E13

Study of spin-spin term in *s*-shell, *sd*-shell hypernuclei (J-PARC E13)

First precise gamma-ray data for "not" p-shell hypernuclei

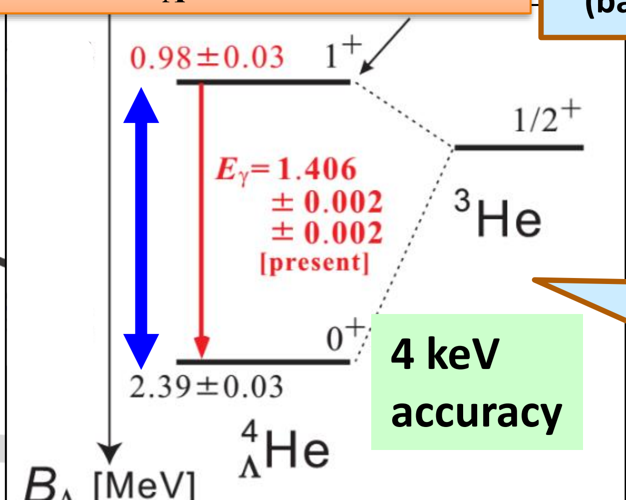






Consistent with shell model calc. w/ NSC int. model (based on *p*-shell knowledge)

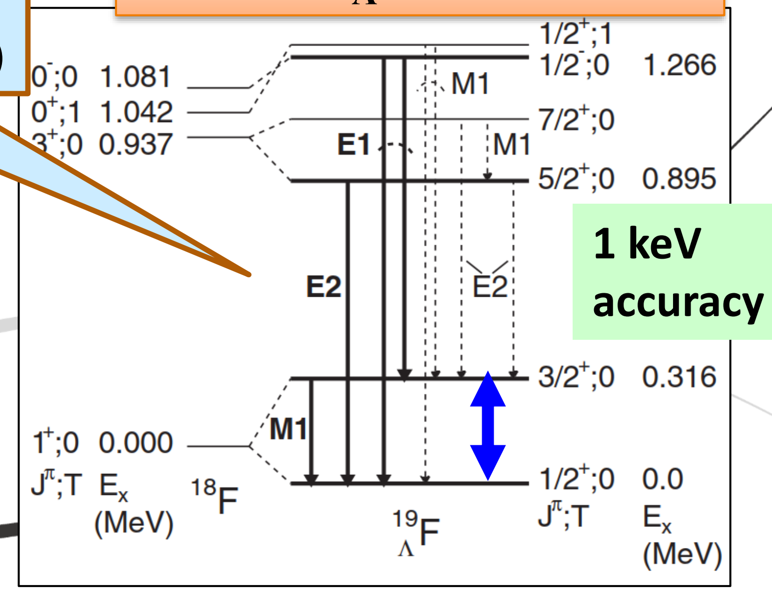
s-shell $^{4}_{\Lambda}$He level scheme



4 keV accuracy

Existence of CSB effect (*later mention*)

sd-shell $^{19}_{\Lambda}$F level scheme



1 keV accuracy

Contents

- Present status of gamma-ray spectroscopy of Λ hypernuclei
- **Prospect of future measurement**
  - **A=3 hypernuclei**

    study of ΛN-ΣN mixing effect
  - **s~p-shell neutron rich hypernuclei**

    study of charge symmetry breaking effect +ΛN-ΛΣ mixing
  - **medium~hevy hypernuclei**

    study of density dependence of ΛN interaction
- Summary

γ-ray spectroscopy exp. @ K1.1 beamline

Motivation of future measurements

- **ΛN-ΣN mixing effect (coupling)**

  - Significant effect on hypernuclear structure

  - Role of Λ in neutron star?

- Large effect in A=3 system? (as expected?)
  -> ${}^{3}_{\Lambda}$H γ-ray spectroscopy
- Relationship with CSB effect?
- How become smaller effect in A>4 hypernuclei? (as expected?)
  -> γ-ray spectroscopy of ${}^{4}_{\Lambda}$H and *p*-shell neutron rich hypernucalei

- **Density dependence of ΛN interaction**
- **Radial dependence of spin-dependent ΛN interaction** *(>sd-shell)*

Three body force?
eutron star?

-> High resolution reaction spectroscopy @HIHR
+ γ-ray spectroscopy for medium-heavy hypernuclei

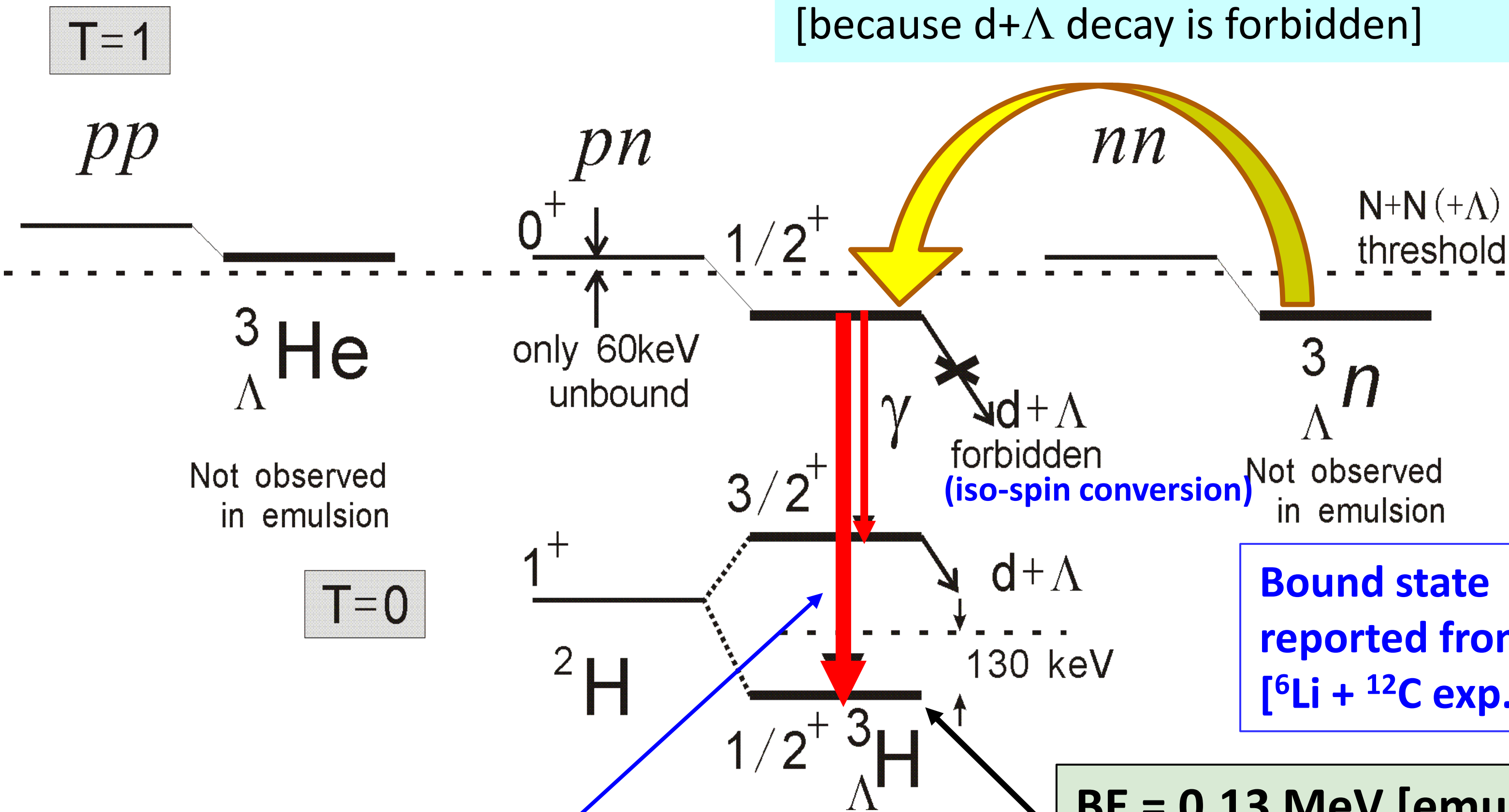
Future gamma-ray spectroscopy

A=3 hypernuclei

Study of ΛN-ΣN mixing effect

Present status of $^{3}_{\Lambda}$H

Same isospin group
→ $^{3}_{\Lambda}$H (1/2⁺, T=1) is particle bound state?
[because d+Λ decay is forbidden]



Bound state reported from GSI [^{6}Li + ^{12}C exp.]

BE = 0.13 MeV [emulsion]
BE = 0.41 MeV [STAR, 2019]

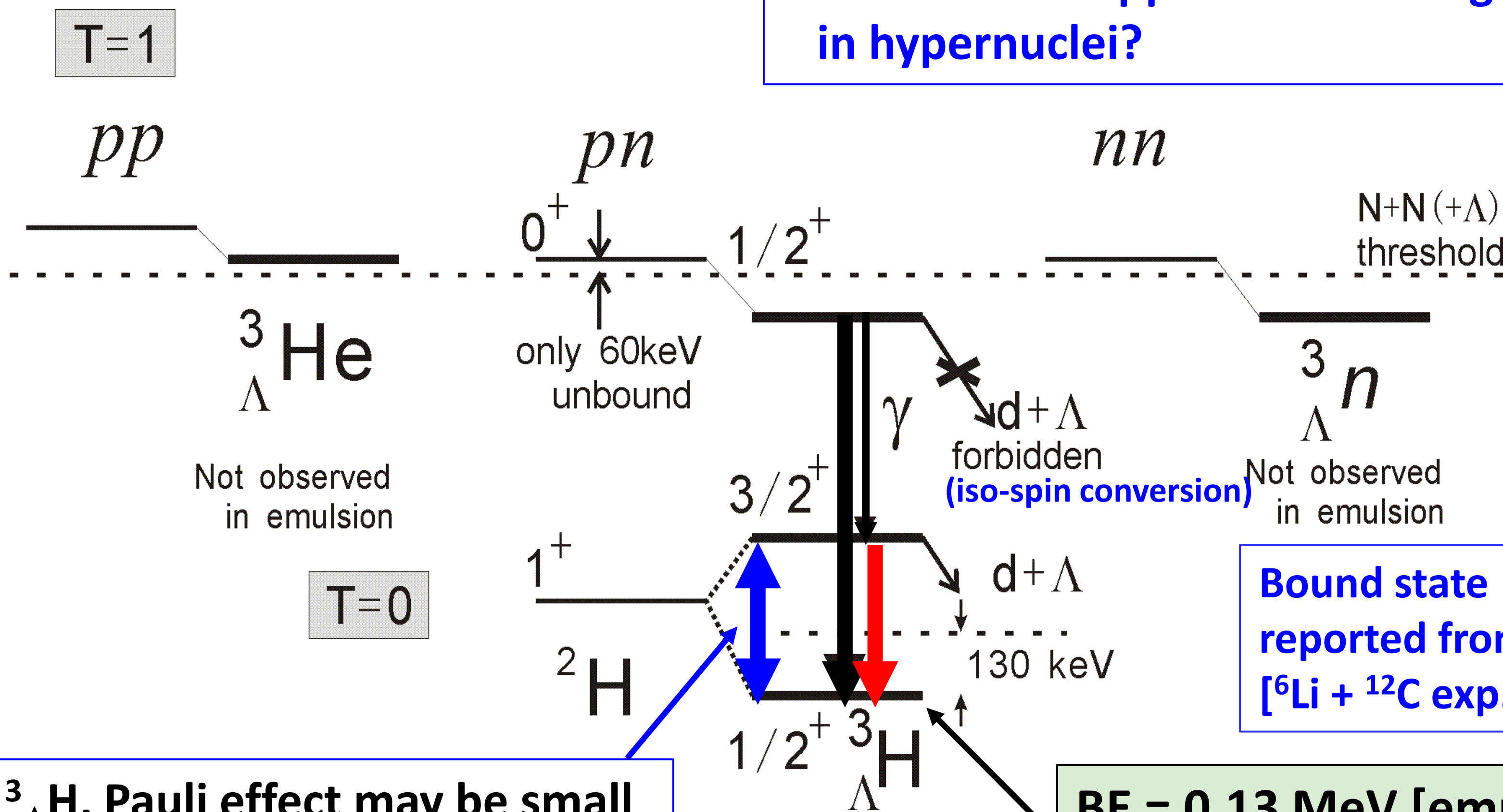
Deeper bound?

If $^{3}_{\Lambda}$H (1/2⁺, T=1) is particle bound state, we can observe γ transition (1/2⁺, T=1) → (1/2⁺)

We can test T=1 bound/unbound by gamma-ray spectroscopy

Present status of $^3_\Lambda$H

Recent lattice QCD and chiralEFT suggest attractive spin parallel channel [free space]
+ Pauli effect suppress $\Lambda\Sigma$ mixing in hypernuclei?



Bound state reported from GSI [^{6}Li + ^{12}C exp.]

In $^3_\Lambda$H, Pauli effect may be small
→ energy spacing may be small
[3/2+ state also bound??]

BE = 0.13 MeV [emulsion]
BE = 0.41 MeV [STAR, 2019]

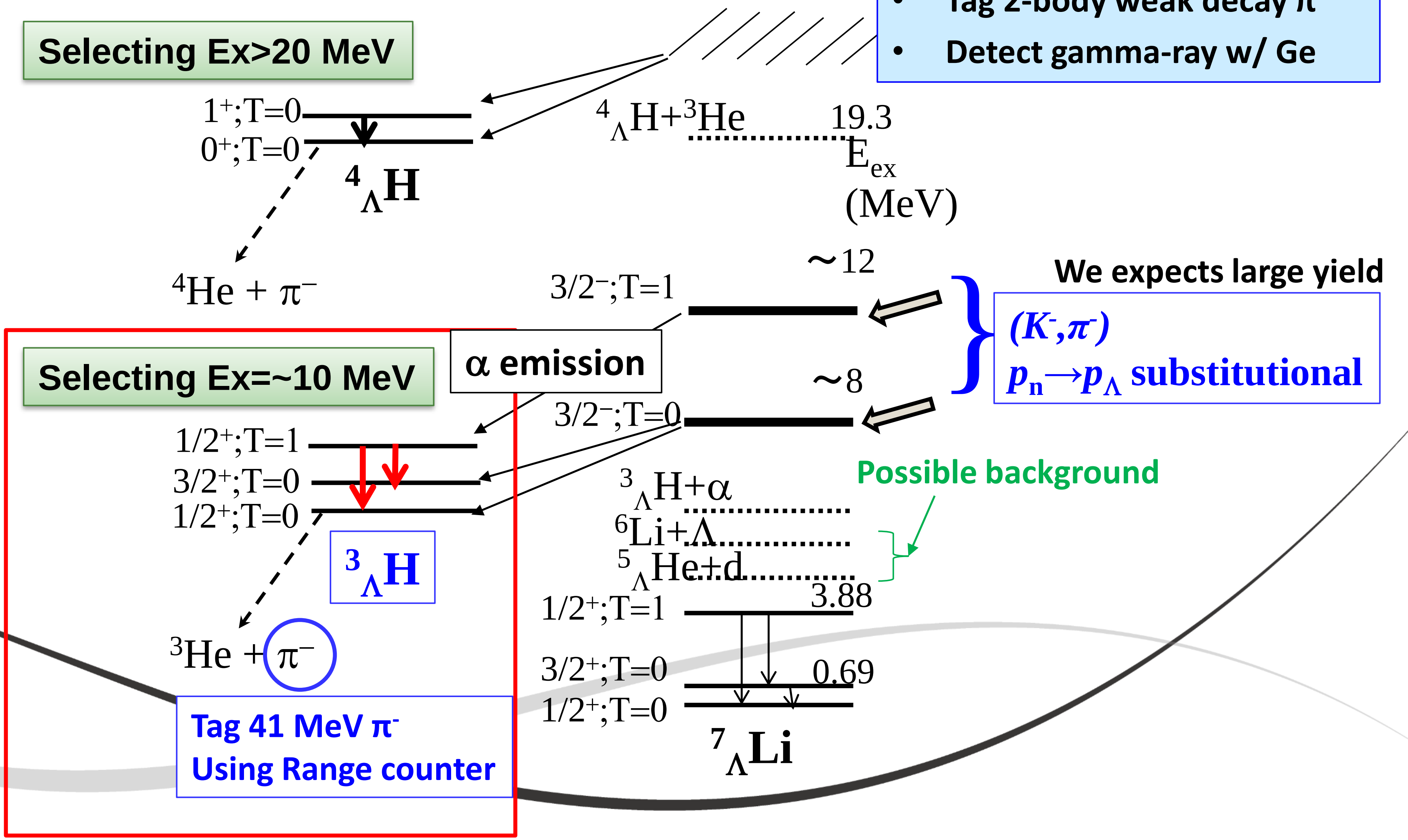
We can study role of $\Lambda\Sigma$ mixing effect form $^3_\Lambda$He g.s. spin doublet

Try γ-ray measurement!

$^{3}_{\Lambda}$H measurement

Method

- ^{7}Li target + (K^{-},π^{-}) reaction
  -> selecting unbound region
- Tag 2-body weak decay π^{-}
- Detect gamma-ray w/ Ge



Experimental setup @K1.1

J-PARC K1.1 beam line

0.8-1.1 GeV/c (K^-,π^-) reaction

- Large production cross-section
- Small Doppler broadening

（also good for hyperfragments）

reaction-γ coincidence experiment

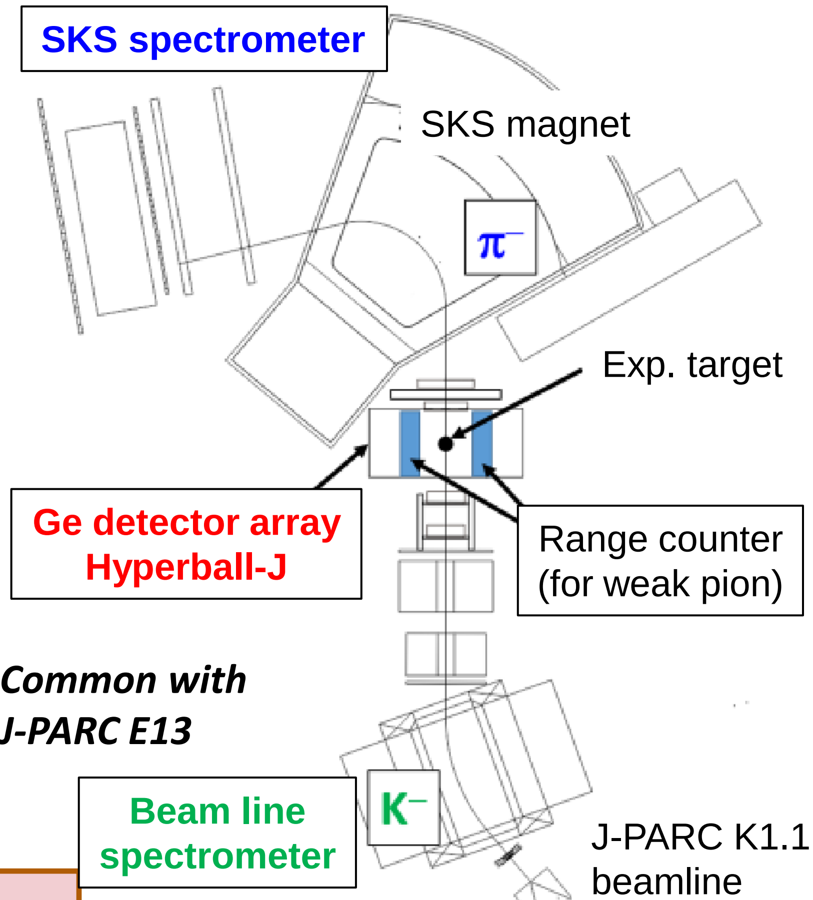
- Tag hypernuclear $({}^{7}_{\Lambda}Li^*)$ production
  - Beam line spectrometer
  - SksMinus spectrometer
- Detect γ–ray
  - Hyperball-J
- Tag weak decay π^-
  - Range counter

Under development

Common with J-PARC E13

Used for gamma–ray peak identification

Experimental setup



1 month beamtime
→ ~400 γ counts
(~40 π-γ coincidence)

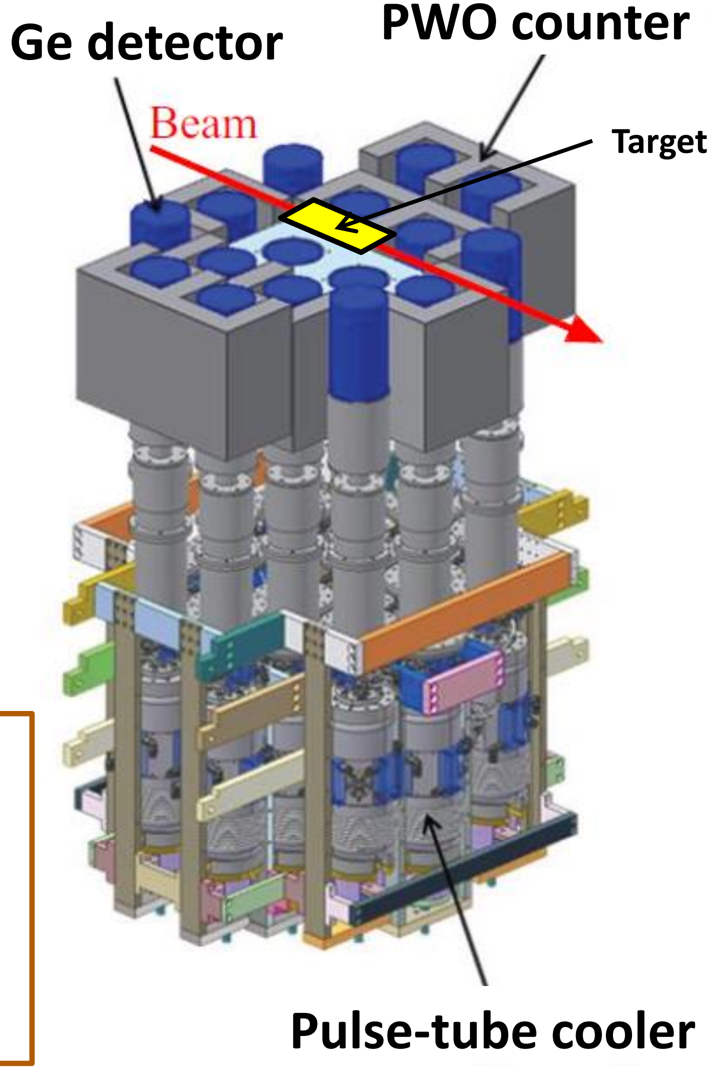
Hyperball-J new Ge detector array

Features

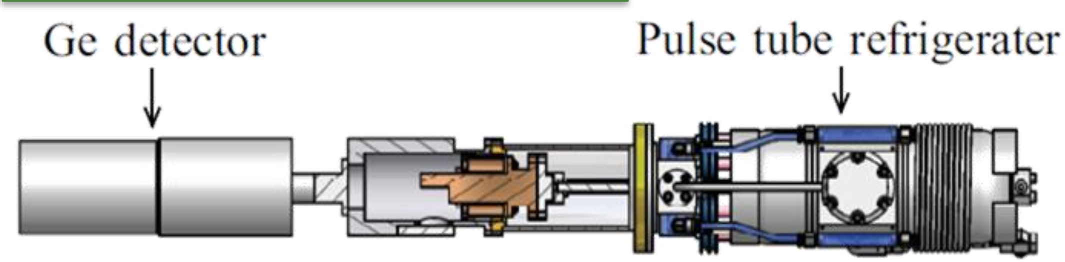
- Large photo-peak efficiency
  → ε ~6 % @1 MeV with 32 Ge detectors
- Fast readout system
- Low temp. Ge detector
  for radiation hardness
  → Mechanical cooling
- Fast background suppressor
  → PWO counter

} for high intensity hadron beam

Lower half of Hyperball-J



Developed Ge detector



Future gamma-ray spectroscopy

s~p-shell neutron rich hypernuclei

Study of CSB effect

+ Study of ΛN-ΣN mixing effect

CSB effect in A=4 mirror hypernuclei

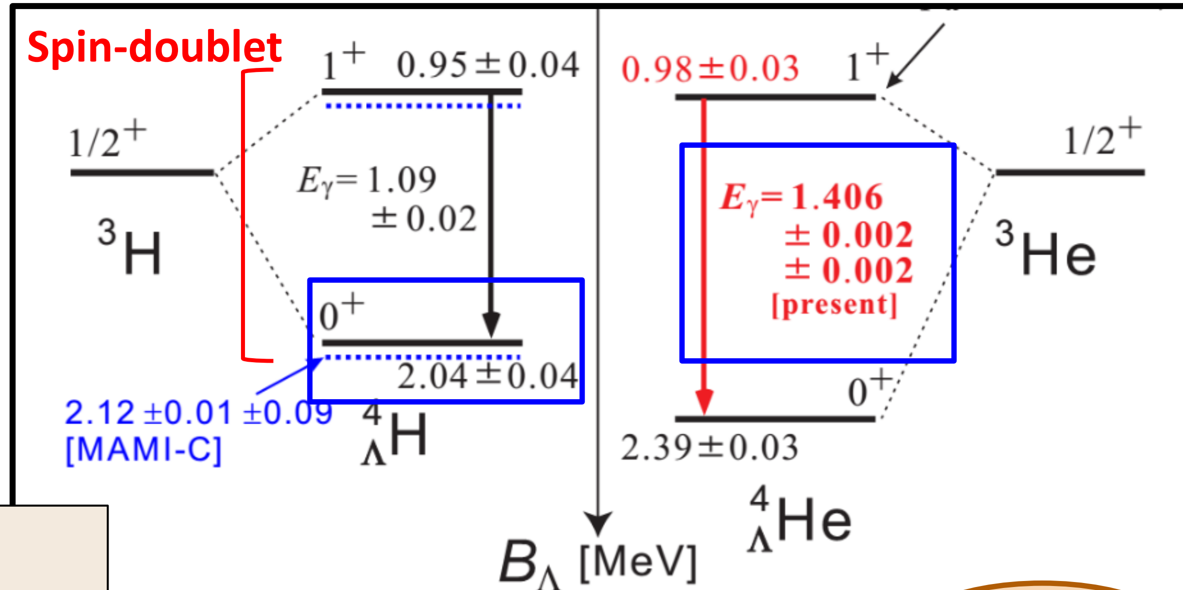
Large CSB effect was reported in 1960s

We are still finding origin.

- CSB effect was reported (only for A=4, so far)
- Few-body ab-initio calc. can be applied

We need solid exp. data w/ enough precision and reliability

$^4_\Lambda$H / $^4_\Lambda$He level scheme



$\Delta E_\gamma = E_\gamma(^4_\Lambda\mathrm{He})[\mathrm{Ge}] - E_\gamma(^4_\Lambda\mathrm{H})[\mathrm{NaI}]$

$= 0.32 \pm 0.02$ MeV

$B_\Lambda(0^+)$: emulsion data

+ $^4_\Lambda$H high resolution weak π spectroscopy[MAMI-C, 2015]

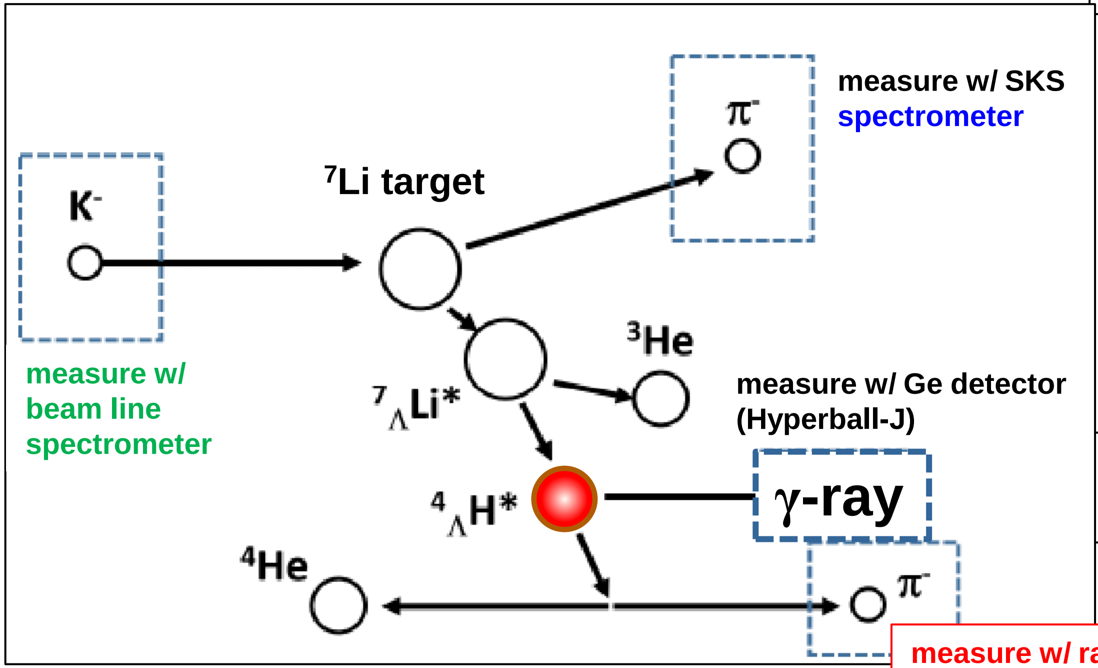
$E_x(1^+)$: γ-ray spectroscopy (NaI)

→ Need to update with precise measurement using Ge detector

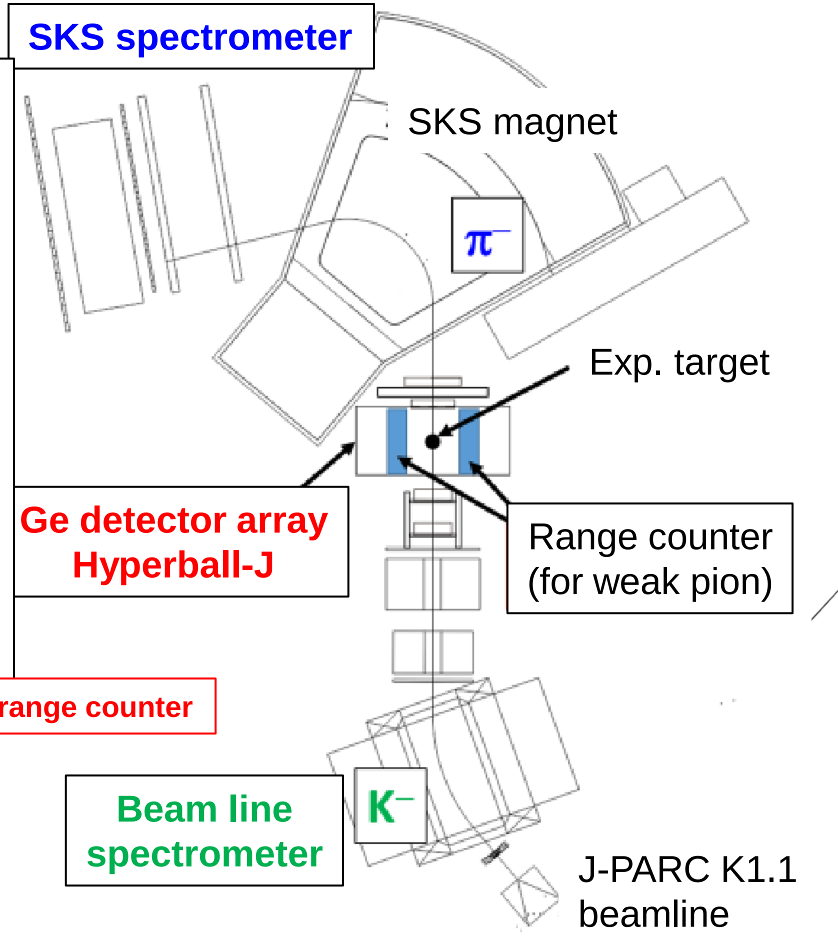
$^4_\Lambda$He [Done [E13, 2015]] -> Next step = $^4_\Lambda$H [J-PARC E63]

$^{4}_{\Lambda}H$ measurement @K1.1

Same method as $^{3}_{\Lambda}H$ measurement



Experimental setup

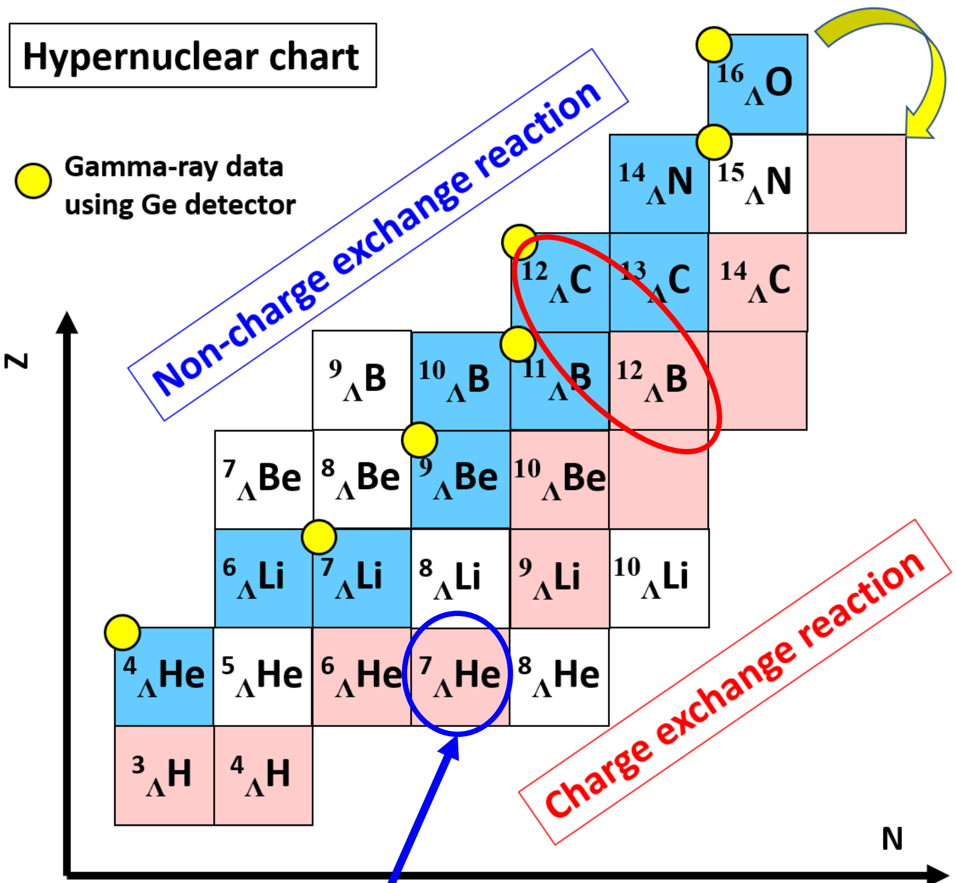


High probability for observation

- NaI data w/ same $^{7}Li(K^{-},\pi^{-})$ reaction
  [but not reported as $^{4}_{\Lambda}H$]
- Easy to tag weak decay π-
  because of uniquely high energy

6 days beamtime (J-PAR E63)
→ >300 γ counts [5 keV accuracy]

γ-ray spectroscopy of neutron rich hypernuclei



How strongly CSB effect apereas for A>4 hypernuclei?

-> may help to understand the origin

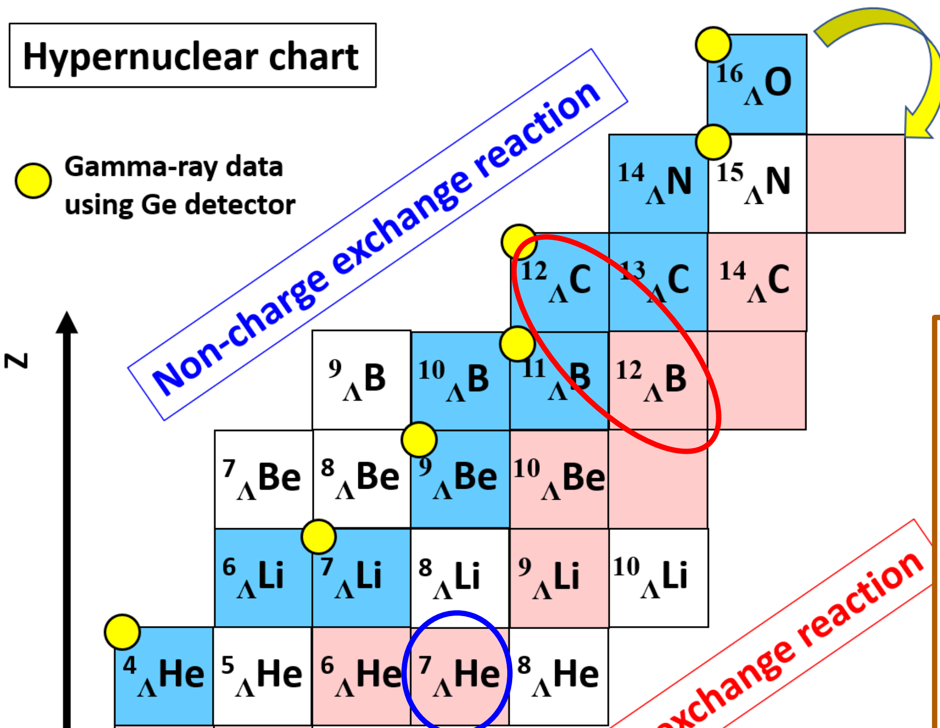
We only have precise data for **proton rich** hypernuclei produced by **"n→Λ reaction"**

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

Other neutron rich hypernuclei can be accessed

→ Help for study of ΛΣ mxing effect which will strongly appear in neutron rich hypernuclei

γ-ray spectroscopy of neutron rich hypernuclei



How strongly CSB effect apereas for A>4 hypernuclei?

-> may help to understand the origin

Non-charge exchange reaction

$$^{12}\mathrm{C}(\pi^{+}, K^{+})^{12}{}_{\Lambda}\mathrm{C}^{*} \longrightarrow {}^{12}{}_{\Lambda}\mathrm{C} + \gamma$$

Charge exchange reaction

$$^{12}\mathrm{C}(K^{-}, \pi^{0})^{12}{}_{\Lambda}\mathrm{B}^{*} \longrightarrow {}^{12}{}_{\Lambda}\mathrm{B} + \gamma$$

$$\pi^{0} \longrightarrow \gamma\gamma$$

$$^{12}\mathrm{C}(\pi^{-}, K^{0})^{12}{}_{\Lambda}\mathrm{B}^{*} \longrightarrow {}^{12}{}_{\Lambda}\mathrm{B} + \gamma$$

$$K^{0}{}_{s} \longrightarrow \pi^{+}\pi^{-} \ (69\%)$$

$$^{12}\mathrm{C}(e, e'K^{+})^{12}{}_{\Lambda}\mathrm{B}^{*} \longrightarrow {}^{12}{}_{\Lambda}\mathrm{B} + \gamma$$

Advantage in γ-ray spectroscopy

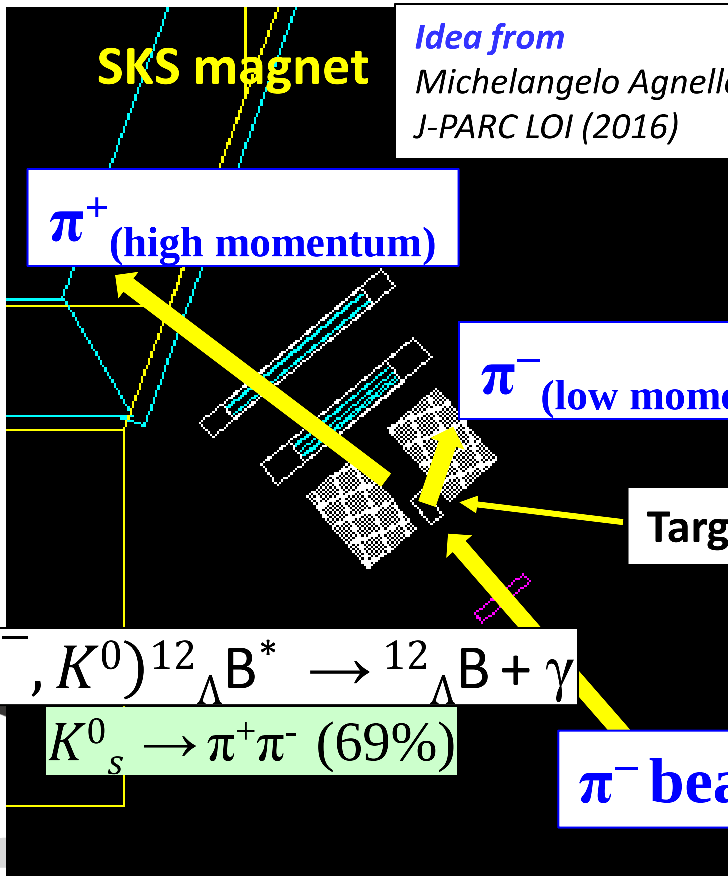
- **Charged particle detection only**
  [no need to use huge volume detector]
- **Acceptable beam rate for**
  good balance of Ge operation and yield

Measurement of neutron rich hypernuclei

Same setup with $^{4}_{\Lambda}$H measurement

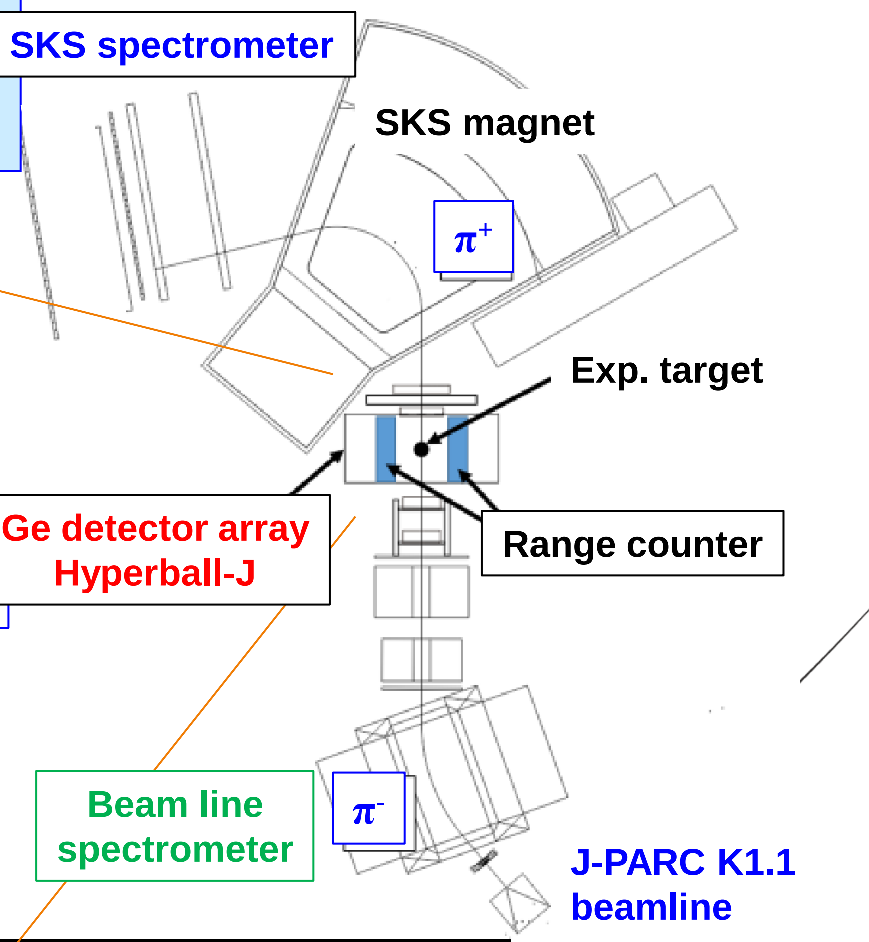
- High momentum π^+ → SKS
- Low momentum π^- → Range counter

Idea from
Michelangelo Agnello et al.
J-PARC LOI (2016)



$$^{12}C(\pi^-, K^0)^{12}_{\Lambda}B^* \rightarrow {}^{12}_{\Lambda}B + \gamma$$

$$K^0_s \rightarrow \pi^+\pi^- \ (69\%)$$



Design work on-going

~100 γ counts w/ several month [$^{12}_{\Lambda}$B]

Future gamma-ray spectroscopy

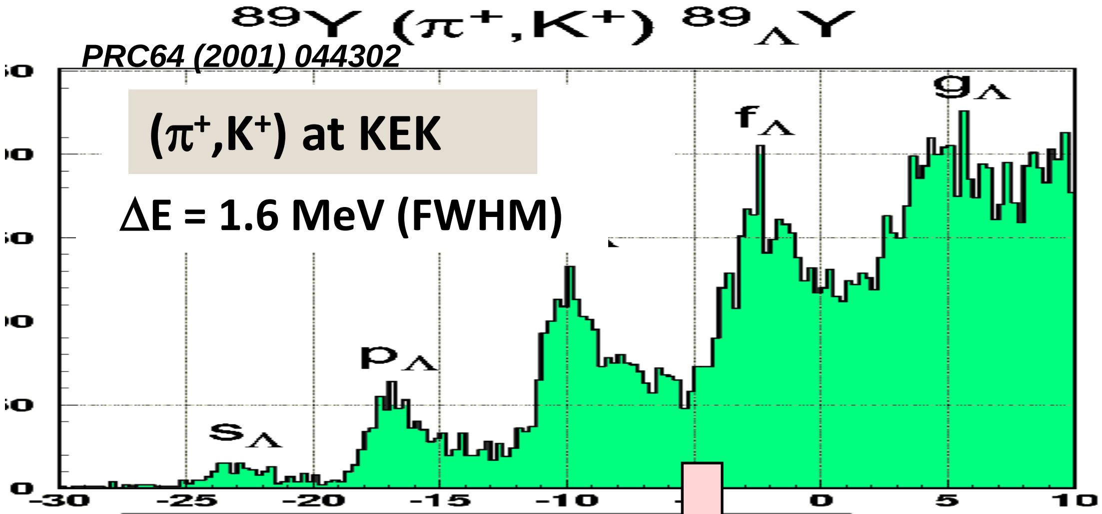
Medium-heavy hypernuclei

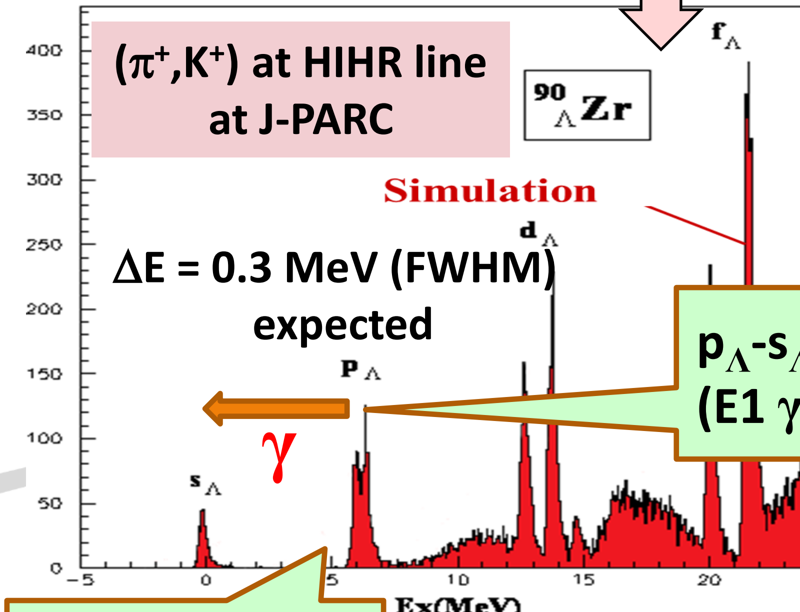
Study of density dependent ΛN int.

Reaction and γ-ray spectroscopy of medium-heavy hypernuclei

High resolution reaction spectroscopy at HIHR [BE accuracy 0.1 MeV]

Study of density dependence of ΛN interaction





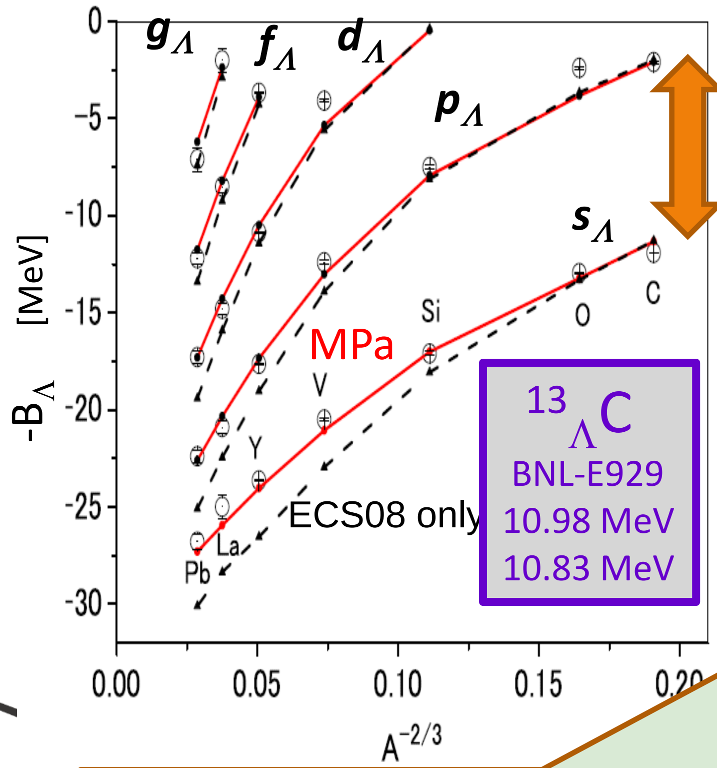
Gamma-ray data may help

- spin splitting measurement
  - -> reaction data to spin-averaged BE data
- E1 γ transition energy
  - -> "another barometer" for density dependence

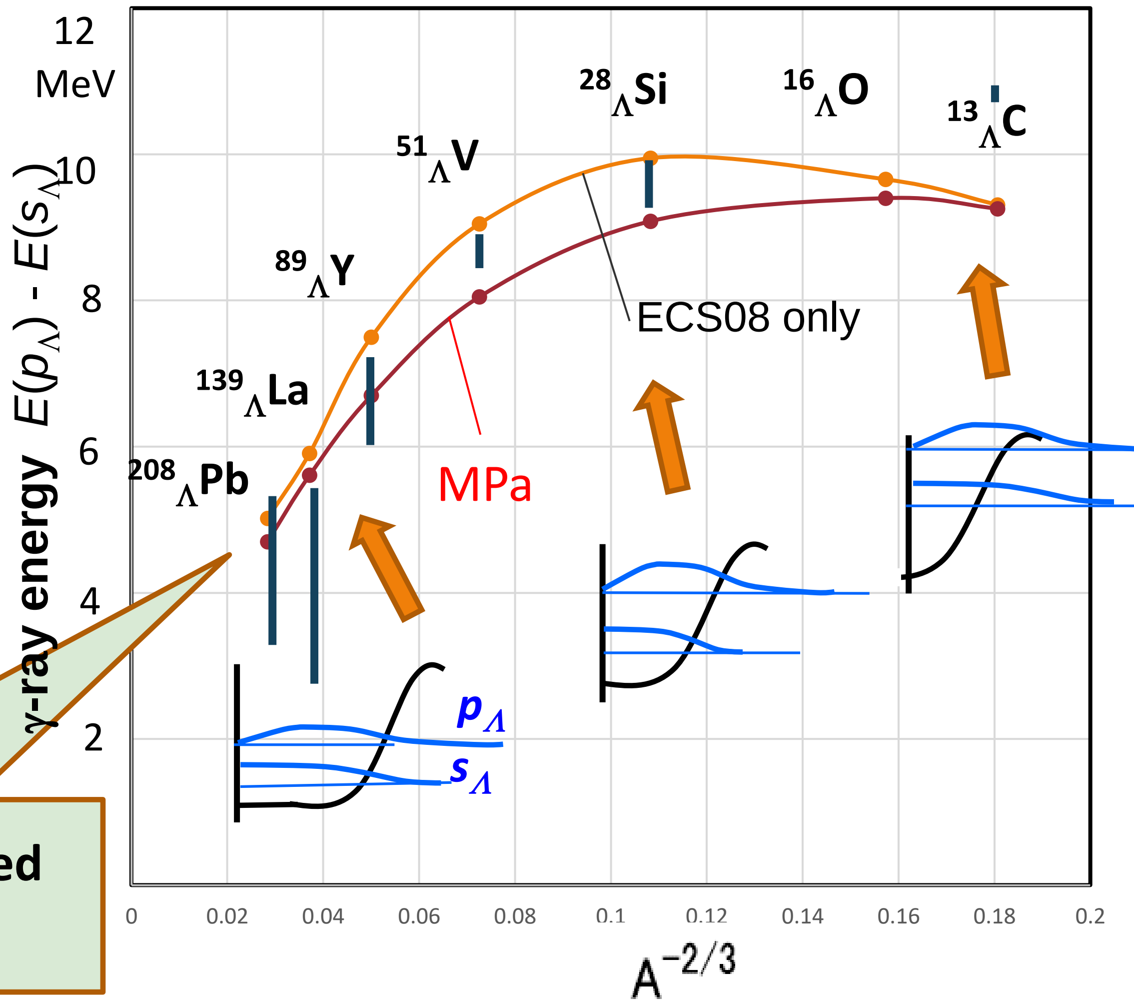
Study of density dependence from p_Λ-s_Λ energy spacing measurement

A dependence of BE [rection spectroscopy]

M.M.Nagel, et. al. Phys. Rev. C99 044003



A dependence of p_Λ-s_Λ energy spacing



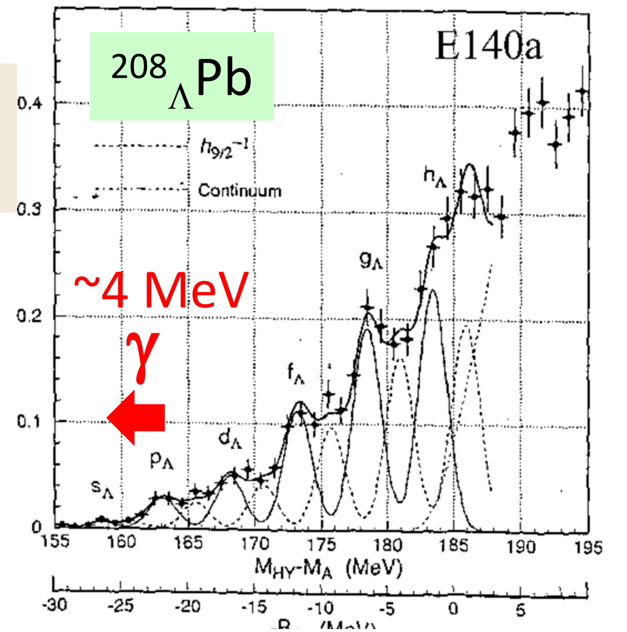
A few keV data can be obtained from E1 γ measurement

gamma-ray spectroscopy of medium-heavy hypernuclei

$^{28}{}_{\Lambda}$Si, $^{40}{}_{\Lambda}$Ca, $^{51}{}_{\Lambda}$V, $^{89}{}_{\Lambda}$Y, $^{139}{}_{\Lambda}$La, $^{208}{}_{\Lambda}$Pb

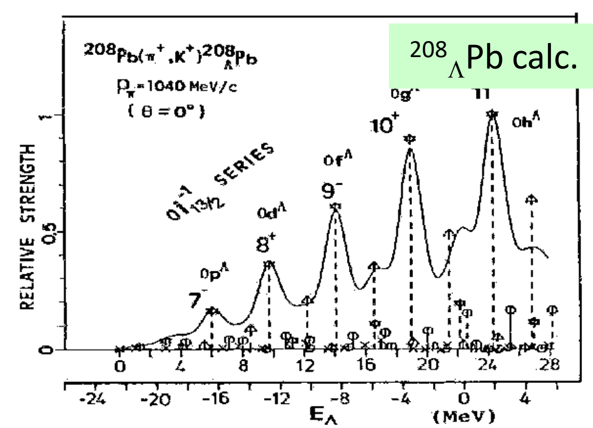
(K^-,π^-) 1.1 GeV/c @K1.1 line
>100 kW, Total ~ 7 weeks

^{208}Pb(π^+,K^+)$^{208}_{\Lambda}$Pb, p_π = 1.06 GeV/c
Hasegawa et al., PRC 53 (1996) 1210



Motivation :

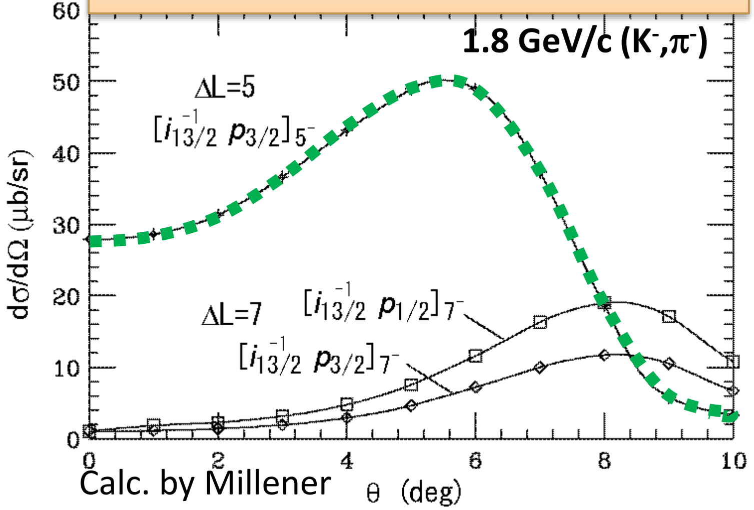
- <u>spin splitting (for both s_Λ- and p_Λ- state)</u>
  - Support reaction spectroscopy data
    -> Density dependence of ΛN interaction
  - Radial dependence of
    spin-dependent of ΛN interaction
  - Study of Nuclear LS splitting
    - *Effect of one pion exchange?*
    - *ΛΣ mixing and tensor force for many body effect?*



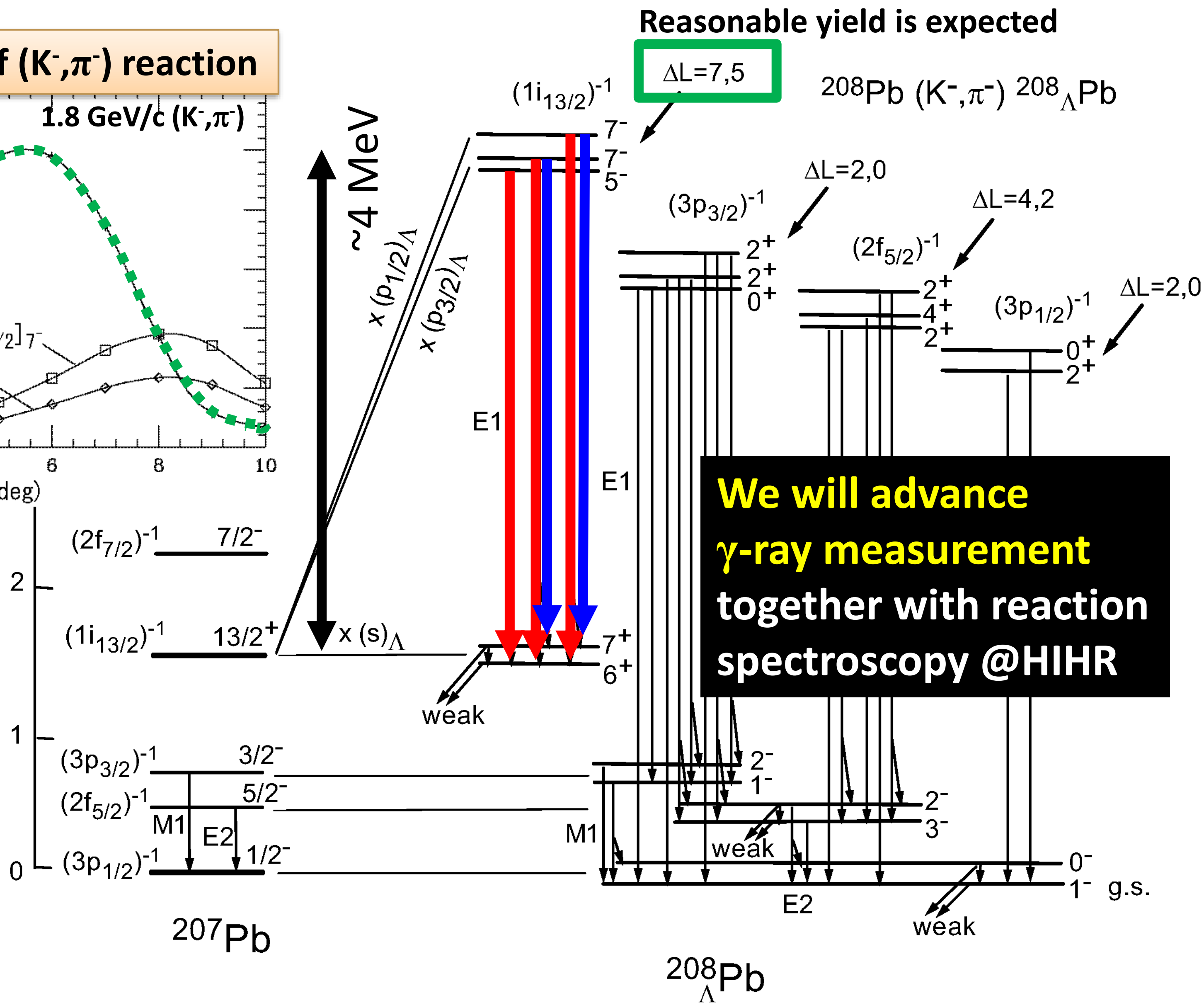
- <u>p_Λ-s_Λ energy spacing</u>
  - "Another barometer" for study of
    density dependence of ΛN interaction

$^{208}{}_{\Lambda}$Pb gamma-ray spectroscopy

Cross-section of (K$^-$,π^-) reaction



Calc. by Millener



15 days at K1.1 @120 kW

Expected accuracy = 1 keV

from J-PARC LOI

We will advance γ-ray measurement together with reaction spectroscopy @HIHR

Summary

- **Present status of hypernyclear γ-ray spectroscopy**
  - *spin-dependent ΛN force was studied in s, p, sd-shell*
  - *Existence of CSB effect in A=4*

- **Future measurements**

  γ-ray spectroscopy exp. @ K1.1 beamline

  - **$^{3}_{\Lambda}H$ measurement**

    Study of ΛN-ΣN mixing effect

  - **s~p-shell neutron rich hypernuclei**

    [$^{4}_{\Lambda}H$ and $^{12}_{\Lambda}C$ at early phase]

    Study of CSB + ΛN-ΛΣ mixing effect

  - **Mediun-heavy hyper nuclei**

    Study of density dependence of ΛN interaction