Future gamma-ray spectroscopic experiment (J-PARC E63) on $^{4}_{\Lambda}H$

2018/6/26

T. O. Yamamoto

KEK IPNS (Japan)

for the E63 collaboration

Contents

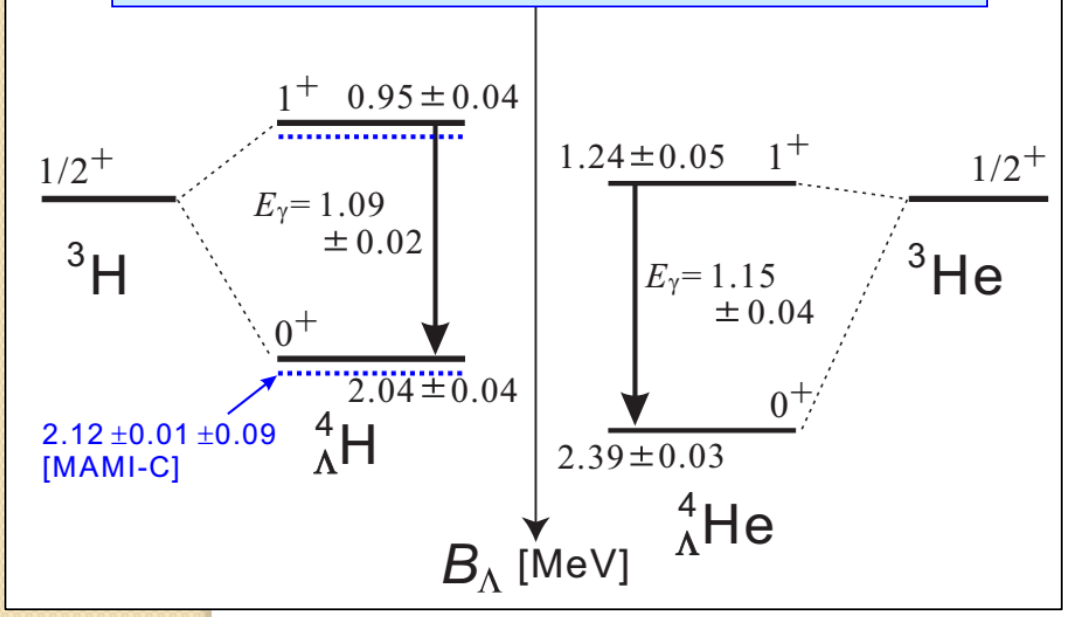
- **CSB in *s*-shell hypernuclear system studied via γ-ray spectroscopy**
  - γ-ray spectroscopy on $^{4}_{\Lambda}$He (J-PARC E13)
- **Next step: γ-ray spectroscopy on $^{4}_{\Lambda}$H (J-PARC E63)**
  - Previous studies on $^{4}_{\Lambda}$H
  - Strategy of new measurement
  - Present status
- **Idea of future experiment**

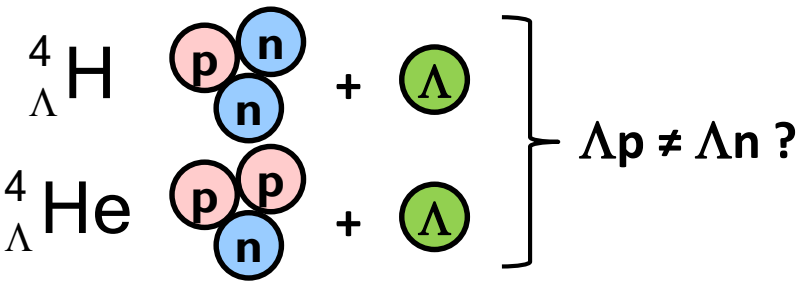
  γ-ray spectroscopy of *p*-shell mirror hypernuclei $^{12}_{\Lambda}$B

- **Summary**

CSB effect in s-shell hypernuclear structure

Level schema of mirror hypernuclei
$^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He (before 2014)





ΔB_{Λ} (0⁺) = 0.35 MeV
ΔB_{Λ} (1⁺) = 0.28 MeV

$B_{\Lambda}(0^{+})$: emulsion technique

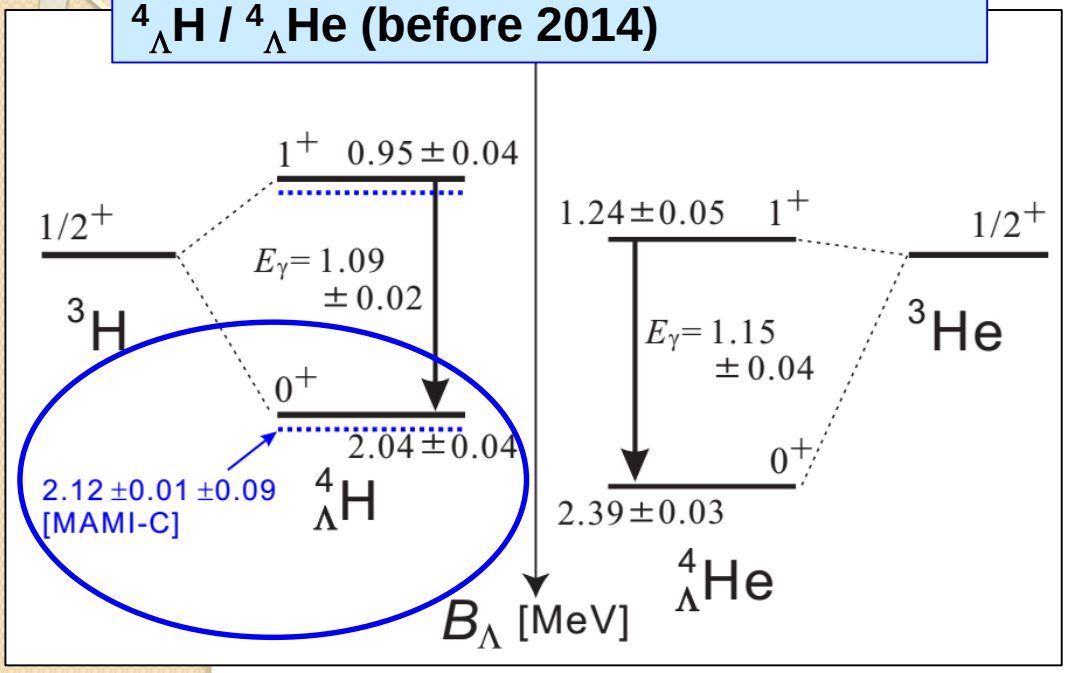
$E_{x}(1^{+})$: γ-ray spectroscopy (NaI)

Un expectedly large B_{Λ} difference
(0.07 MeV in theoretical study with NSC interaction model)

→ **Need to examine old data with modern technique**

Recent experiment for s-shell

Level schema of mirror hypernuclei $^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He (before 2014)



Precise measurement

Emulsion → Decay π^- spectroscopy

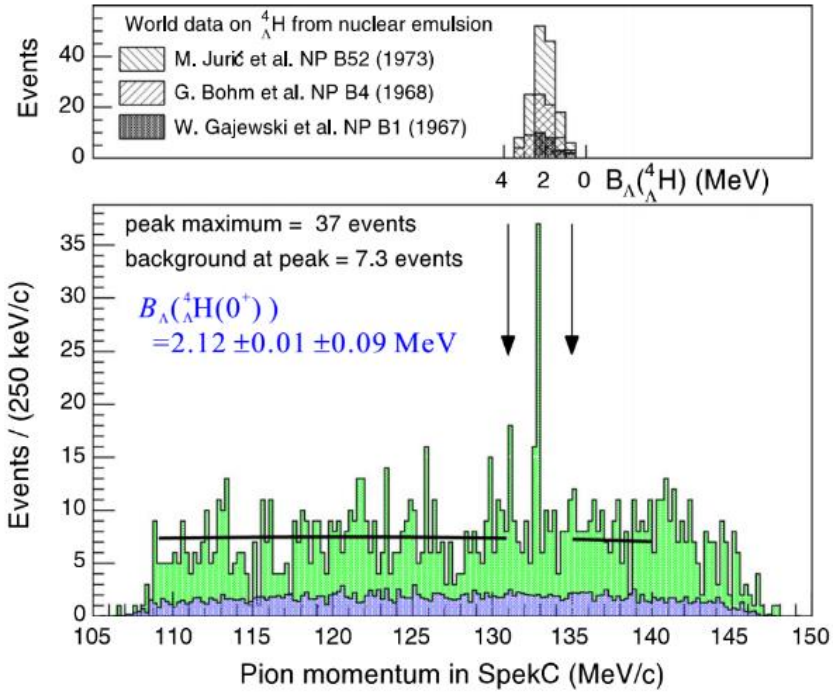
The result supports existence of CSB effect in $B_{\Lambda(g.s.)}$

$B_{\Lambda}(^{4}_{\Lambda}H(0^{+}))$, 2015 (MAMI-A1)

2.157 ± 0.077 MeV

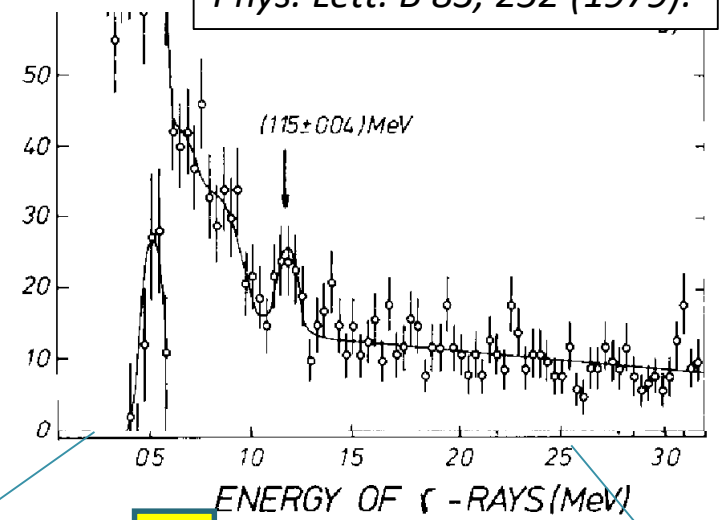
(chance to reduce systematic errors)

A. Esser, S. Nagao et al.,
Phys. Rev. Lett. 114, 232501 (2015)
A1 collaboration., NPA 954 (2016) 149

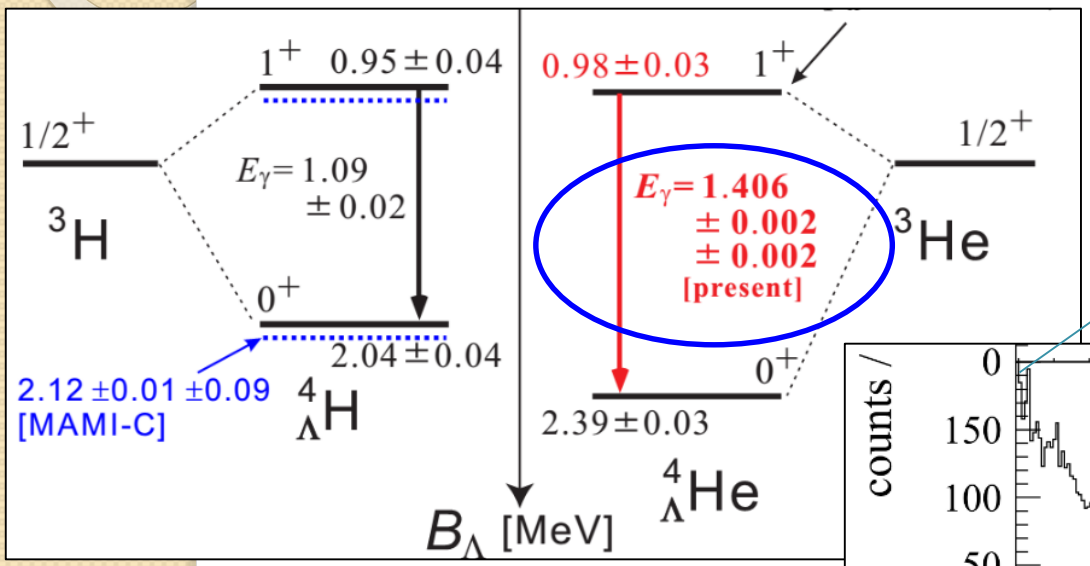


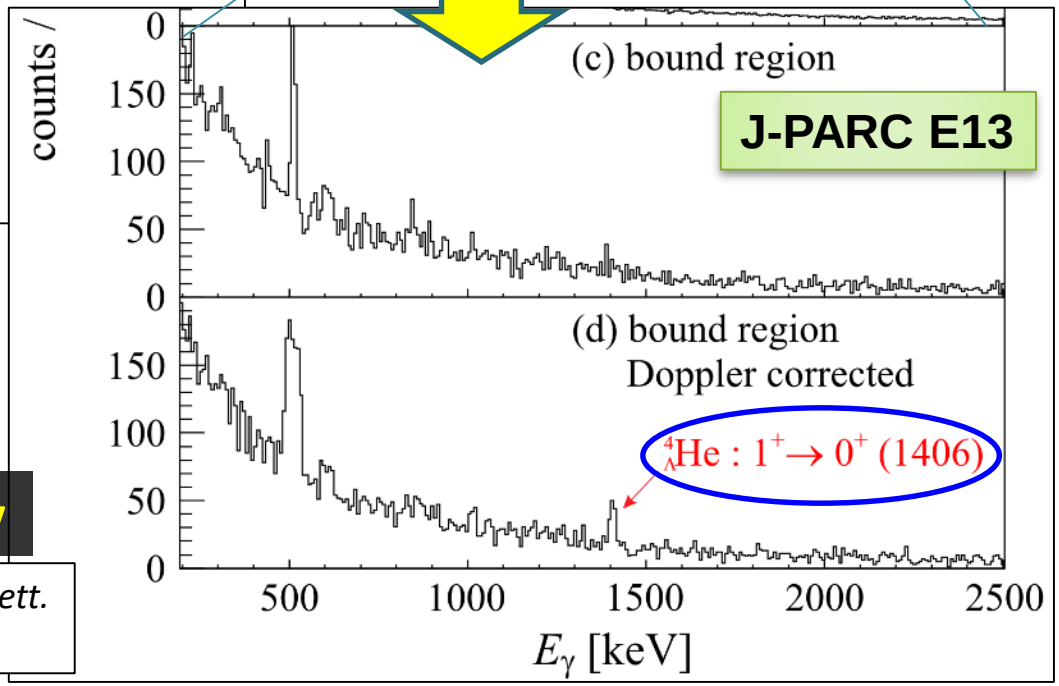
Recent experiment for s-shell

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



Level schema of mirror hypernuclei
$^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He **Updated**





1.406 ± 0.004 MeV

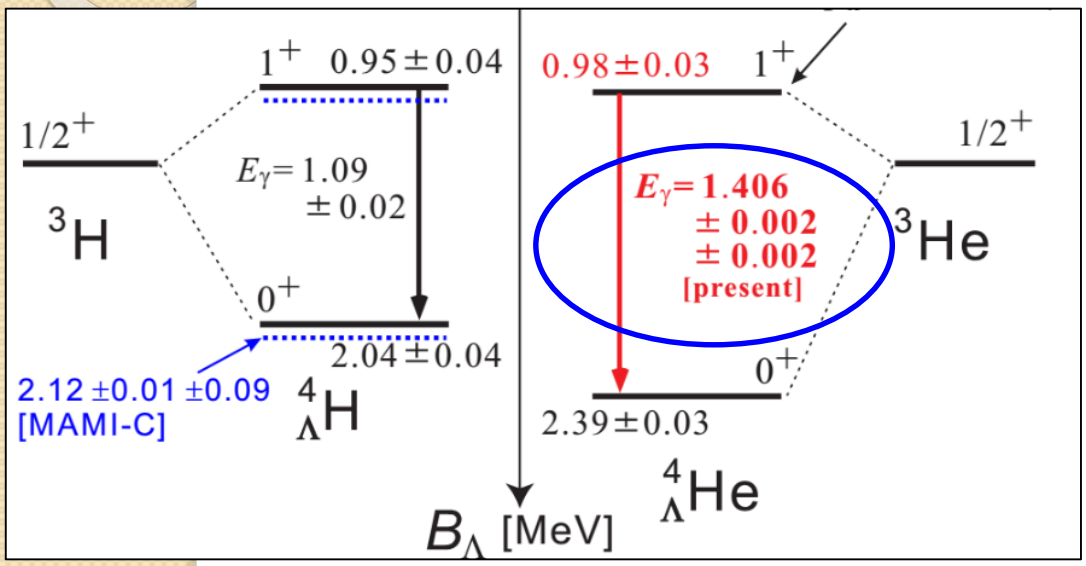
In flight (K-,π-) reaction w/ SKS + Ge detector

CSB effect also in excitation energy

T. O. Yamamoto et al., Phys. Rev. Lett. 115, 222501 (2015)

Recent experiment for s-shell

Level schema of mirror hypernuclei
$^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He **Updated**



- **Existence of CSB effect was confirmed ($B_{\Lambda(g.s)}$ and γ-ray)**
- **Strongly spin-dependent : $\Delta B_{\Lambda}(1^{+}) = 0.03 \pm 0.05$ MeV**

  $\Delta B_{\Lambda}(0^{+}) = 0.35 \pm 0.05$ MeV

Recent experiment for s-shell

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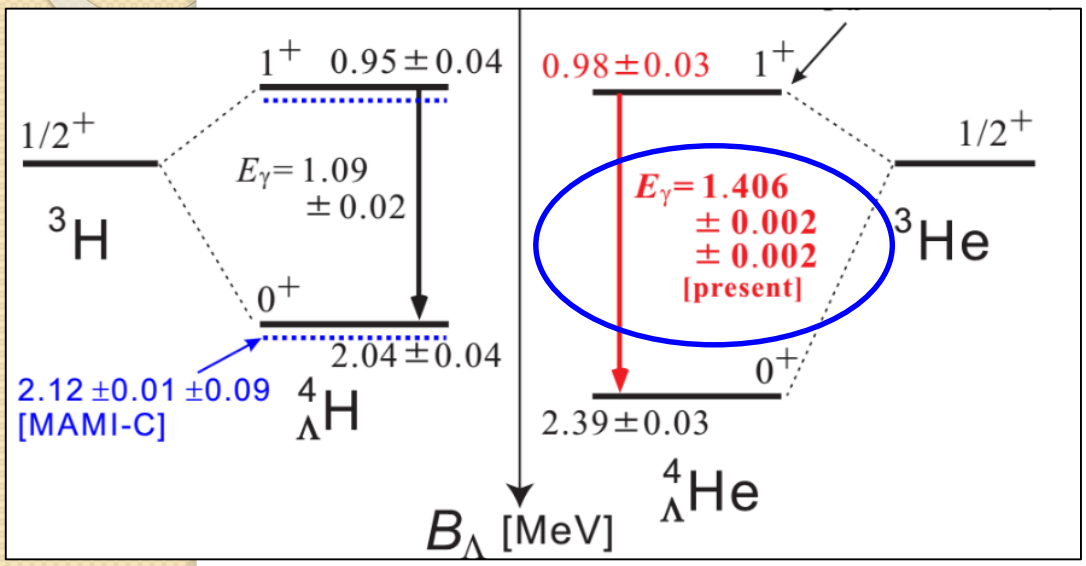


Need high accurate data to investigate origin of CSB and underlying ΛN interaction

Precise γ-ray spectroscopy is powerful tool to study CSB

We will continue measurement using Ge detector

- **Existence of CSB effect was confirmed ($B_{\Lambda(g.s)}$ and γ-ray)**
- **Strongly spin-dependent : $\Delta B_{\Lambda}(1^{+}) = 0.03 \pm 0.05$ MeV**
  $\Delta B_{\Lambda}(0^{+}) = 0.35 \pm 0.05$ MeV

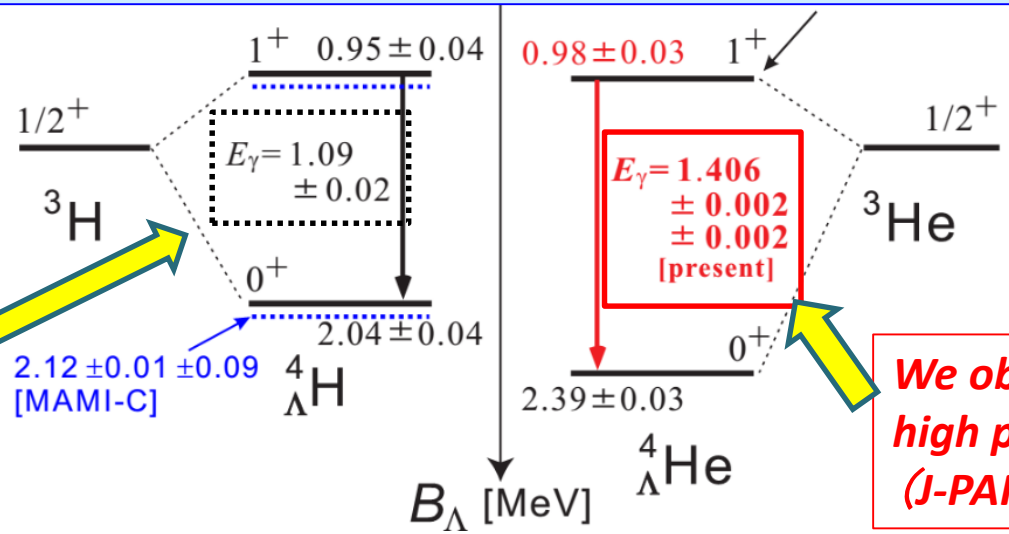
Future measurement

Gamma-ray spectroscopy on $^{4}_{\Lambda}H$

(J-PARC E63)

Gamma-ray data on $^{4}_{\Lambda}$H

Level schema of mirror hypernuclei $^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He

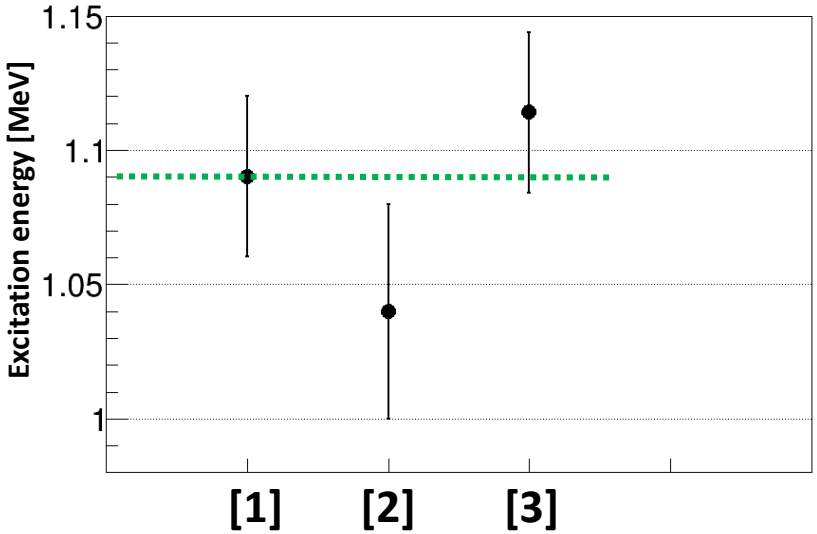


Three old data are available

We obtained high precision data (J-PARC E13)

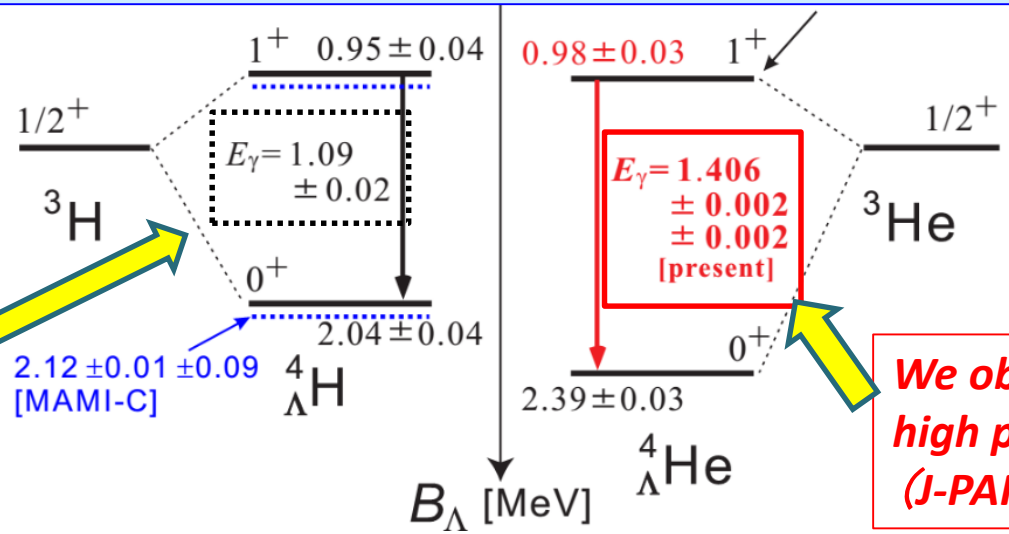
	$^{4}_{\Lambda}$H($1^+ \rightarrow 0^+$)
[1] M. Bedjidian *et al.* (1976)	1.09 ±0.03
[2] M. Bedjidian *et al.* (1979)	1.04 ±0.04
[3] A. Kawachi (1997)	1.114 ±0.030
Weighted average	1.09 ±0.02

rather large deviation



Gamma-ray data on $^{4}_{\Lambda}$H

Level schema of mirror hypernuclei $^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He



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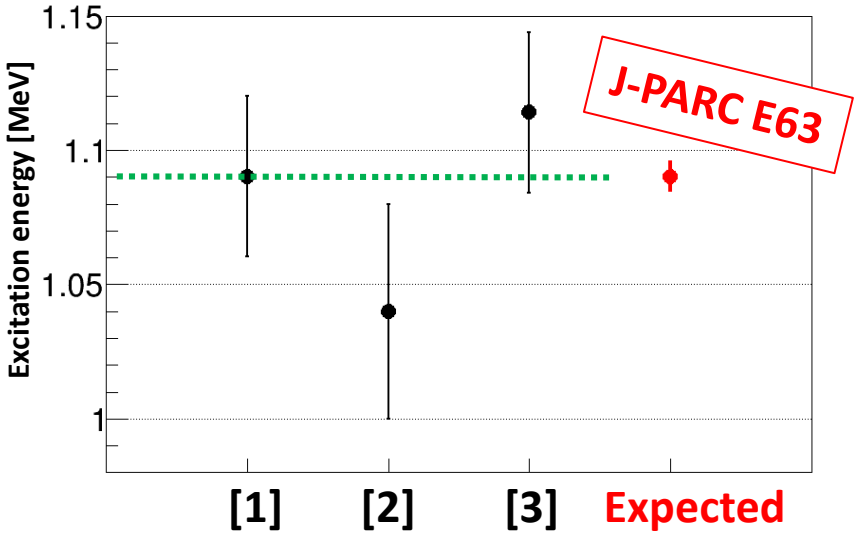
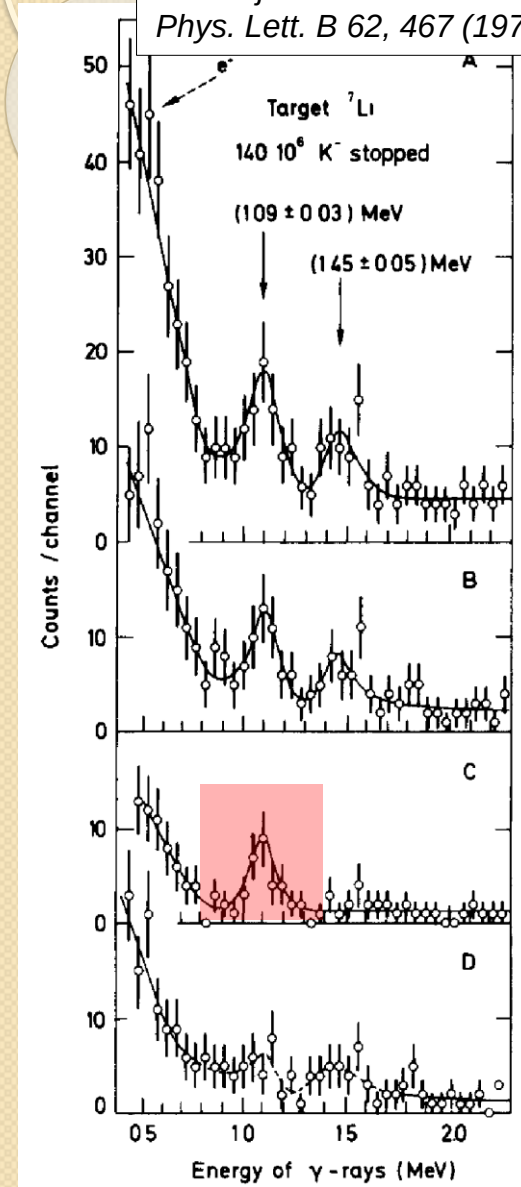


Limitation on old measurement

M. Bedjidian et al.
Phys. Lett. B 62, 467 (1976).



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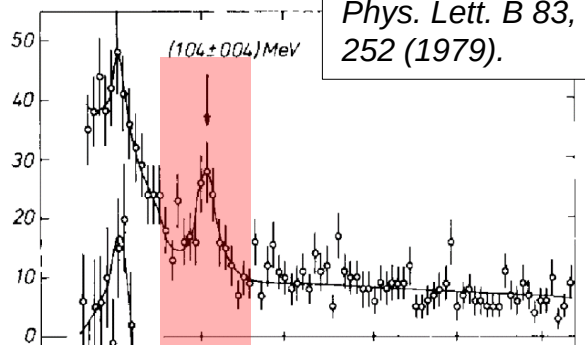
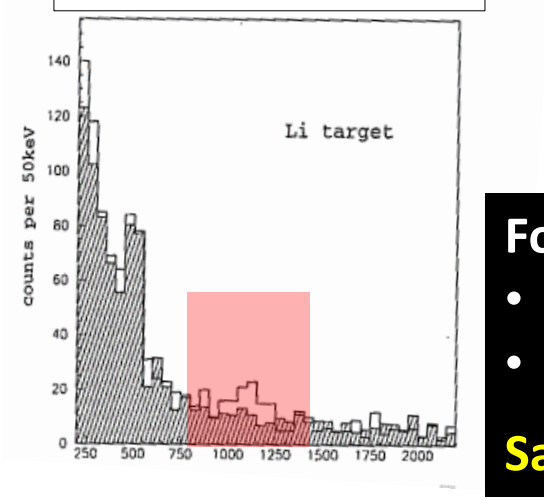


A. Kawachi, Doctoral thesis
Univ. of Tokyo (1997)



All γ-ray measurements on $^4_\Lambda$H used

- Stopped K$^-$
- NaI detector

150 ~ 200 keV(FWHM) resolution
due to detector resolution and Doppler broadening

For higher precision

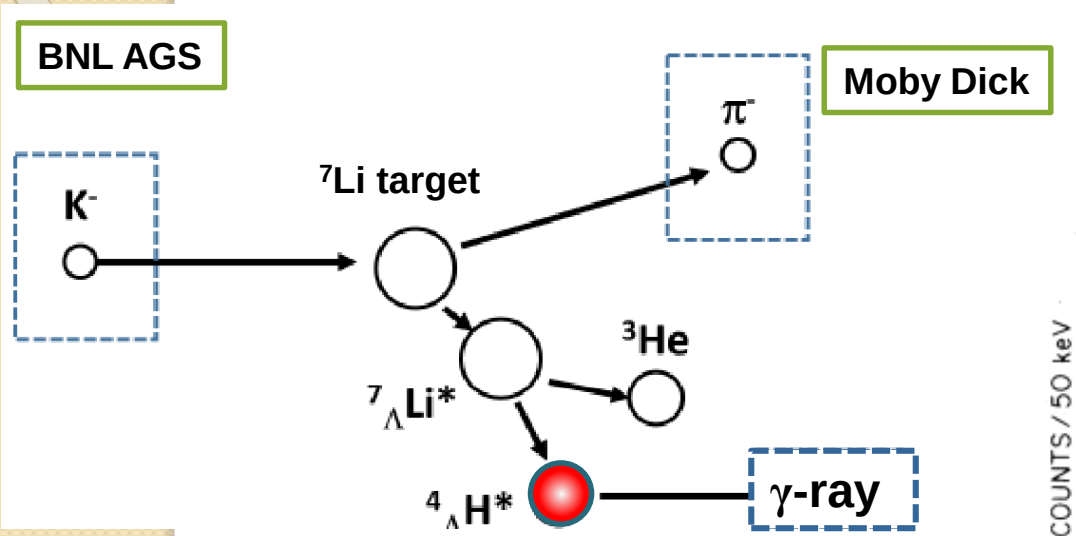
- Stopped K- → **in-flight (K^-,π^-)**
- NaI detector → **Ge detector**

Same strategy as $^4_\Lambda$He measurement

Expected resolution : ~40 keV(FWHM)

Previous study via in-flight $^{7}Li(K^{-},\pi^{-})$ @ 0.9 GeV/*c*

$^{4}_{\Lambda}H$ (and $^{4}_{\Lambda}He$) generates as hyperfragment via the in-flight $^{7}Li(K^{-},\pi^{-})^{7}_{\Lambda}Li$ reaction

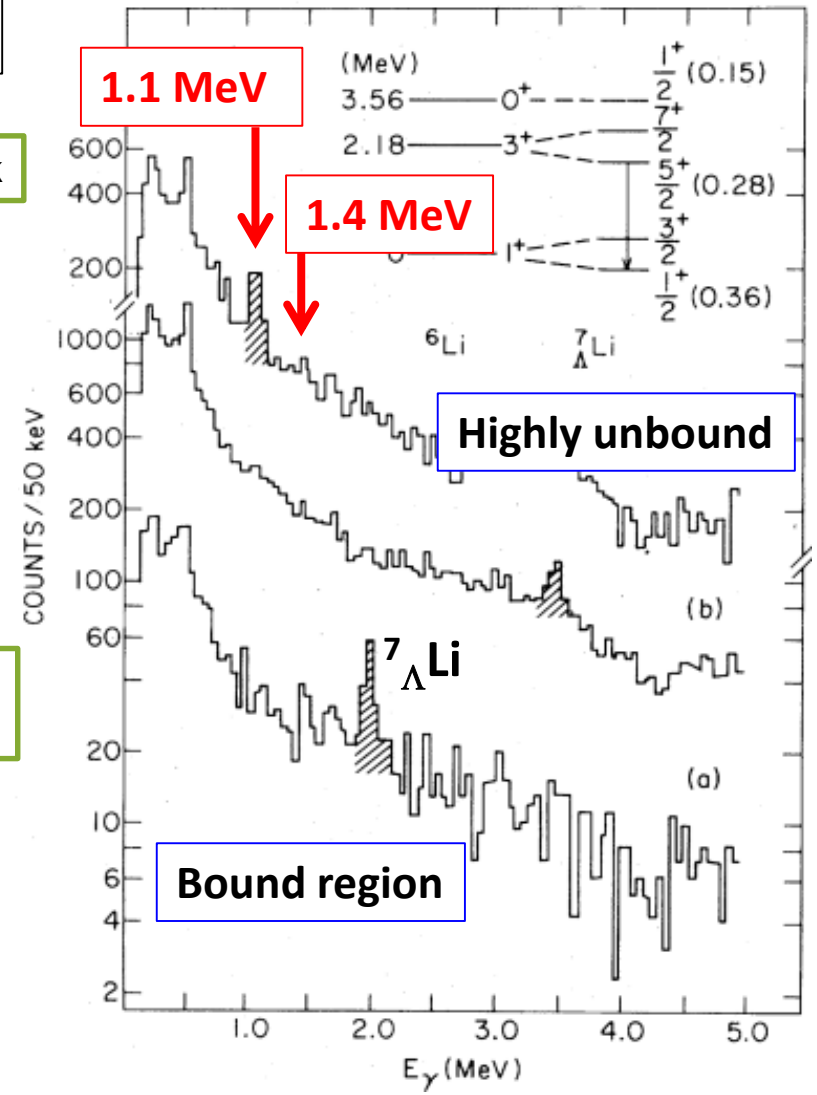


NaI detector energy resolution : 74 keV(FWHM)

+ ~80keV Doppler broadening

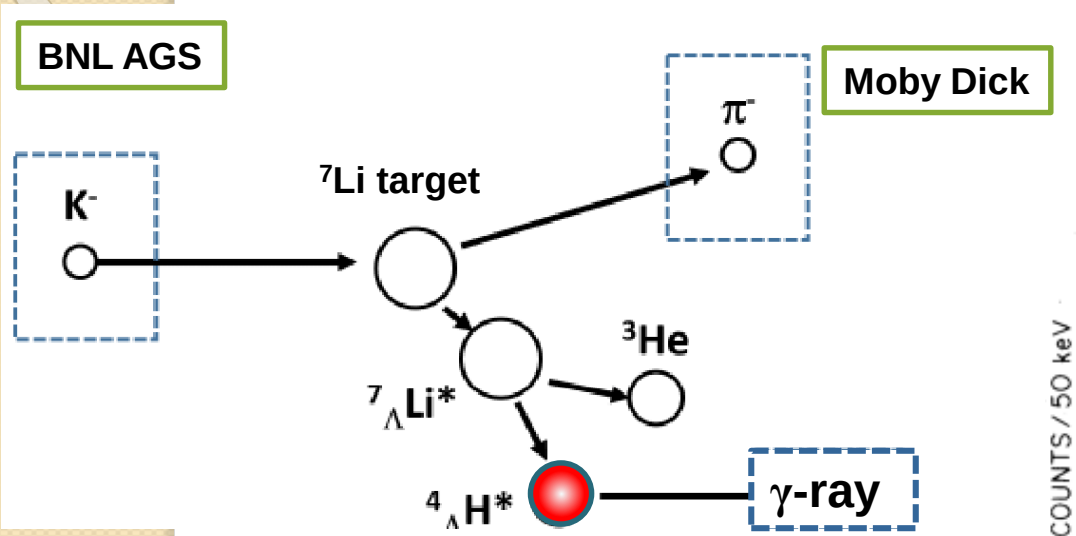
They reported 1.108 ± 0.010 MeV peak as "mixture of $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$"

M.May, PRL 51(1983)2085



Previous study via in-flight ^{7}Li(K$^-$,π^-) @ 0.9 GeV/*c*

$^4_\Lambda$H (and $^4_\Lambda$He) generates as hyperfragment via the in-flight ^{7}Li(K$^-$,π^-)$^7_\Lambda$Li reaction



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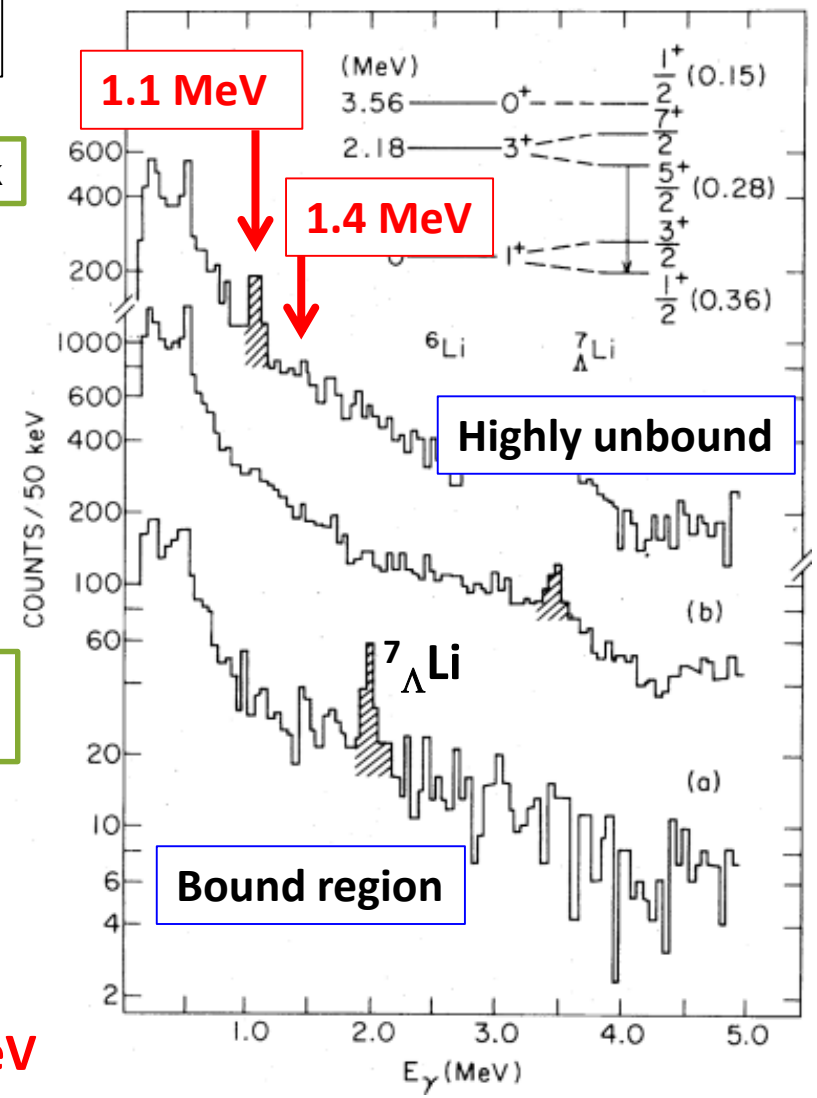
J-PARC E13 → 1.4 MeV

M.May, PRL 51(1983)2085



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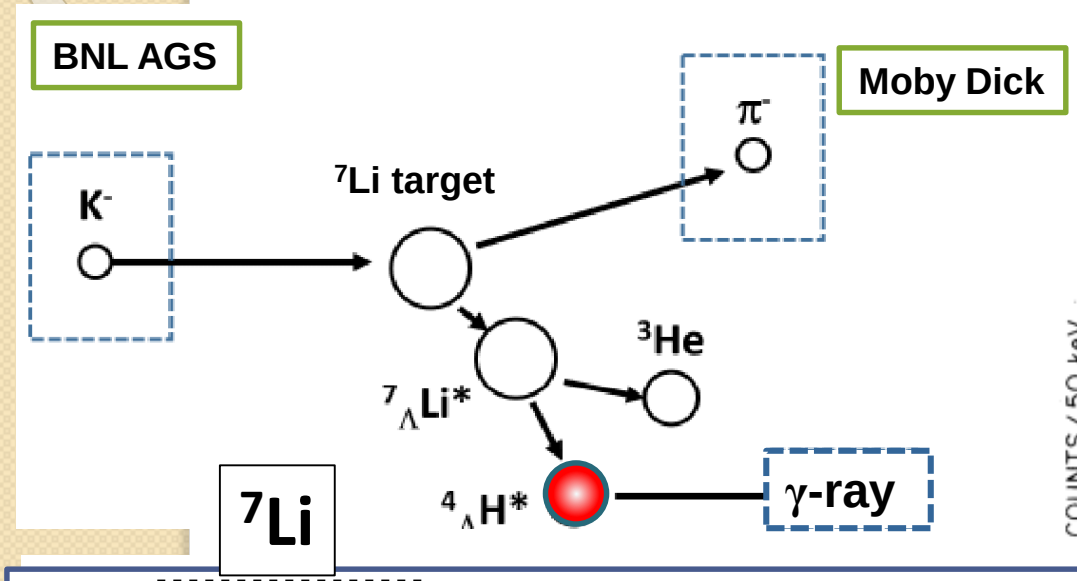
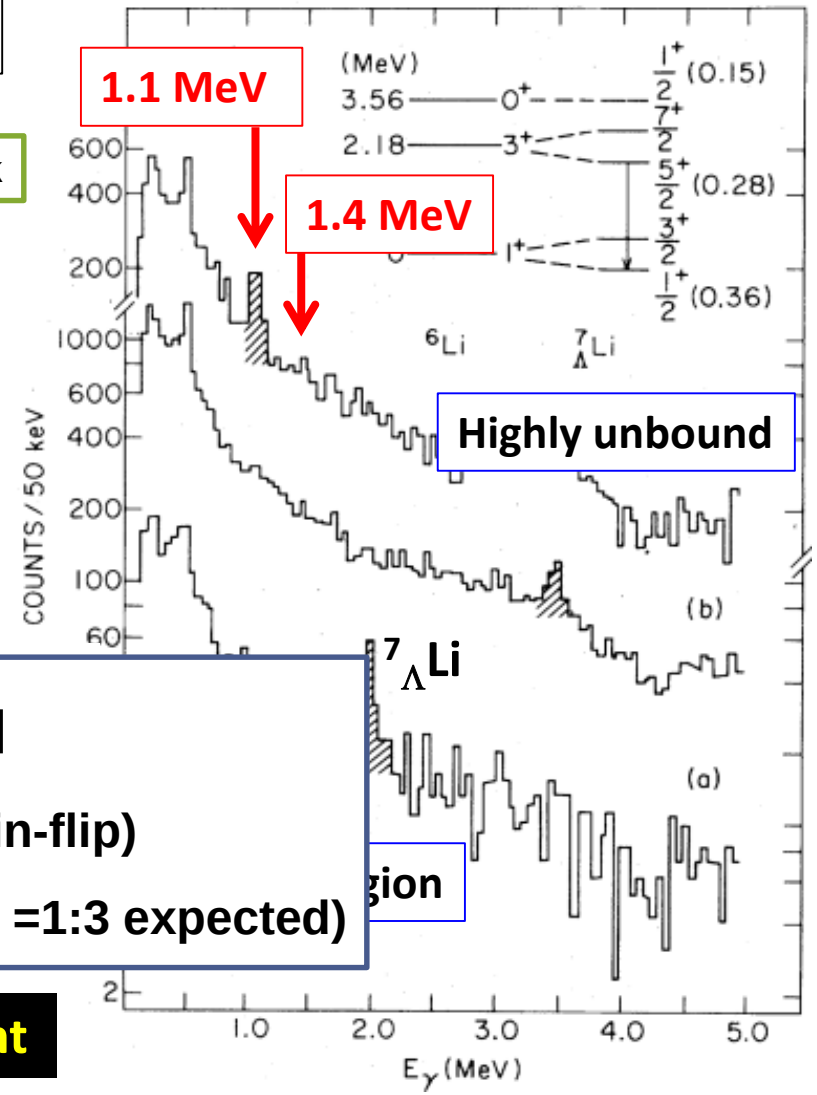




$K^- + {}^4He + {}^3H \rightarrow \Lambda + {}^3He + \pi^- + {}^3H$

[direct] ^{4}He(K$^-$,π^-)$^4_\Lambda$He (0$^+$ only, non-spin-flip)

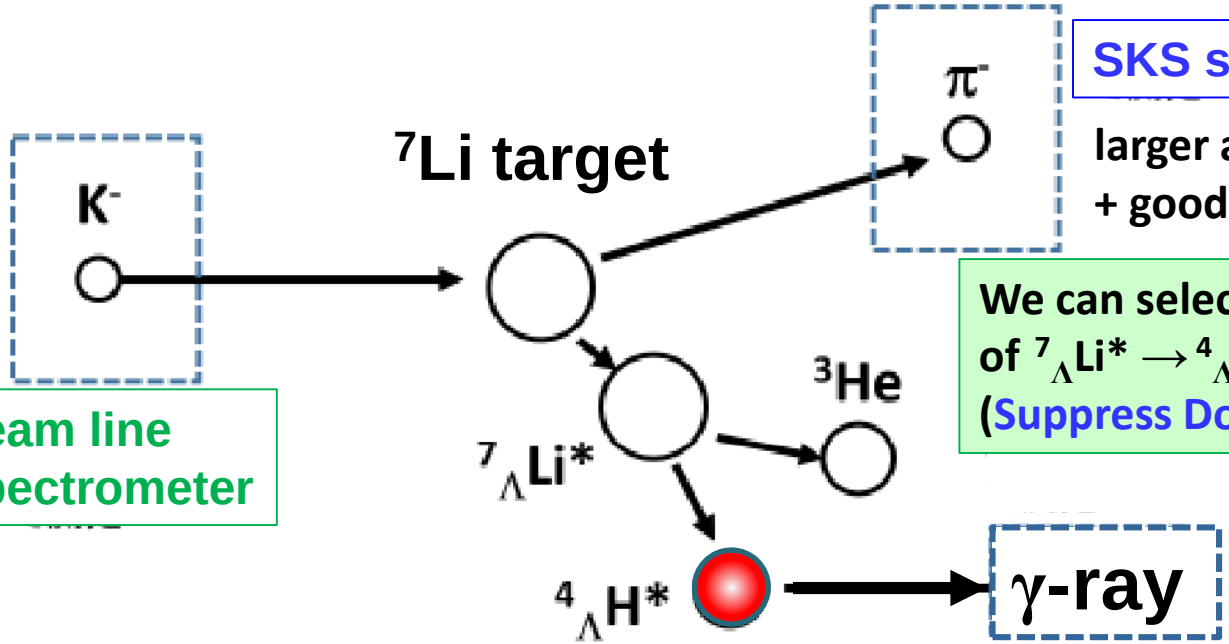
[two step] $\Lambda + {}^3H \rightarrow {}^4_\Lambda H$ (Both 0$^+$,1$^+$, ratio =1:3 expected)

We chose this reaction for $^4_\Lambda$H measurement

γ-ray spectroscopy of $^{4}_{\Lambda}$H (J-PARC E63)

$^{4}_{\Lambda}$H generates as hyperfragment via the in-flight ^{7}Li(K^-,π^-)$^{7}_{\Lambda}$Li reaction

Similar setup as $^{4}_{\Lambda}$He measurement



beam line spectrometer

SKS spectrometer

larger acceptance (~100msr) + good energy resolution

We can select threshold region of $^{7}_{\Lambda}$Li* → $^{4}_{\Lambda}$H + ^{3}He [Ex=~20MeV] (Suppress Doppler broadening)

~40 keV (FWHM)

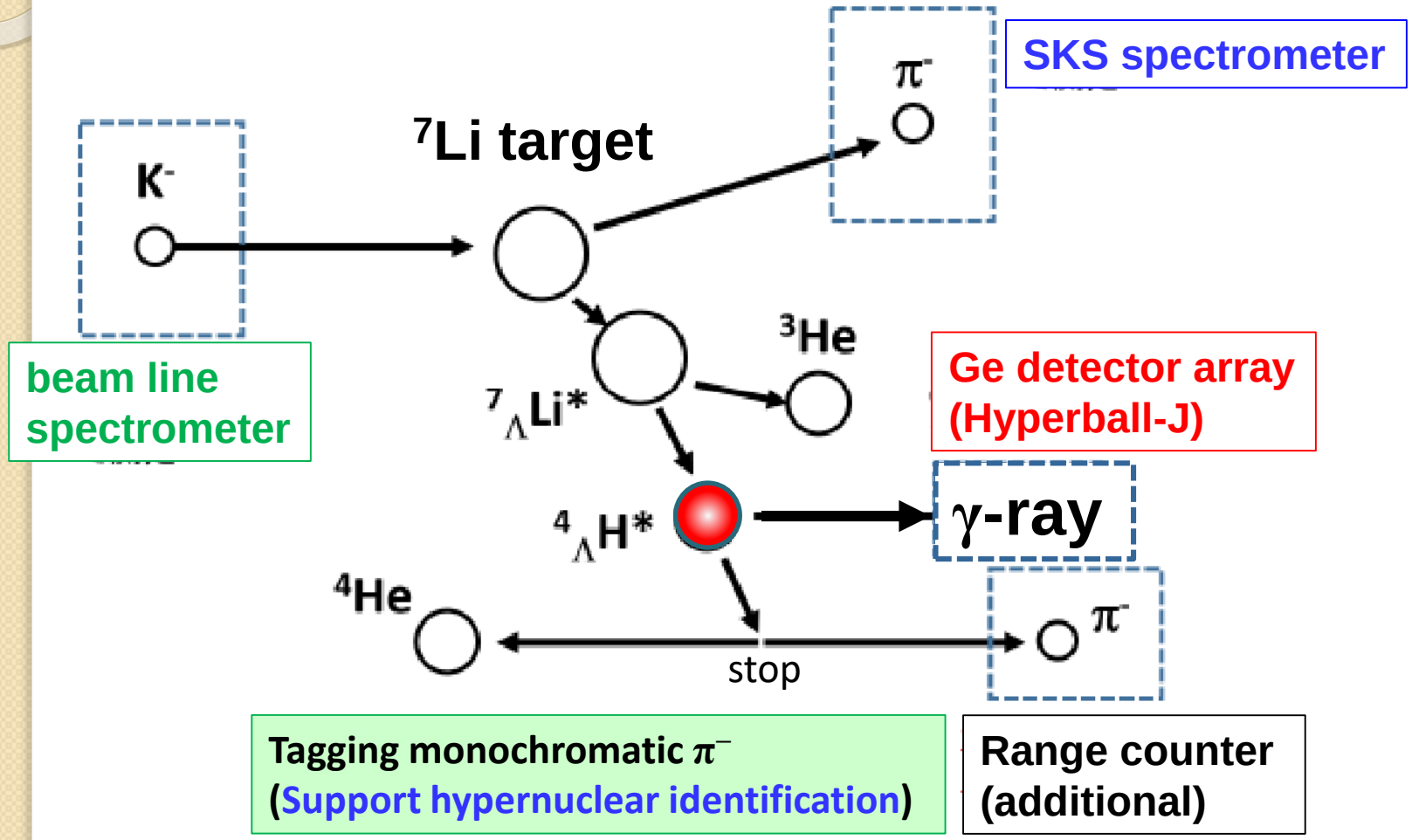
Ge detector array (Hyperball-J)

Good energy resolution

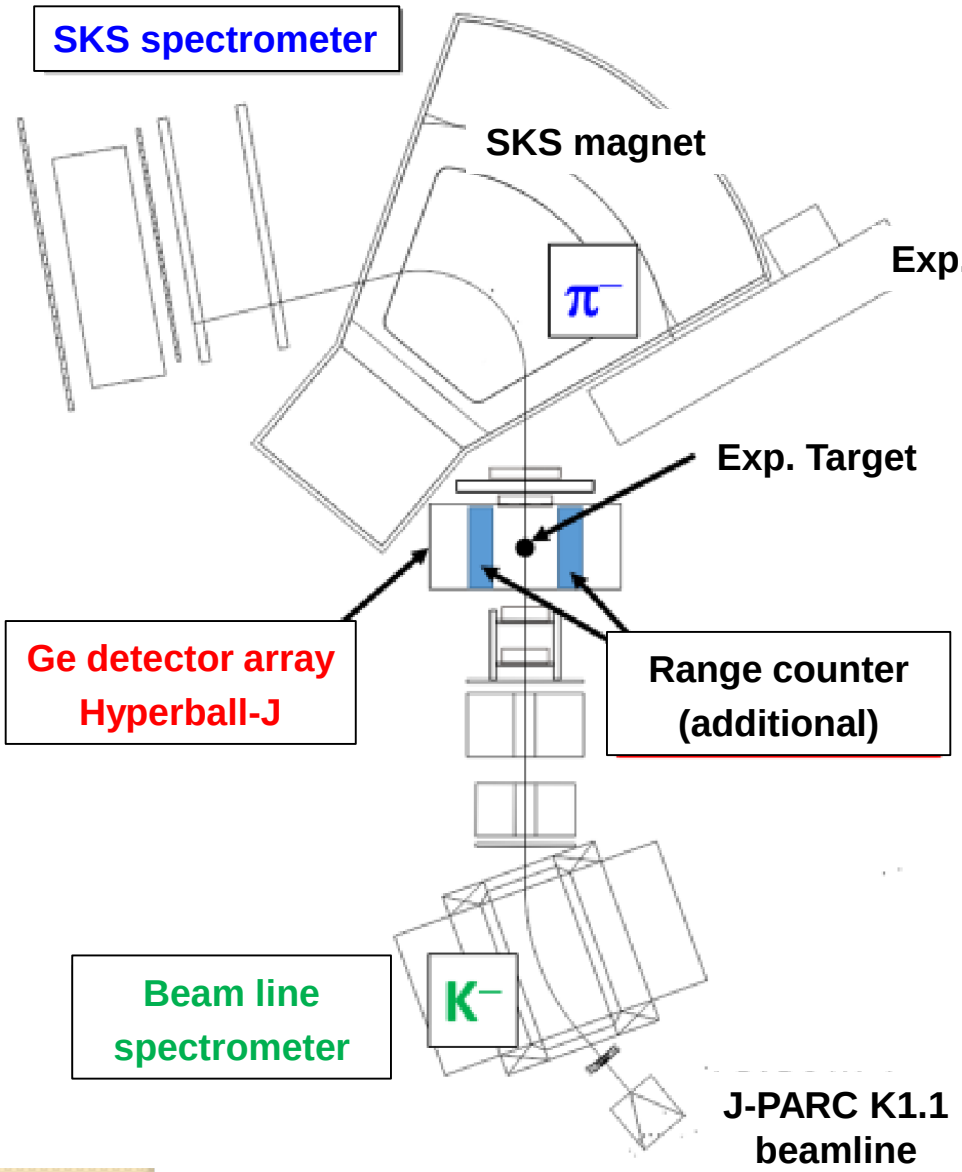
γ-ray spectroscopy of $^{4}_{\Lambda}$H (J-PARC E63)

$^{4}_{\Lambda}$H generates as hyperfragment via the in-flight ^{7}Li(K^-,π^-)$^{7}_{\Lambda}$Li reaction

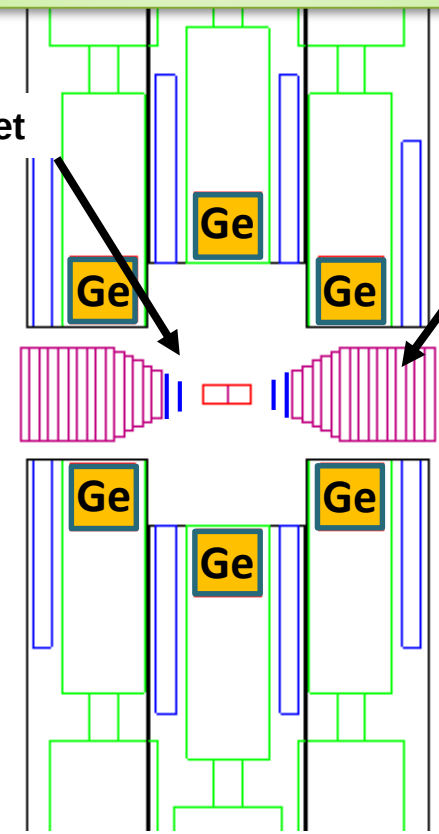
Similar setup as $^{4}_{\Lambda}$He measurement



Experimental setup for $^{4}_{\Lambda}H$ (J-PARC E63)



New detector configuration around target
(view from beam upstream)



Range counter system

Thickness:
~0.5 cm thick
Layers:
>15 layers
Coverage:
30^{W} x 10^{H} cm

Share with other experiment? (weak decay, etc.)

$E_x(1^+)$ will be measured with <5 keV accuracy
(w/6 days beam time)

Gamma-Ray Spectroscopy of Light Λ Hypernuclei II

31 participants from 12 institutes

Y. Akazawa, M. Fujita, N. Ichige, M. Ikeda, T. Koike, K. Miwa, Y. Ogura, H. Tamura(spokesperson), Y. Sasaki, S. Suto, T. Yamamoto
Department of Physics, Tohoku University, Japan

K. Aoki, T. Takahashi, M. Ukai
Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Japan

K. Hosomi, K. Tanida
Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Japan

P. Evtoukhovitch, Z. Tsamalaidze
Joint Institute for Nuclear Research, Russia

S. Yang
Department of Physics and Astronomy, Seoul National University, Korea

R. Honda
Department of Physics, Osaka University, Japan

K. Shirotori
Research Cetner for Nuclear Physics, Osaka University, Japan

E. Botta
Dipartimento di Fisica, Universitá di Torino, and Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Italy

A. Feliciello
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Italy

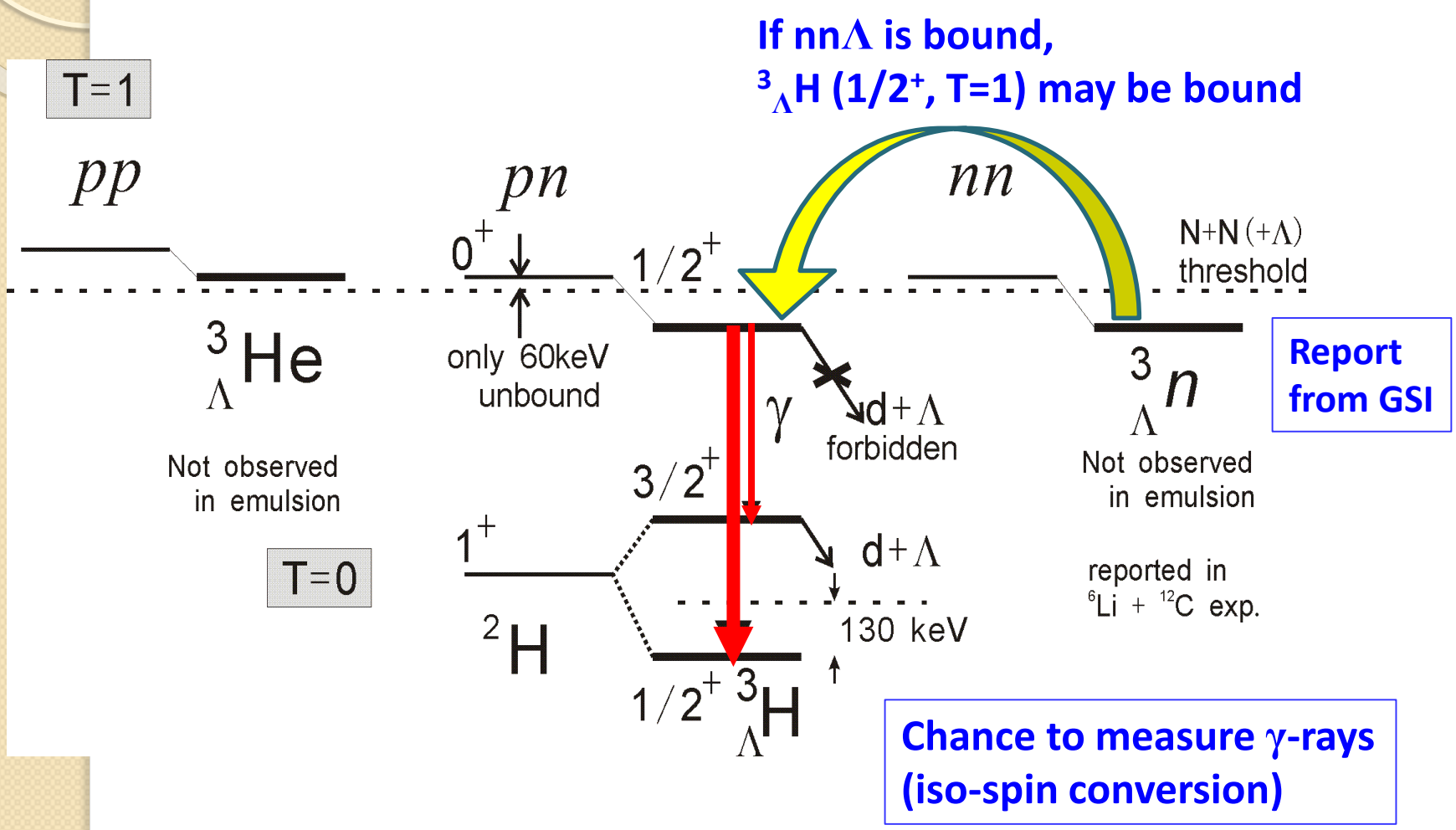
M. Agnello
Dipartimento di Scienze Applicate e Tecnologia, Politecnico di Torino, Italy

J-PARC
E63 (E13-2)
Submitted in 2015
stage-2 approval

- **$^{4}_{\Lambda}$H excitation energy**
- **$^{7}_{\Lambda}$Li lifetime**
  (Λ magnetic moment in nuclear medium)

Byproduct:
γ-ray measurement of $^{3}_{\Lambda}H$

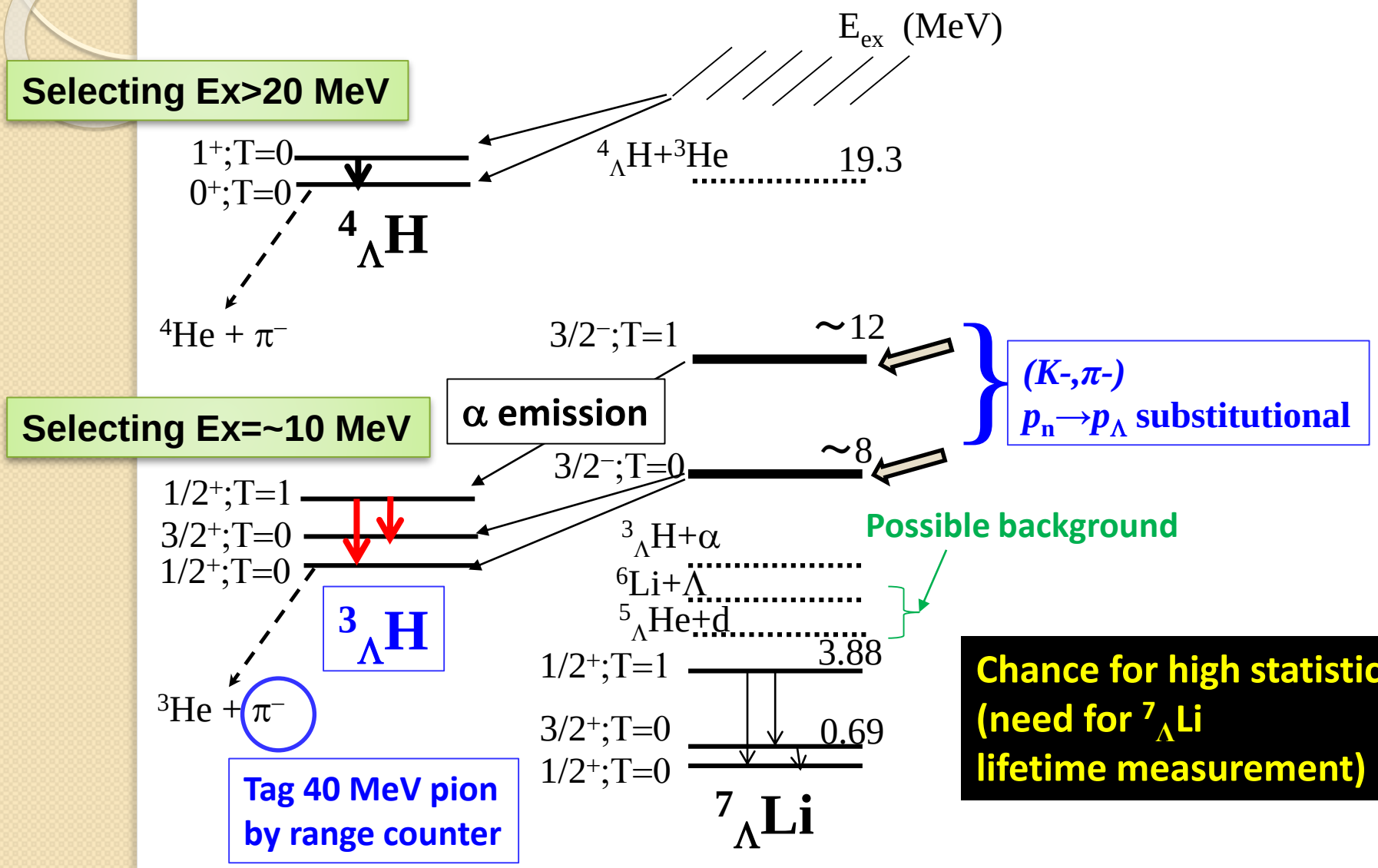
Idea from M. Ukai



Chance to measure γ-rays (iso-spin conversion)

Byproduct:
γ-ray measurement of $^{3}_{\Lambda}$H

Idea from M. Ukai

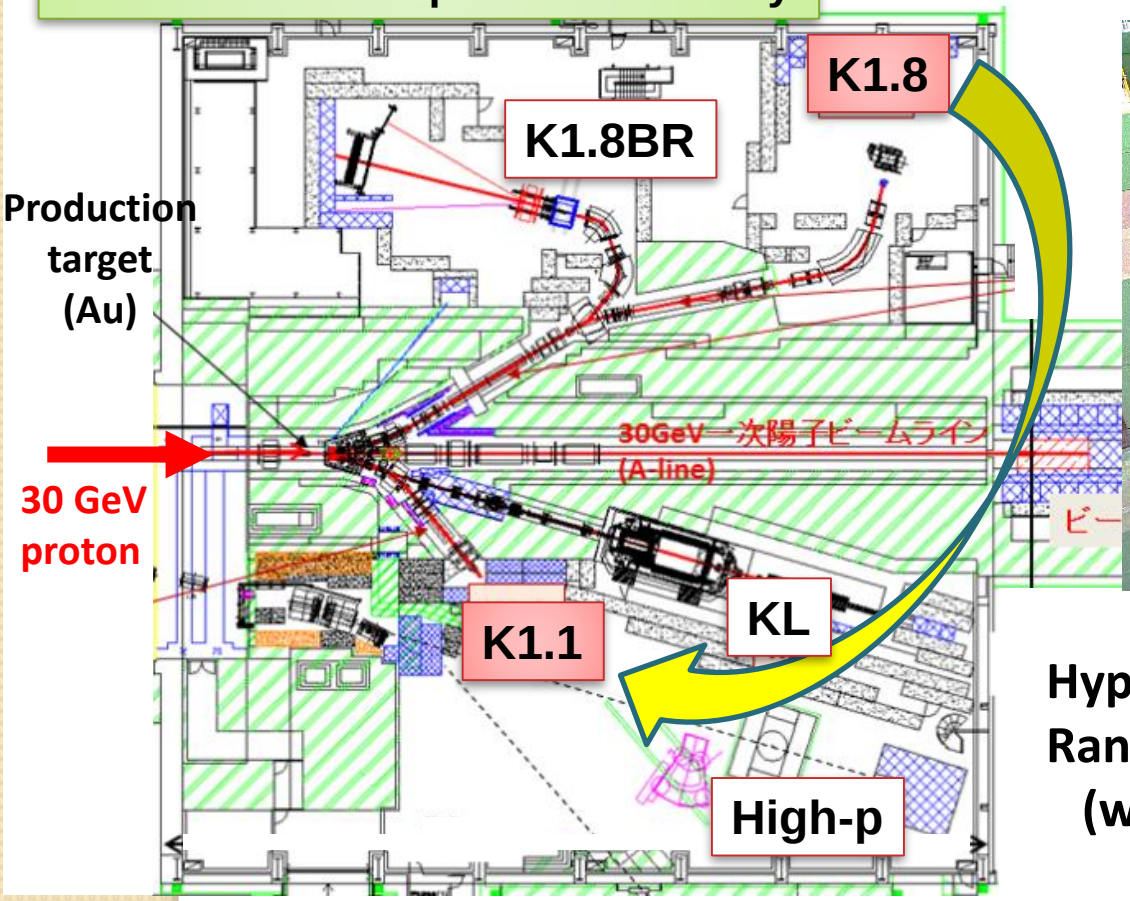


Chance for high statistic (need for $^{7}_{\Lambda}$Li lifetime measurement)

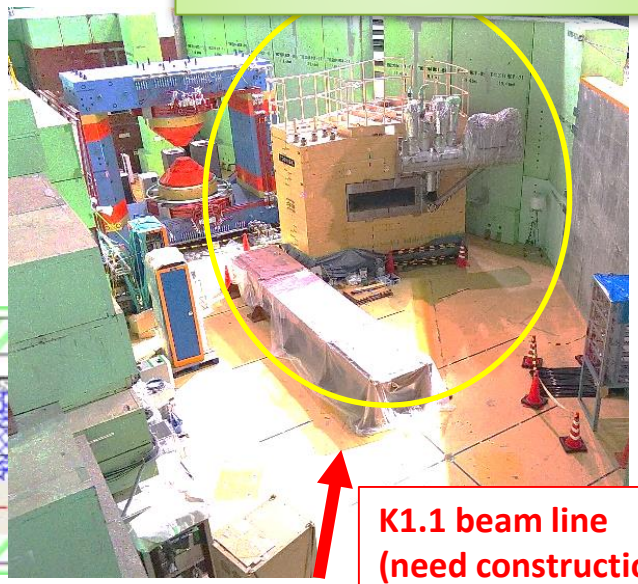
Preparation status

0.9 GeV/c K^- beam for suppress Doppler broadening and higher cross section
→ **move to J-PARC K1.1 beam line with SKS magnet**

J-PARC hadron experimental facility



SKS moved to K1.1



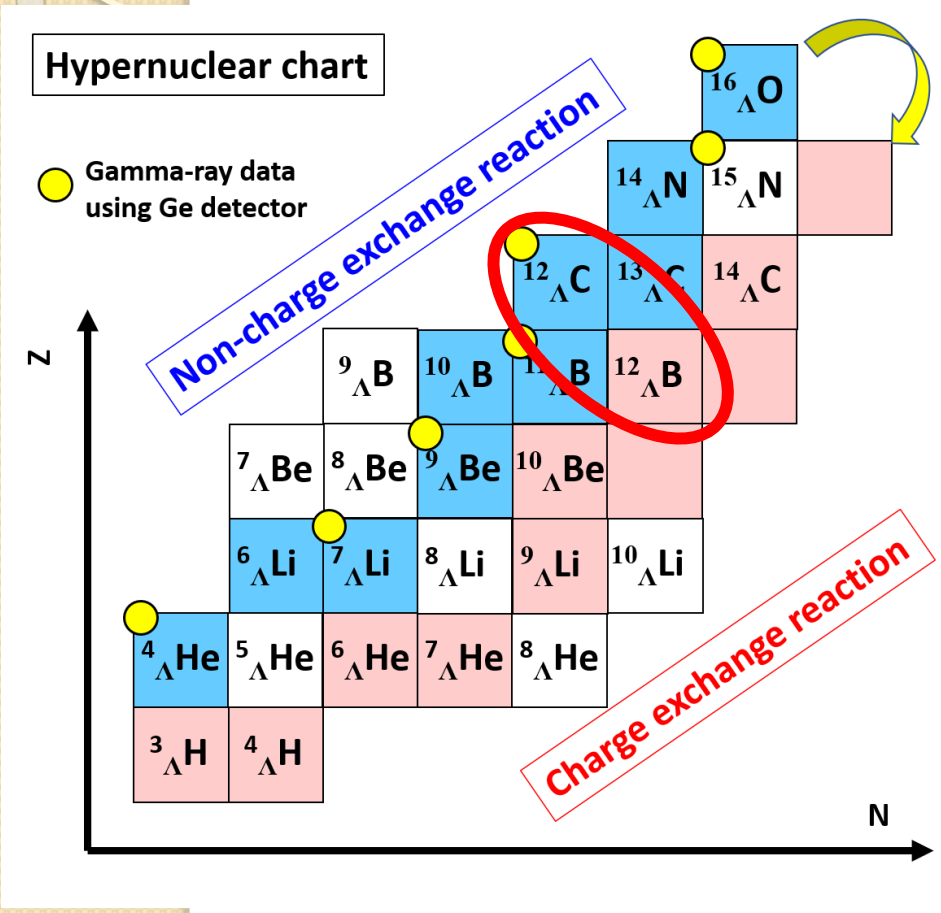
Hyperball-J: Established
Range counter: Designing
(will be constructed in next year)

Idea of new measurement

Gamma-ray spectroscopy

to study CSB effect in *p*-shell hypernuclei

Reaction for γ-ray spectroscopy on mirror hypernuclei



Need to extend gamma-ray data to neutron rich side

Non-charge exchange reaction

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

Charge exchange reaction

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

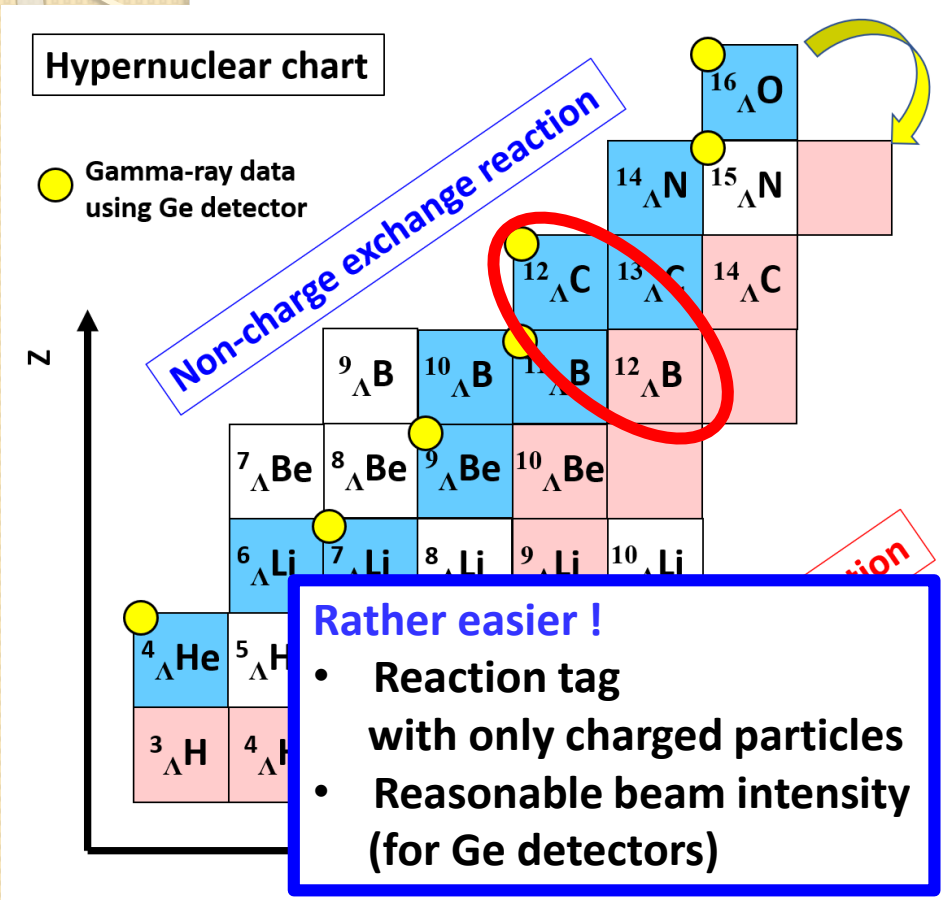
$$\pi^{0} \longrightarrow \gamma\gamma$$

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

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

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

Reaction for γ-ray spectroscopy on mirror hypernuclei



Rather easier !

- Reaction tag with only charged particles
- Reasonable beam intensity (for Ge detectors)

Prof. Alessandro's talk on Friday

Need to extend gamma-ray data to neutron rich side

Non-charge exchange reaction

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

Charge exchange reaction

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

$\pi^0 \longrightarrow \gamma\gamma$

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

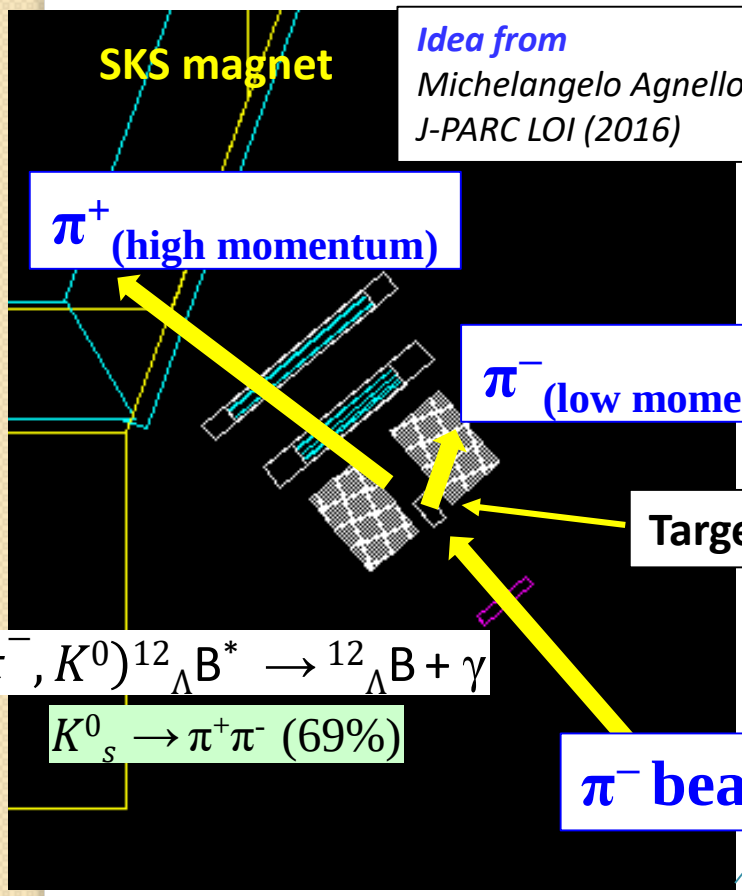
$K^0{}_s \longrightarrow \pi^+\pi^-$ (69%)

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

Setup for the gamma-ray spectroscopy

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

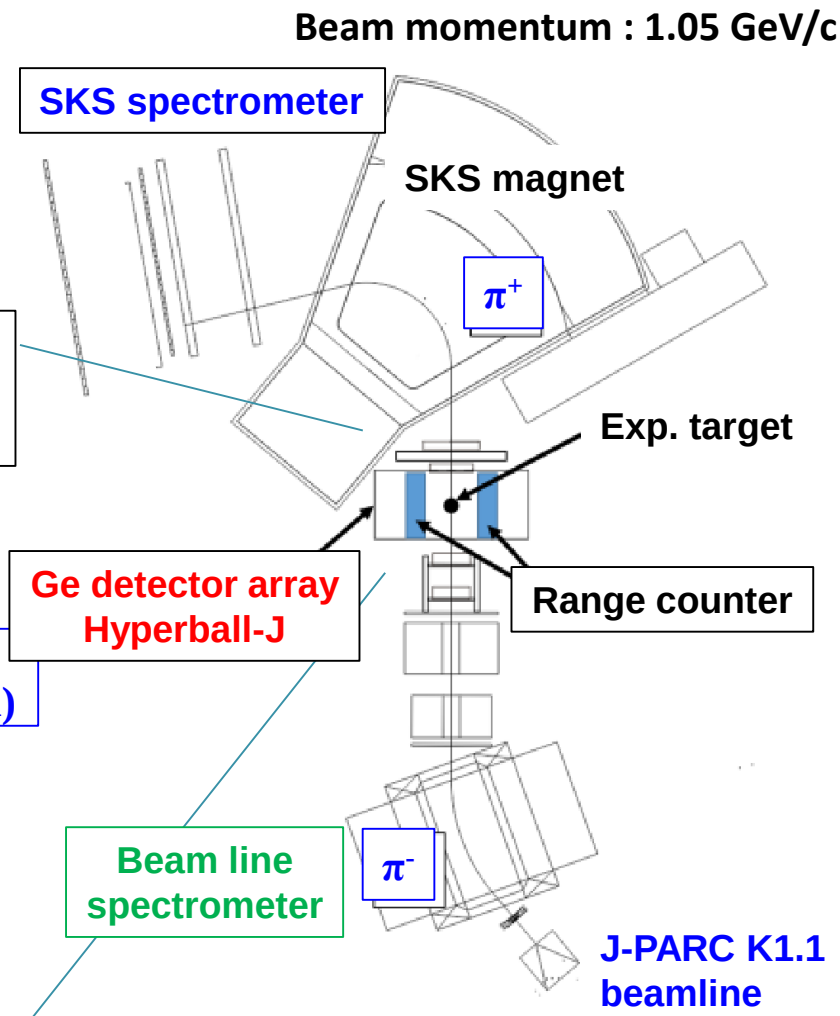
- **Beam line spectrometer + SKS**
- **Hyperball-J**
- **Range counter** (similar configuration)



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

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

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



Designing of detector system is ongoing

Summary

- **CSB in *s*-shell hypernuclear system studied via γ-ray spectroscopy**
  - γ-ray spectroscopy on $^{4}_{\Lambda}$He (J-PARC E13)

    $E_x(^{4}_{\Lambda}He(1^+)) = 1.406 \pm 0.004$ MeV

    CSB effect also appear in excitation energy + spin-dependence

- **Next step: γ-ray spectroscopy on $^{4}_{\Lambda}$H (J-PARC E63)**
  - In-flight $^{7}Li(K^-,\pi^-)$ reaction + Ge detector
  - Common setup as $^{4}_{\Lambda}$He measurement + range counter system
  - Better than 5 keV accuracy w/ 6 days beamtime

    (stage-2 approval)

- **idea of γ-ray spectroscopy to study CSB in *p*-shell**

Backup

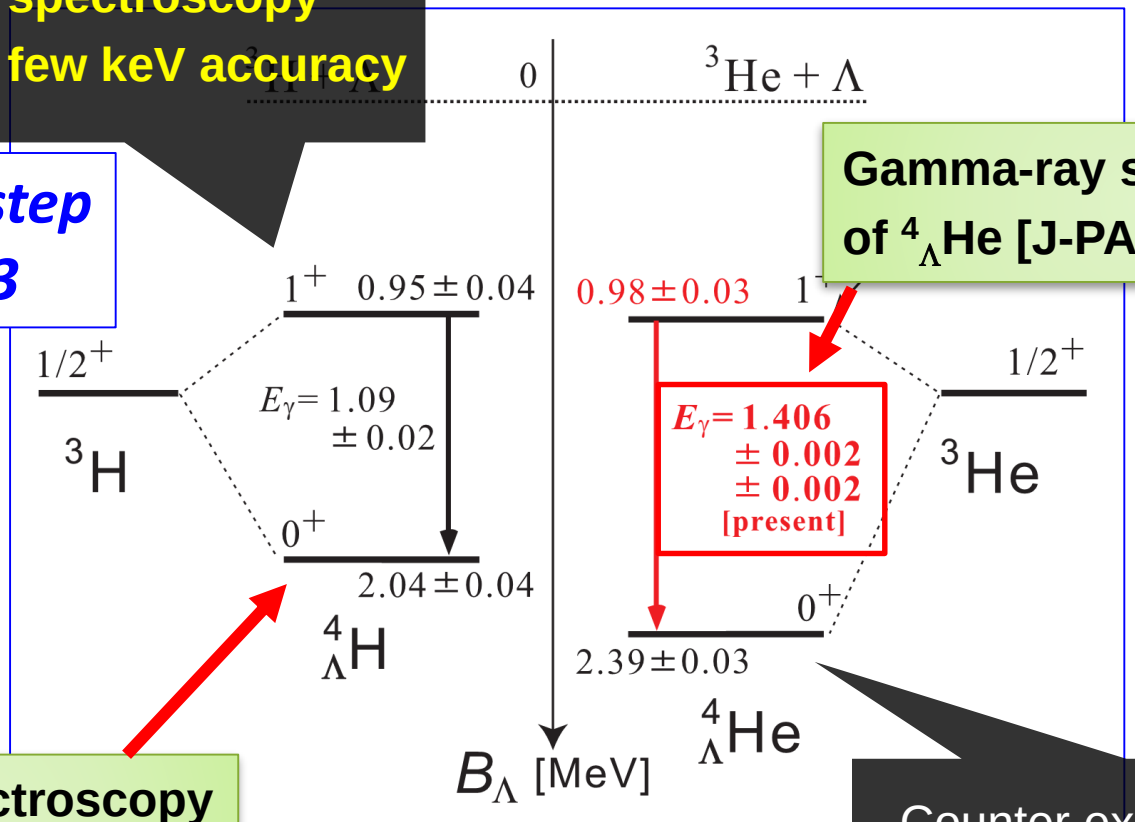
Toward the exp. completeness for s-shell

Gamma-ray spectroscopy of $^{4}_{\Lambda}$H w/ a few keV accuracy

Our Next step J-PARC E63

Gamma-ray spectroscopy of $^{4}_{\Lambda}$He [J-PARC E13]

Done



Decay π^- spectroscopy ($^{4}_{\Lambda}$H) [MAMI-C]

Done

Counter experiment ($^{4}_{\Lambda}$He) [J-PARAC HIHR]

Need J-PARC HEF extension

Present status of CSB in s-shell

- Existence of CSB effect was confirmed ($B_{\Lambda(g.s)}$ and γ-ray)
- Difference in 0^+ and 1^+ : $\Delta B_\Lambda(1^+) = 0.03 \pm 0.05$ MeV
  $\Delta B_\Lambda(0^+) = 0.35 \pm 0.05$ MeV

Strongly spin-dependent

CSB effect calc. w/ $\Lambda\Sigma$ mixing

(unit : MeV)

	Exp. (old)	Exp. (new)	Calc. Nogga	Calc. Gal	Calc. Gazda
$\Delta B_\Lambda(1^+)$	0.28(5)	0.03(5)	-0.01	0.03	-0.19
$\Delta B_\Lambda(0^+)$	0.35(5)	0.35(5)	0.07	0.22	0.14

A. Nogga et al., Phys. Rev. Lett. 88, 172501 (2002).

A. Gal, Phys. Lett. B 744, 352 (2015).

D. Gazda, A. Gal, NPA 954 (2016) 161

Widely accepted NSC97e interaction model

simple potential

Chiral EFT model

ΛN-ΣN coupling may be key of CSB effect

High accurate data of CSB effect may provide new information to investigate underlying ΛN interaction

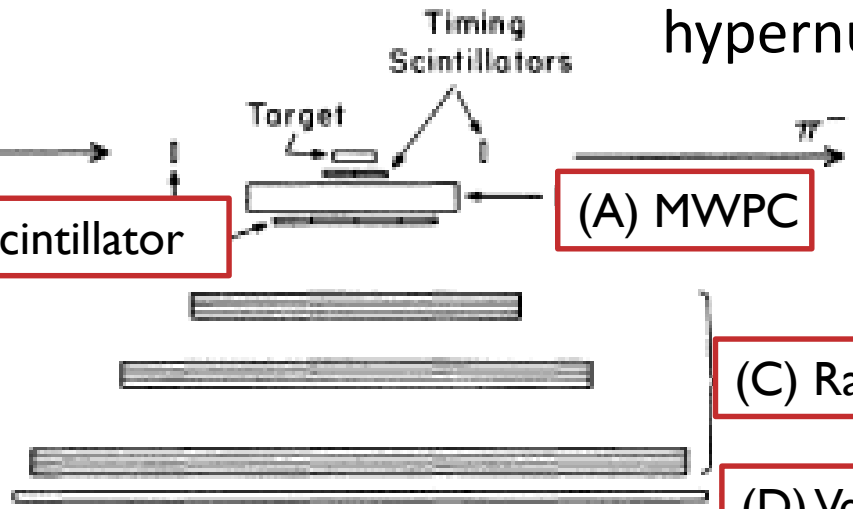
Yield estimation of $^{4}_{\Lambda}H$

	BNL exp	E63
Total K-	10 G Kaon	5 G Kaon
Target thickness	8 g/cm^2	15 g/cm^2
$\pi-$ spectrometer	Moby-dick (18 msr)	SKS (35 msr < 6°)
$1^+ \rightarrow 0^+$ γ yield	150	300
γ-ray Efficiency	6%	3% (x 0.8 live)
$^{4}_{\Lambda}H(1^+)$ yield		12,500
$^{4}_{\Lambda}H(0^+)$ yield Direct + γ-feeding		16,200

Decay counter configuration for lifetime measurement

PhysRevC.43.849

Range counter system for hypernuclear π- decay in BNL



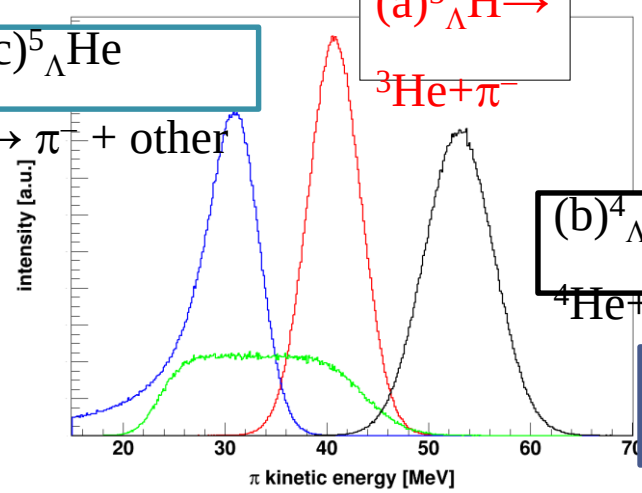
(B) Timing scintillator

(A) MWPC

(C) Range counter

Plastic scintillator
Total 7.6cm thickness

(D) Veto counter



Range counter Total E resolution
~ 15%(FWHM) @50 MeV

Optimum missing mass gate of $^7_\Lambda$Li
Certain states will be enhanced.

Lifetimes of $^3_\Lambda$H, $^4_\Lambda$H can be measured

CSB data in *p*-shell hypernuclei

Theoretical study: 10~100 keV CSB effect in *p*-shell

A. Gal, Phys. Lett. B 744, 352 (2015).

Existing data on B_Λ

hypernuclei	B_Λ(g.s.) emulsion	reaction	ΔB_Λ(g.s.) emulsion	with reaction
${}^{7}_{\Lambda}$He	-	5.60 ± 0.17 [70, 71]	-	−0.44 ± 0.19
${}^{7}_{\Lambda}$Be	5.16 ± 0.08	-		
${}^{8}_{\Lambda}$Li	6.80 ± 0.03	-	+0.04 ± 0.06	-
${}^{8}_{\Lambda}$Be	6.84 ± 0.05	-		
${}^{9}_{\Lambda}$Li	8.50 ± 0.12	8.36 ± 0.16 [72]	−0.21 ± 0.22	−0.07 ± 0.24
${}^{9}_{\Lambda}$B	8.29 ± 0.18	-		
${}^{10}_{\Lambda}$Be	9.11 ± 0.22	8.60 ± 0.18 [12]	−0.22 ± 0.25	(−0.50 ± 0.21)
${}^{10}_{\Lambda}$B	8.89 ± 0.12	(8.1 ± 0.1)* [73]		+0.04 ± 0.21*
${}^{12}_{\Lambda}$B	11.37 ± 0.06	11.524 ± 0.019 [74]	(−0.57 ± 0.19)	(−0.72 ± 0.18)
${}^{12}_{\Lambda}$C	(10.80 ± 0.18)*	-	−0.03 ± 0.19*	−0.18 ± 0.18*

Experiment with (e,e'K$^+$) reaction (JLAB)
-> A=7, 10 hypernuclei (~100 keV accuracy)

T. Gogami et al.: Phys. Rev. C 94 (2016) 021302.
T. Gogami et al.: Phys. Rev. C 93 (2016) 034314.

Difficulty: Need accurate data in both mirror pair

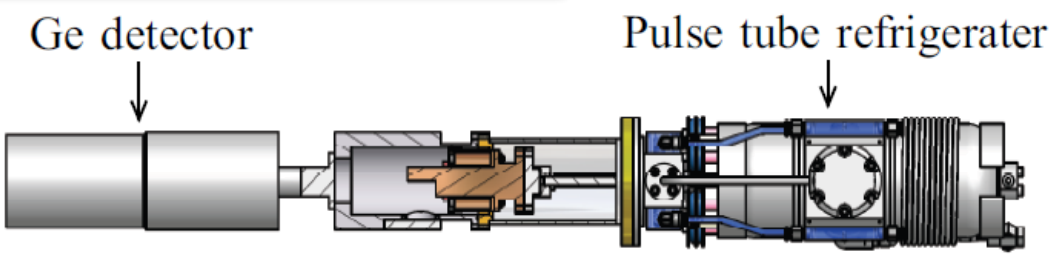
Hyperball-J new Ge detector array

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

Developed Ge detector



Lower half of Hyperball-J