

After the previous J-PARC symposium,
J-PARC E13 was successfully performed.
Thank you for great support !

Recent result and future plan of hypernuclear γ -ray spectroscopic experiment at J-PARC

2019/9/26

T. O. Yamamoto

JAEA (Japan)

for the J-PARC E13/E63 collaboration

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➤ Introduction

Hypernuclear γ -ray spectroscopy at J-PARC

➤ Recent results [J-PARC E13, 2015]

- ${}^4_{\Lambda}\text{He}$
- ${}^{19}_{\Lambda}\text{F}$

➤ Future measurement [J-PARC E63]

- ${}^4_{\Lambda}\text{H}$
- ${}^7_{\Lambda}\text{Li}$

➤ Summary

Hypernuclear structure and spin-dependent ΛN interaction

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

central

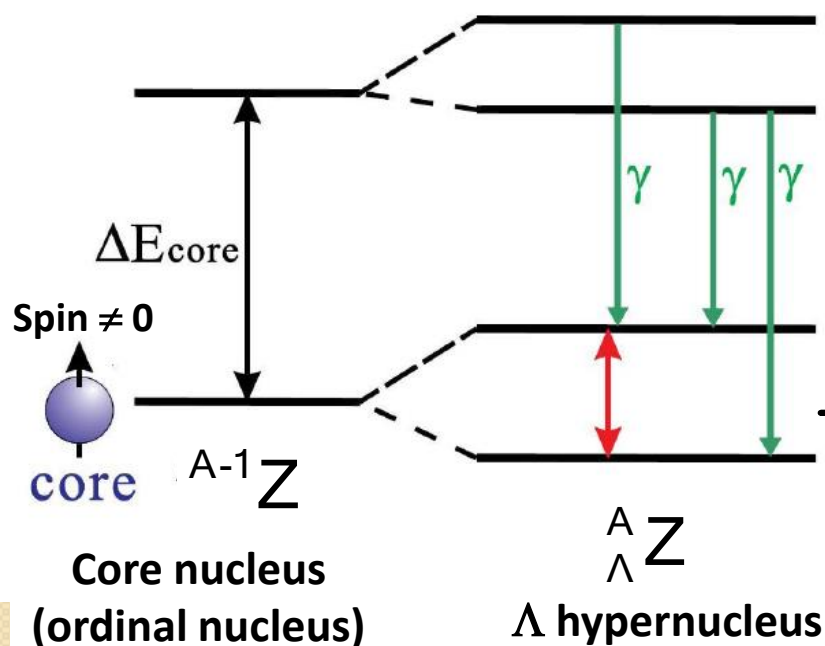
spin-spin

spin-orbit (s_Λ)

spin-orbit (s_N)

Tensor

Level scheme of hypernucleus



1 core nuclear state



Spin-dependent interaction
(spin of $\Lambda = \pm 1/2$ (Λ in s state))

2 hypernuclear states

spin-doublet

Energy spacing :
10 keV ~ 1 MeV

High resolution
 γ -ray spectroscopy

We can get Information of spin-dependent ΛN interaction from level scheme

Hypnuclear structure and spin-dependent ΛN interaction

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

central

spin-spin

spin-orbit (s_Λ)

spin-orbit (s_N)

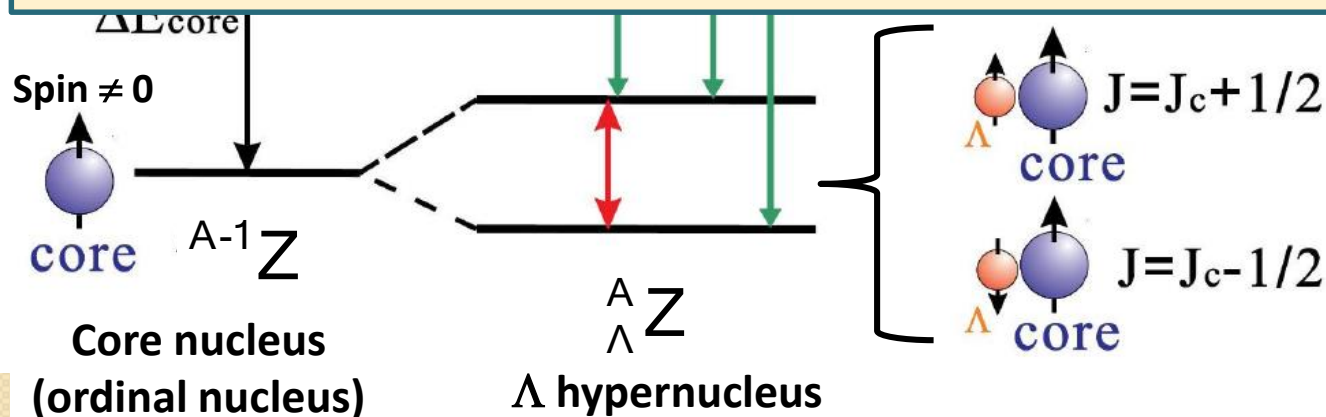
Tensor

Hypnuclear γ -ray spectroscopy at KEK and BNL (1998~)

${}^7_{\Lambda}\text{Li}$, ${}^9_{\Lambda}\text{Be}$, ${}^{11}_{\Lambda}\text{B}$, ${}^{12}_{\Lambda}\text{C}$, ${}^{15}_{\Lambda}\text{N}$, ${}^{16}_{\Lambda}\text{O}$

Strengths of spin-dependent terms were determined (for p-shell)

-> Study of different (s-, sd-) shell hypnuclei at J-PARC



spin-doublet

Energy spacing :
10 keV ~ 1 MeV

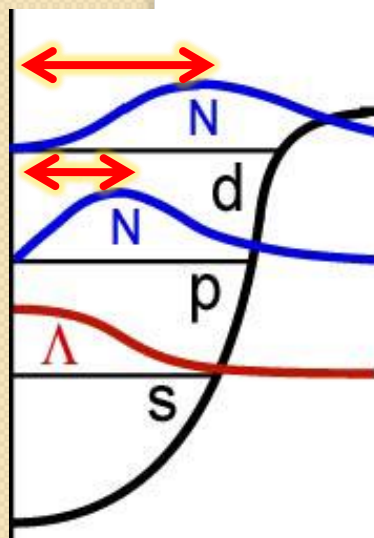
High resolution
 γ -ray spectroscopy

We can get Information of spin-dependent ΛN interaction from level scheme

Study of radial dependence of ΛN **spin-spin** interaction (J-PARC E13)

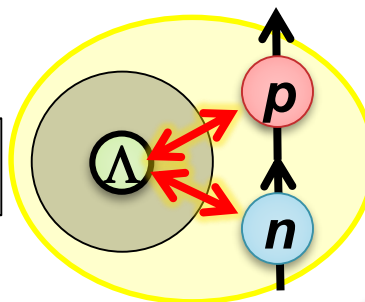
Effect of spin-dependent interaction on hypernuclear level structure

Λ (s-shell) \leftrightarrow N(most outer shell)



Wave functions of Nucleon and Λ (s-state)

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

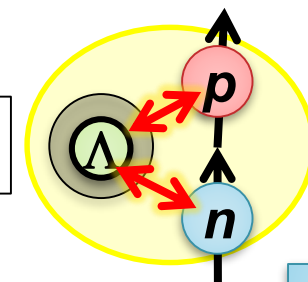


sd-shell

First measurement in sd-shell hypernuclei

J-PARC E13

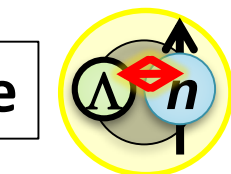
$^7_{\Lambda}\text{Li}$



p-shell

Well studied in **previous experiments**

$^4_{\Lambda}\text{He}$



s-shell

First precise measurement using Ge detector

Charge symmetry breaking?

J-PARC E13

$$V_{\sigma}(r) \mathbf{s}_N \cdot \mathbf{s}_{\Lambda}$$

Radial dependence can be studied from these difference

Experimental setup (E13)

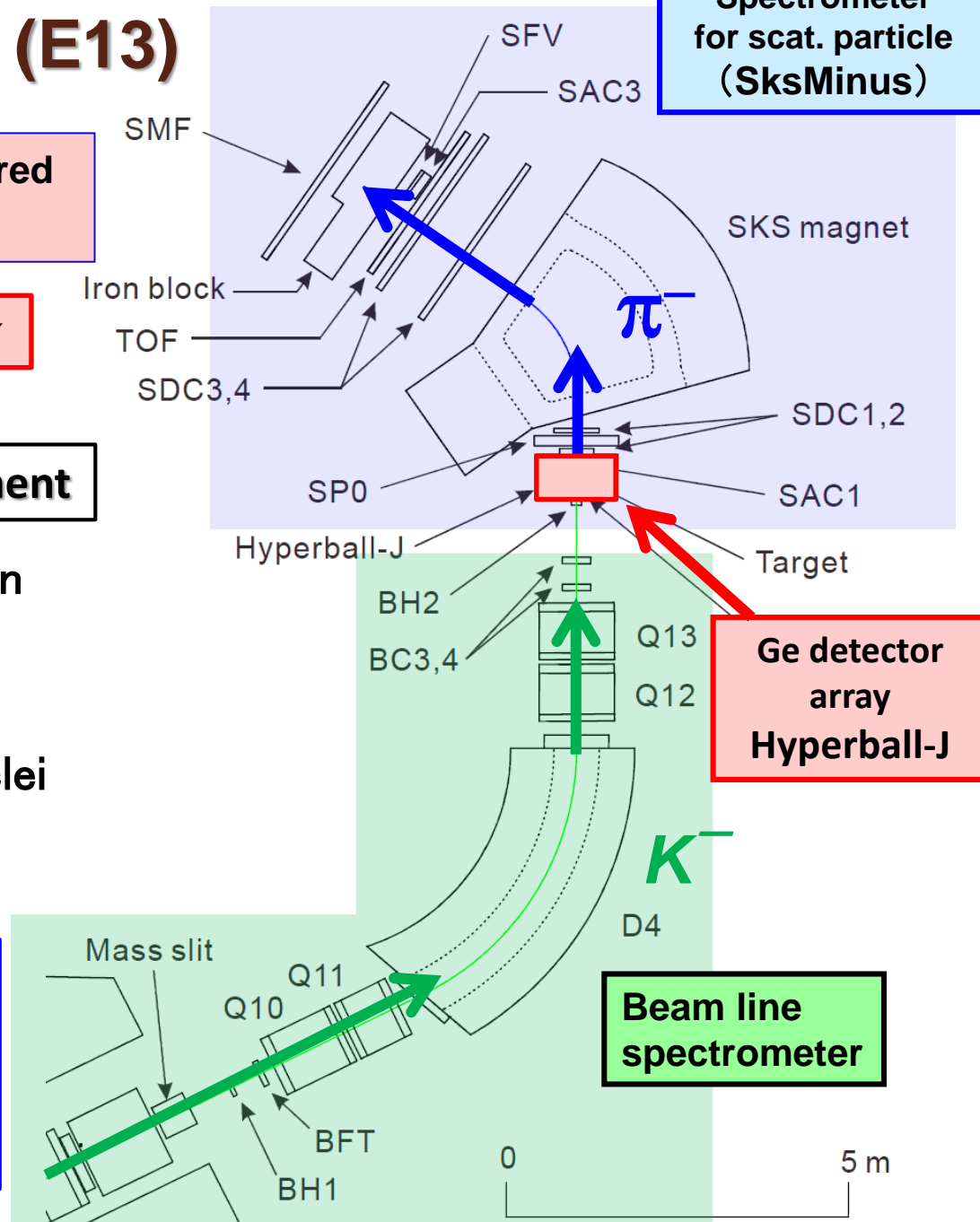
Use high intensity K- beam delivered from J-PARC K1.8 beam line



reaction- γ coincidence experiment

- Tag hypernuclear production
 - Beam line spectrometer
 - SksMinus spectrometer
- Detect γ ray from hypernuclei
 - Hyperball-J

${}^4_\Lambda\text{He}$: liq. He target (2.5 g/cm²)
 $p_K = 1.5$ GeV/c
 ${}^{19}_\Lambda\text{F}$: lip. CF₄ target (20 g/cm²)
 $p_K = 1.8$ GeV/c



Spectrometer
for scat. particle
(SksMinus)

Ge detector
array
Hyperball-J

Beam line
spectrometer

Hyperball-J new Ge detector array

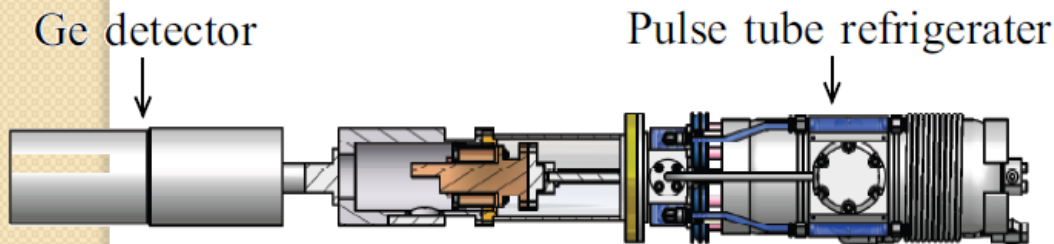


Features

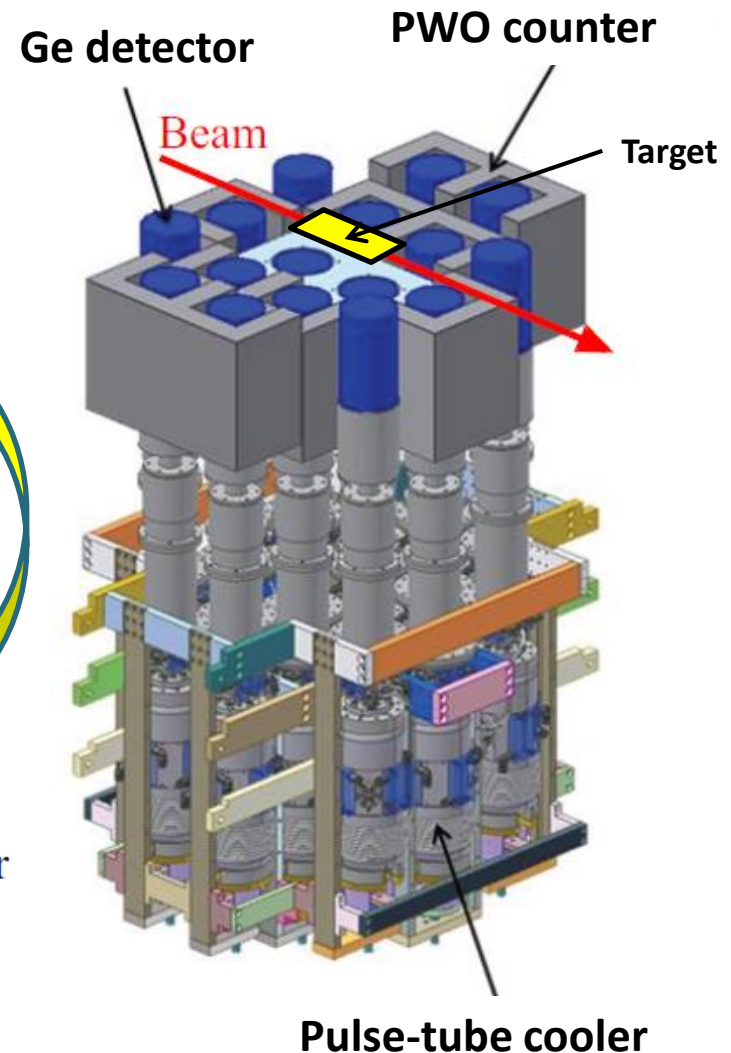
- ◆ **Large photo-peak efficiency**
→ $\epsilon \sim 6\%$ @1 MeV with 32 Ge detectors
- ◆ **Fast readout system**
- ◆ **Low temp. Ge detector**
→ Mechanical cooling
- ◆ **Fast background suppressor**
→ PWO counter

For high intensity hadron beam

- high count and energy deposit rate
- radiation damage due to hadron beam



Lower half of Hyperball-J



Data taking (2015)



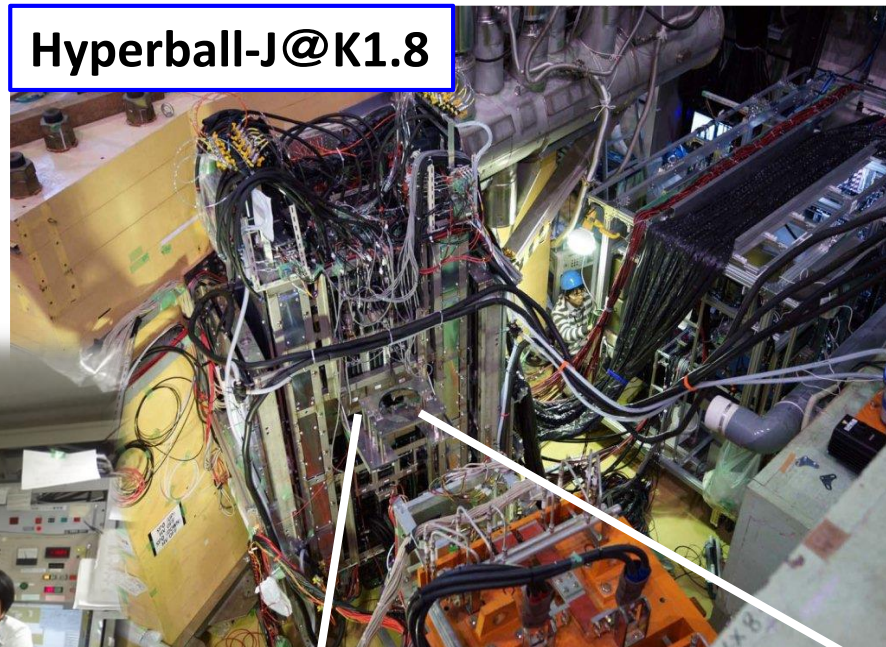
(Re-)started just after recovery
from the accident at hadron facility

Beam time for physics data taking

${}^4_{\Lambda}\text{He}$: ~5 days

${}^{19}_{\Lambda}\text{F}$: ~14 days

Hyperball-J@K1.8



Liq. Target system

Recent results

**Gamma-ray spectroscopy on $^4_{\Lambda}\text{He}$, $^{19}_{\Lambda}\text{F}$
(J-PARC E13)**

Result of $^4_{\Lambda}\text{He}$ (s-shell)



PRL 115, 222501 (2015)

PHYSICAL REVIEW LETTERS

week ending
27 NOVEMBER 2015



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

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A. Feliciello,³ M. Fujita,¹ T. Gogami,⁷ S. Hasegawa,⁹ S. H. Hayakawa,¹⁰ T. Hayakawa,¹⁰ R. Honda,¹⁰ K. Hosomi,⁹
S. H. Hwang,⁹ N. Ichige,¹ Y. Ichikawa,⁹ M. Ikeda,¹ K. Imai,⁹ S. Ishimoto,⁵ S. Kanatsuki,⁷ M. H. Kim,¹¹ S. H. Kim,¹¹
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M. Nakagawa,¹⁰ Y. Ogura,¹ A. Sakaguchi,¹⁰ H. Sako,⁹ Y. Sasaki,¹ S. Sato,⁹ T. Shiozaki,¹ K. Shirotori,¹⁴ H. Sugimura,⁹
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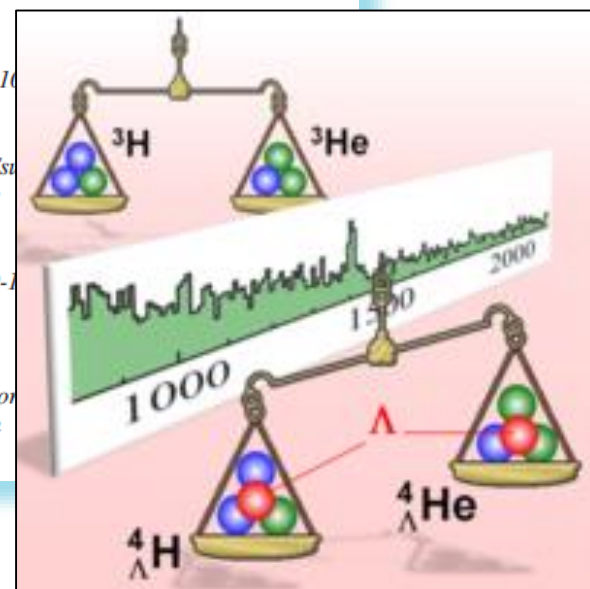
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(Received 12 August 2015; published 24 November 2015)



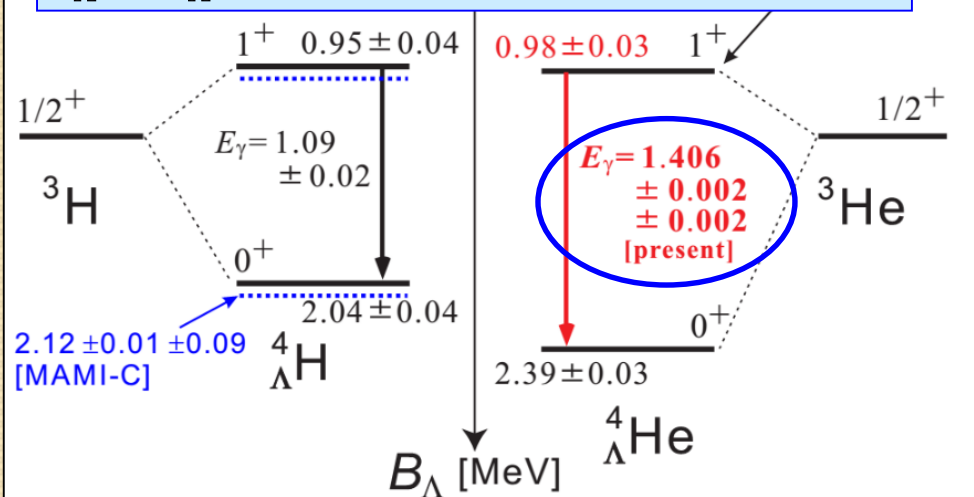
Press release

<http://www.sci.tohoku.ac.jp/news/20151125-7613.html>

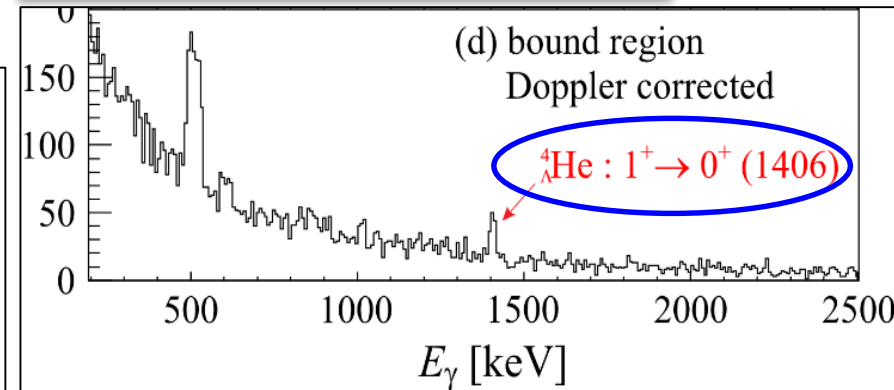
Result of ${}^4_{\Lambda}\text{He}$ (s-shell)

Level schema of mirror hypernuclei

${}^4_{\Lambda}\text{H} / {}^4_{\Lambda}\text{He}$



Obtained energy spectrum



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

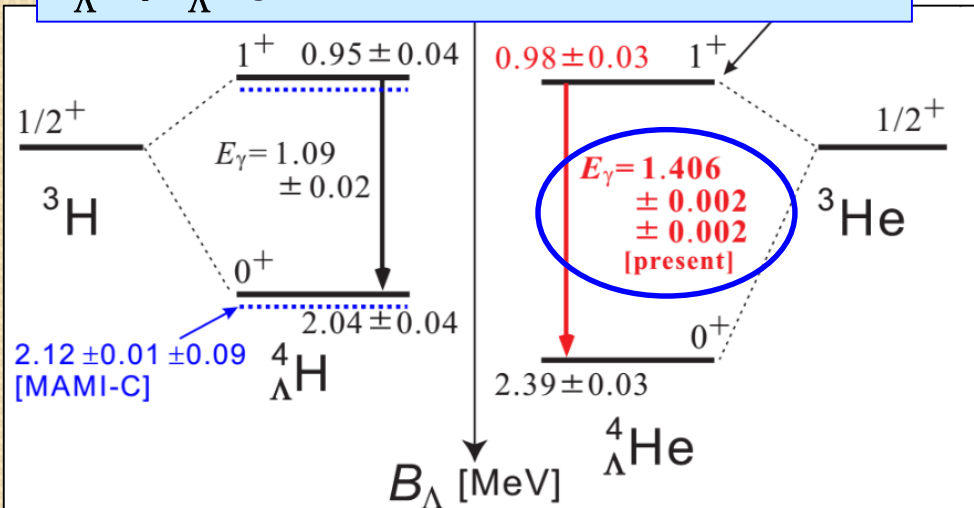
$$\text{Ex}({}^4_{\Lambda}\text{He}; 1^+) = 1.406 \pm 0.004 \text{ MeV}$$

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

Result of ${}^4_{\Lambda}\text{He}$ (s-shell)

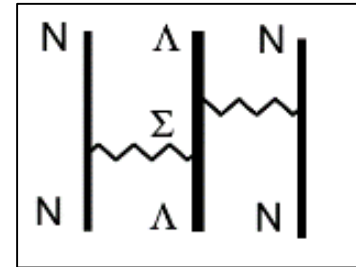
Level schema of mirror hypernuclei

${}^4_{\Lambda}\text{H} / {}^4_{\Lambda}\text{He}$



Y. Akaishi, et. al.,
Phys. Rev. Lett. 84, 3539 (2000).

**3 body $\Lambda\Sigma$ coupling
has important roll
+ same spin tendency**



**Key of CSB effect?
No large effect with NSC model?**

**Many theoretical work
based on ab-initio calc.
(accuracy: ~ 10 keV)**

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

Need high accurate data (< 10 keV)

**Precise γ -ray spectroscopy
is powerful tool to study CSB**

**We will continue with our technique
in future measurement**

Result of $^{19}_{\Lambda}\text{F}$ (*sd*-shell)



PHYSICAL REVIEW LETTERS **120**, 132505 (2018)

First Determination of the Level Structure of an *sd*-Shell Hypernucleus, $^{19}_{\Lambda}\text{F}$

S. B. Yang,^{1,2,*} J. K. Ahn,³ Y. Akazawa,⁴ K. Aoki,⁵ N. Chiga,⁴ H. Ekawa,⁶ P. Evtoukhovitch,⁷ A. Feliciello,⁸ M. Fujita,⁴ S. Hasegawa,⁹ S. Hayakawa,¹⁰ T. Hayakawa,¹⁰ R. Honda,¹⁰ K. Hosomi,⁹ S. H. Hwang,¹¹ N. Ichige,⁴ Y. Ichikawa,⁹ M. Ikeda,⁴ K. Imai,⁹ S. Ishimoto,⁵ S. Kanatsuki,⁶ S. H. Kim,³ S. Kinbara,¹² K. Kobayashi,¹⁰ T. Koike,⁴ J. Y. Lee,¹ K. Miwa,⁴ T. J. Moon,¹ T. Nagae,⁶ Y. Nakada,¹⁰ M. Nakagawa,¹⁰ Y. Ogura,⁴ A. Sakaguchi,¹⁰ H. Sako,⁹ Y. Sasaki,⁴ S. Sato,⁹ K. Shirotori,² H. Sugimura,⁹ S. Suto,⁴ S. Suzuki,⁵ T. Takahashi,⁵ H. Tamura,⁴ K. Tanida,⁹ Y. Togawa,⁴ Z. Tsamalaidze,⁷ M. Ukai,⁴ T. F. Wang,¹³ and T. O. Yamamoto⁴

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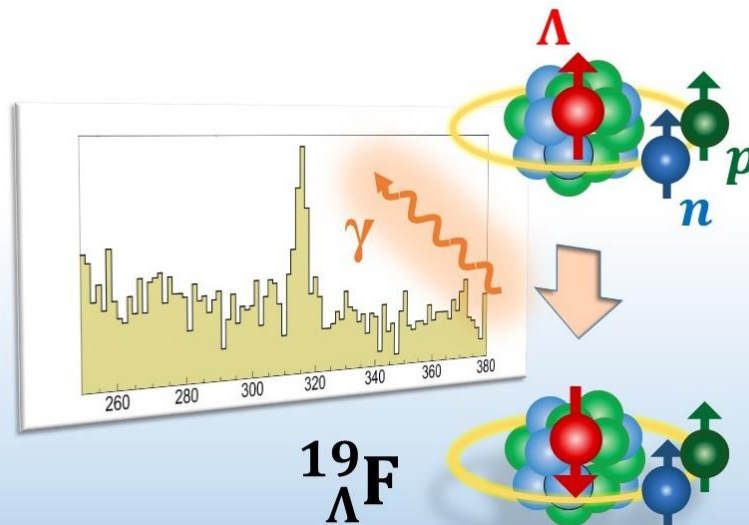
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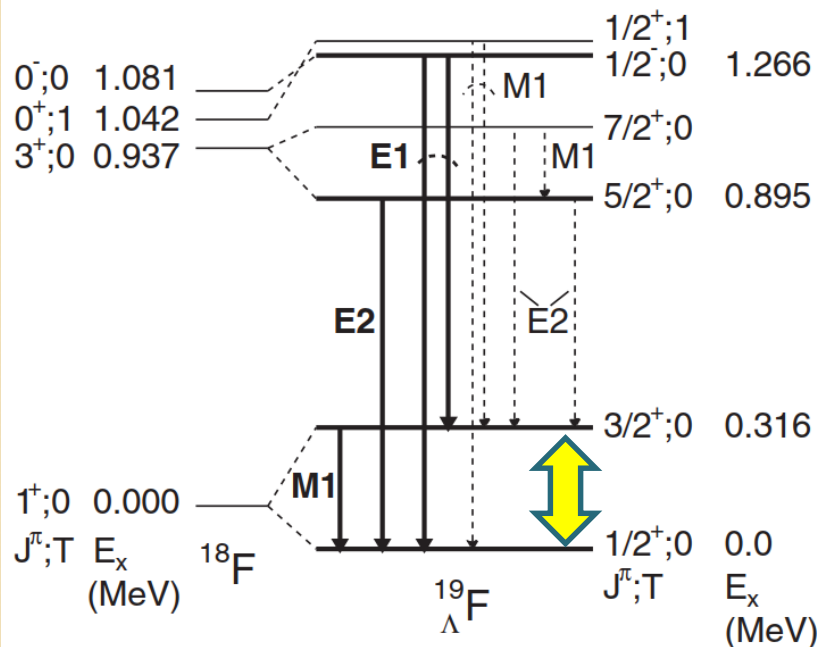
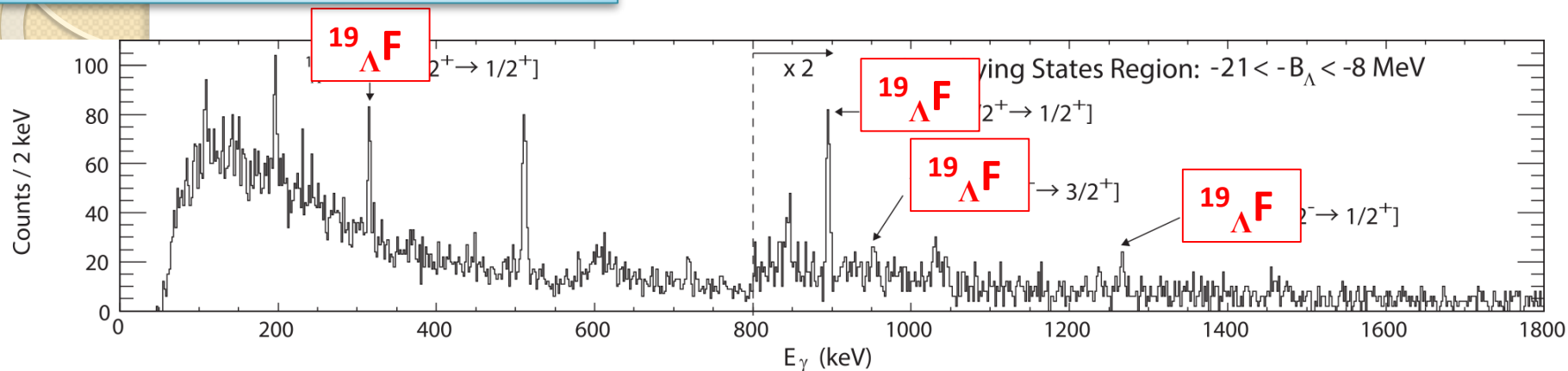


Press release

<https://www2.kek.jp/ipns/ja/release/hyper/>

Result of $^{19}_{\Lambda}\text{F}$ (sd-shell)

Obtained energy spectrum



S.B. Yang et al., Phys. Rev. Lett. 120, 132505 (2018)

Energy of g.s. spin-doublet
was determined
(First data on sd-shell)

$$E_x(^{19}_{\Lambda}\text{F}; 3/2^+) = 315.5 \pm 0.4^{+0.6}_{-0.5} \text{ keV}$$

Radial dependence

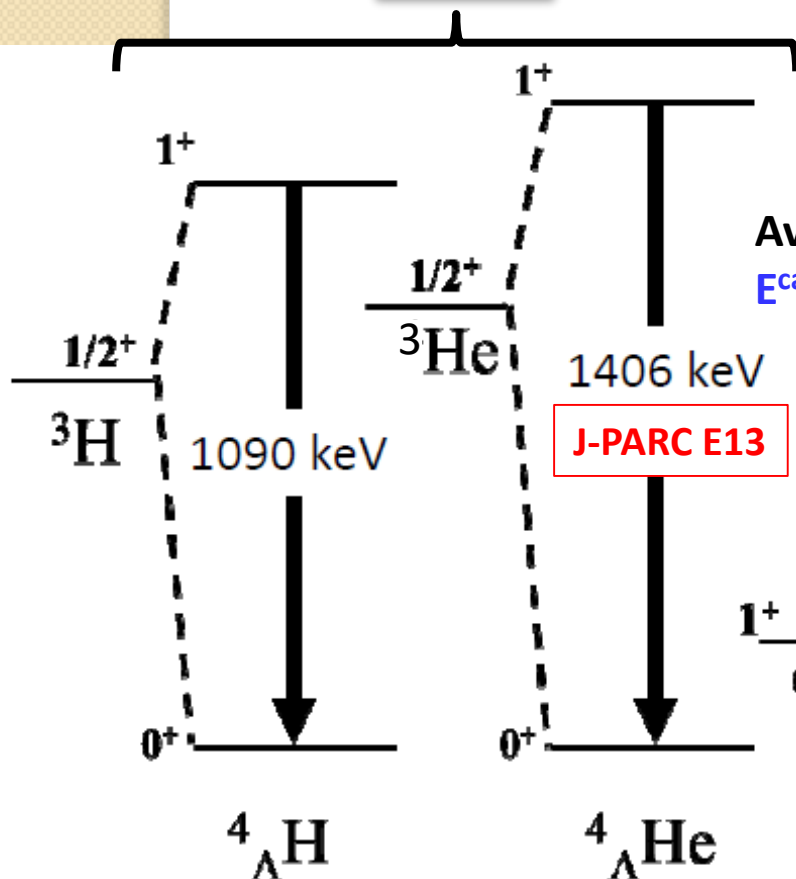
Now, we have s-, p-, sd-shell data.

Shell model calc. (Umeya & Motoba) reproduce experimental data.

with NSC(e,f) model

* adjusted to p-shell data

s-shell



Our knowledge and theoretical framework is also good in s- and sd-shell

Ave(E^{exp}) = 1248 keV

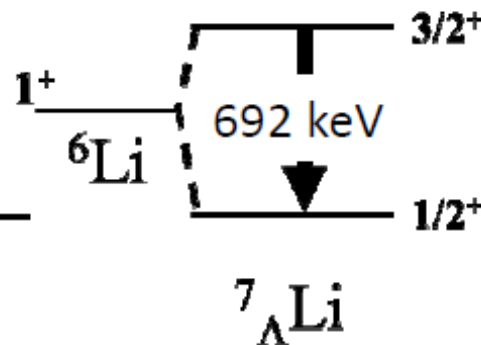
$E^{\text{cal}} = 1232 \text{ keV}$

Spin-dependent ~50%
 $\Lambda\Sigma$ coupling ~50%

J-PARC E13

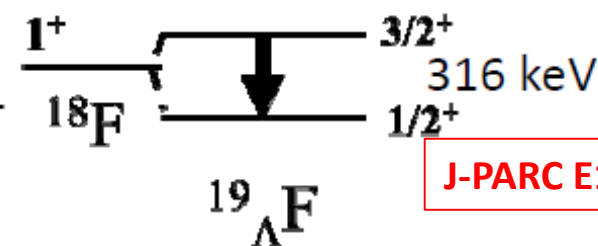
p-shell

$E^{\text{cal}} = 692 \text{ keV}$
(adjusted)



sd-shell

$E^{\text{cal}} = 346 \text{ keV}$



J-PARC E13

Future measurement

**Gamma-ray spectroscopy on ${}^4_{\Lambda}\text{H}$, ${}^7_{\Lambda}\text{Li}$
(J-PARC E63)**

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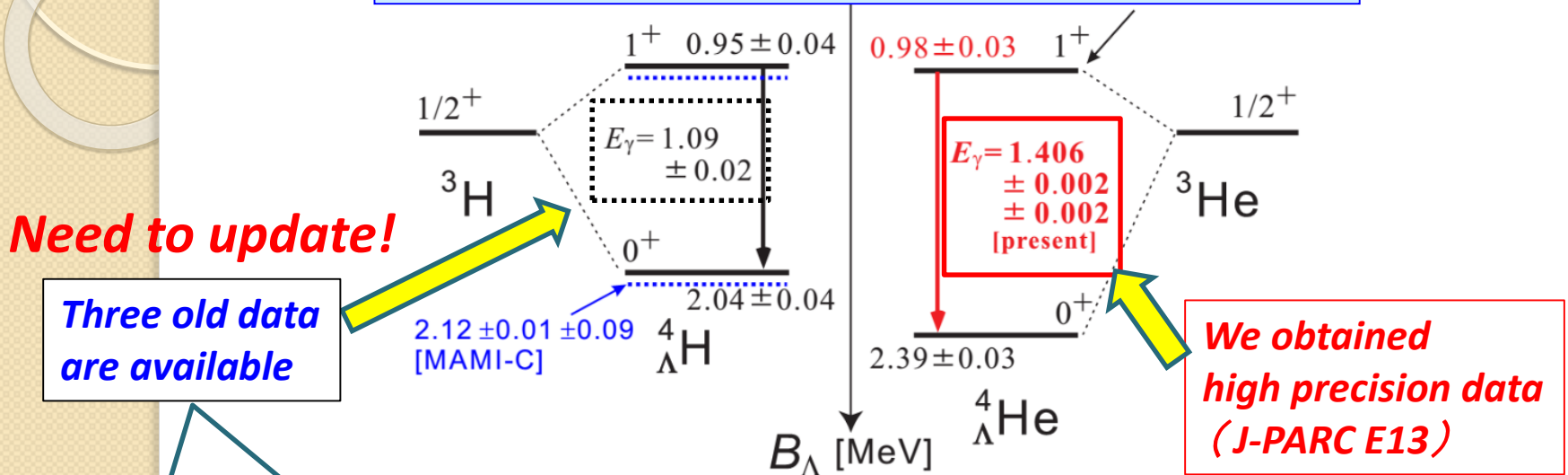
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J-PARC
E63 (E13-2)
Submitted in 2015
stage-2 approval

- ${}^4_{\Lambda}\text{H}$ excitation energy
(Strength of CSB effect)
- ${}^7_{\Lambda}\text{Li}$ lifetime
(Λ magnetic moment
in nuclear medium)

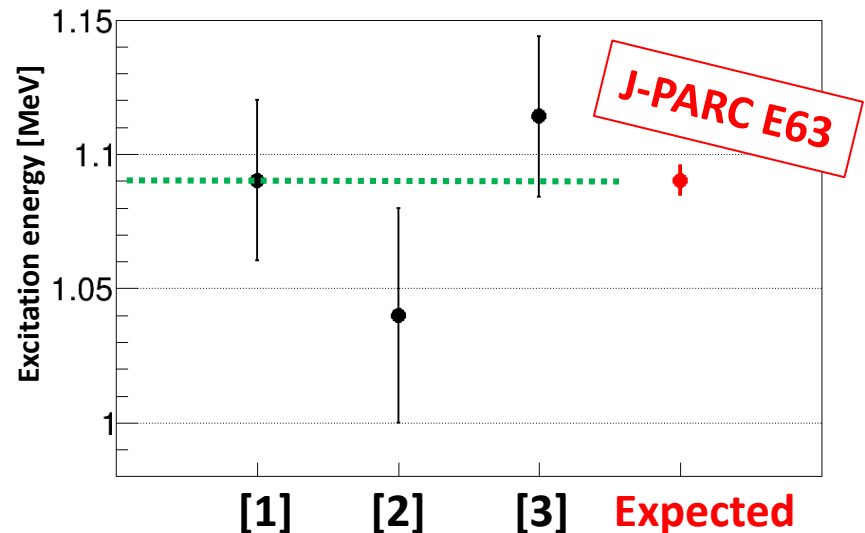
CSB effect in A=4 system

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



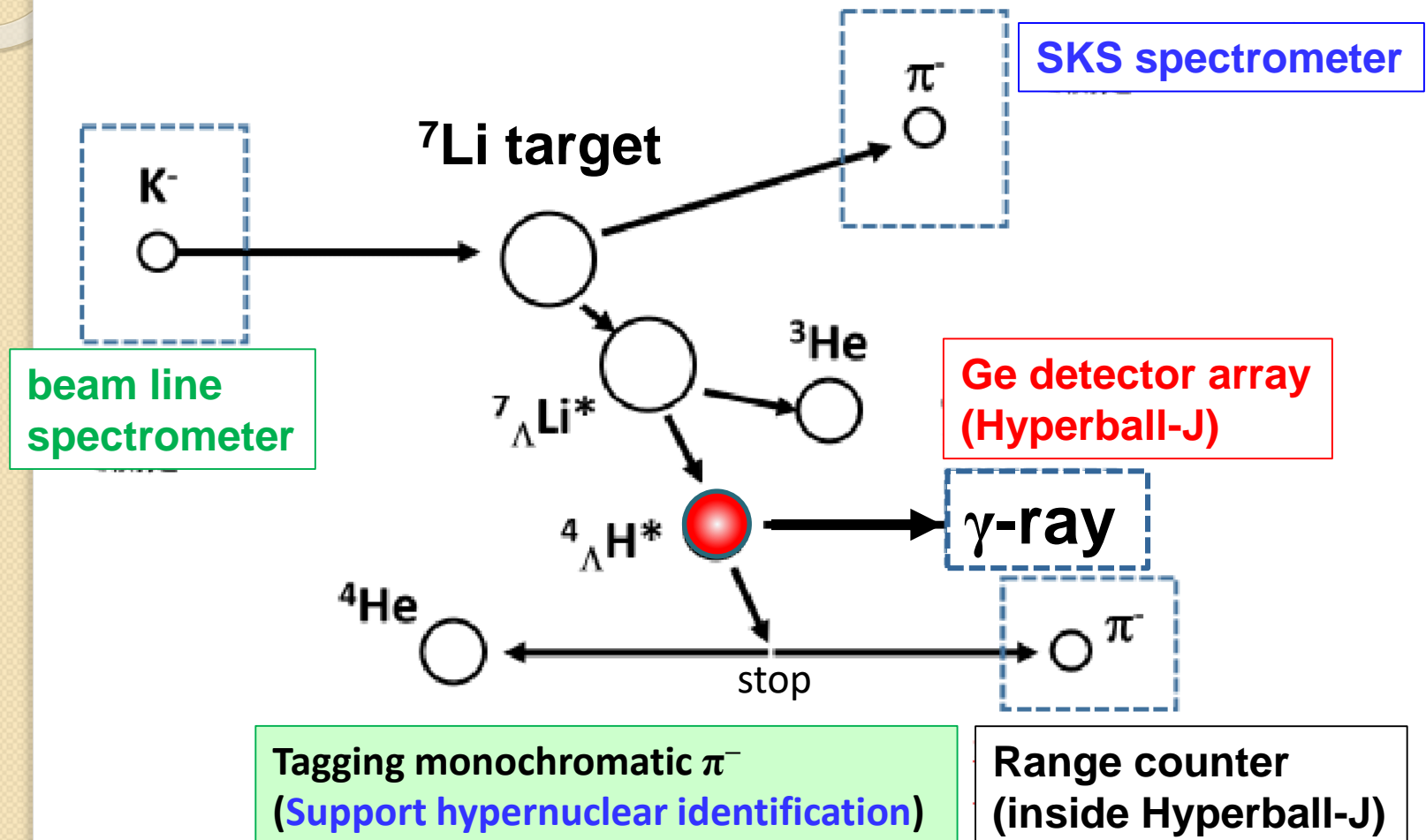
	${}^4_{\Lambda}\text{H}(1^+ \rightarrow 0^+)$
[1] M. Bedjidian <i>et al.</i> (1976)	1.09 ± 0.03
[2] M. Bedjidian <i>et al.</i> (1979)	1.04 ± 0.04
[3] A. Kawachi (1997)	1.114 ± 0.030
Weighted average	1.09 ± 0.02

rather large deviation



TOHOKU

Almost common with J-PARC E13



γ -ray spectroscopy of ${}^7_{\Lambda}\text{Li}$

Λ magnetic moment in nuclear density

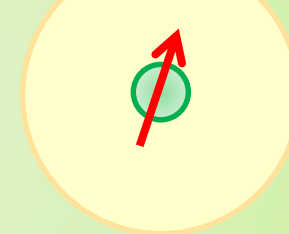
$$\mu_{\Lambda} = \frac{e\hbar}{2m_{\Lambda}c} \quad (m_s: \text{constituent quark mass})$$

Mass change ?

Λ in free space



Λ in nuclear medium

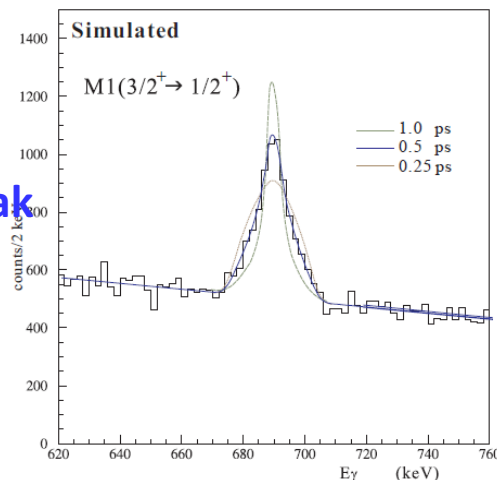


Different?

Life time of M1 transition [${}^7_{\Lambda}\text{Li}; 3/2^+ \rightarrow 1/2^+$] (~ 0.5 ps)
 $\rightarrow \Lambda$ magnetic moment

$$\frac{1}{\tau} = \frac{16\pi}{9} E_{\gamma}^3 \left(\frac{3}{8\pi} \frac{(2J_{low} + 1)}{2J_c + 1} (g_c - g_{\Lambda})^2 \right) \quad \text{Assuming weak coupling between core and } \Lambda$$

shape analysis on
Doppler broaden peak



Key point:

High stopping power
 \rightarrow **Dense target**

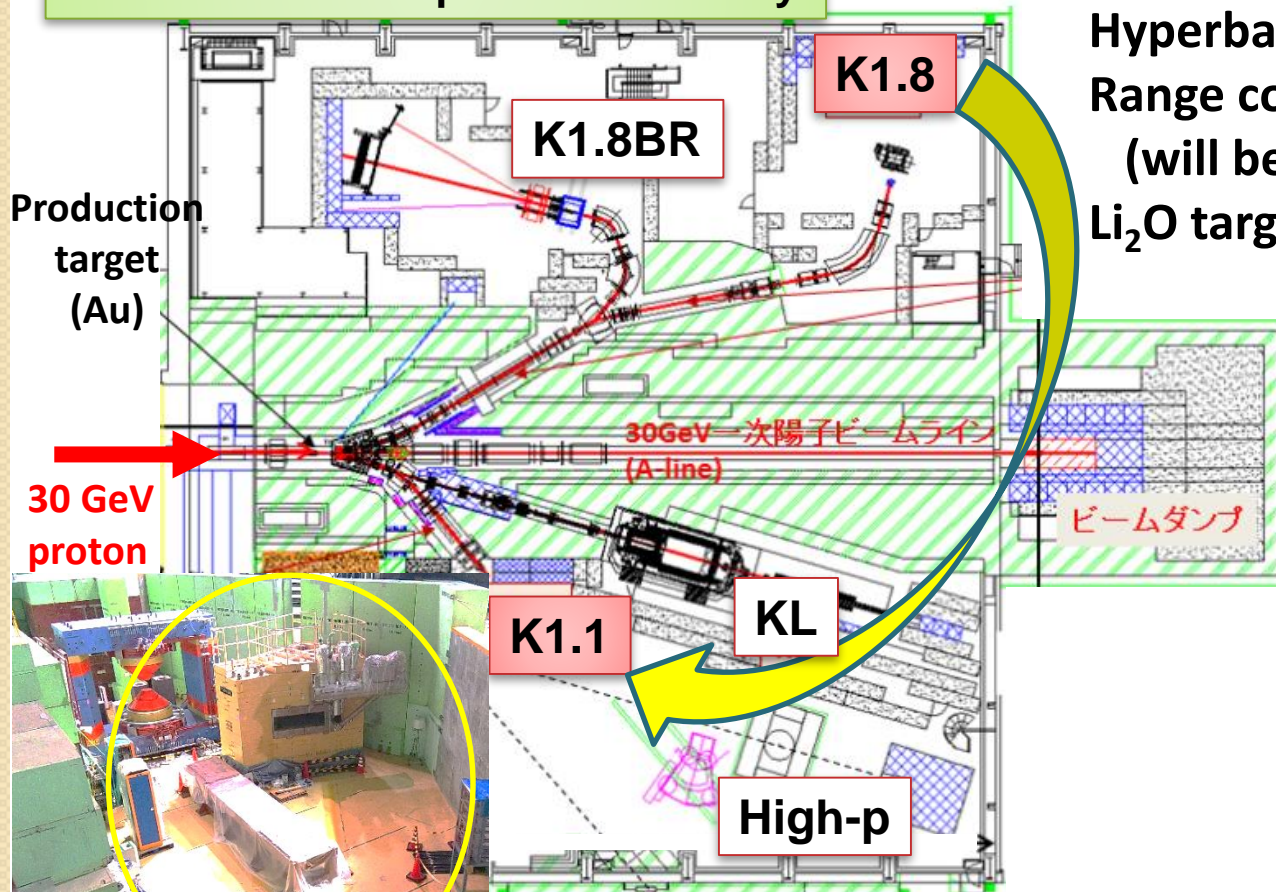
Li_2O crystal
($\rho = 2.013 \text{ g/cm}^3$)



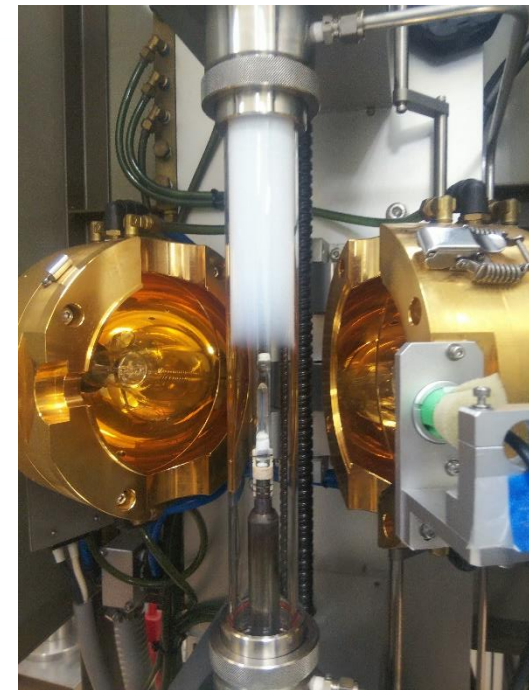
Preparation status

0.9-1.1 GeV/c K^- beam to adjust Doppler broadening
→ 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)
 Li_2O target: making crystal @JAEA



Summary



- **Gamma-ray spectroscopy is powerful tool for study of spin-dependent term and CSB in Λ N interaction**
- **Measurement for s- and sd-shell hypernuclei (E13) was successfully done.**
 - ${}^4_{\Lambda}\text{He}$ **CSB in excitation energy + spin-dependence**
 - ${}^{19}_{\Lambda}\text{F}$ **Test theoretical framework**
- **Future measurement (J-PARC E63) [stage-2 approval]**
 - ${}^4_{\Lambda}\text{H}$ **Precise data for CSB study**
 - ${}^7_{\Lambda}\text{Li}$ **Lifetime measurement for Λ magnetic moment in medium**