Hypernuclear gamma-ray spectroscopy: summary and future prospect

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ΛN interaction study

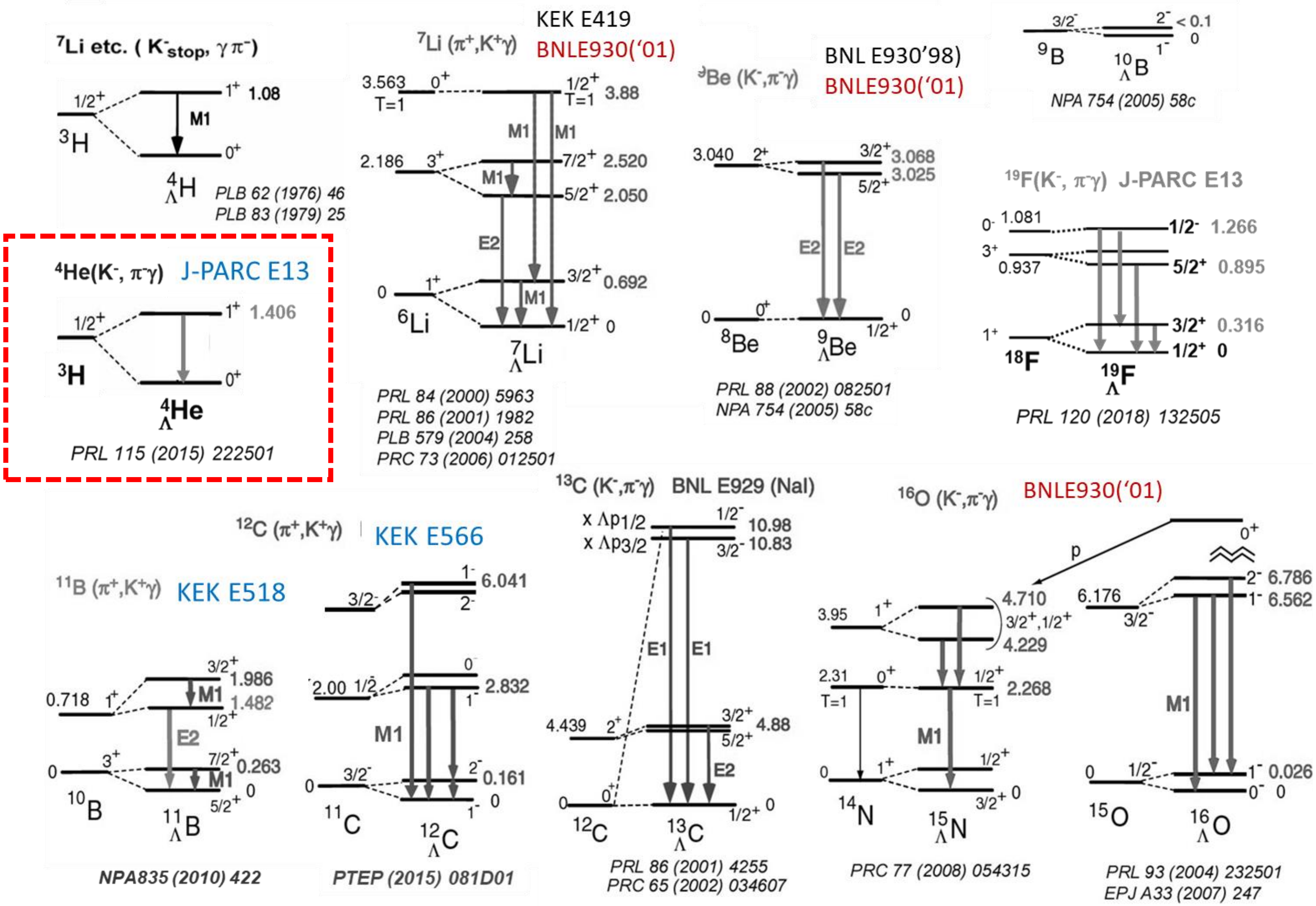
- Light hypernuclear gamma-ray spectroscopy
  - ${}^{4}_{\Lambda}He$, ${}^{4}_{\Lambda}H$
  - ${}^{3}_{\Lambda}H$ gamma search

In-medium Λ g-factor

- B(M1) of the spin-flip M1 transition
  - ${}^{7}_{\Lambda}Li$ (3/2+→1/2+)
  - ${}^{12}_{\Lambda}C$ ($2^{-} \rightarrow 1^{-}$)

Summary

Hypernuclear γ-ray data (2021)



ΛN spin dependent interactions (spin-spin, spin-orbit, tensor)

✓ Charge symmetry breaking between Λn and Λp interaction

Λ impurity effect in nuclei

Future plans

- ✓ Light hypernuclei
  - ${}^{4}_{\Lambda}H$ (CSB), ${}^{3}_{\Lambda}H^*$ J-PARC E63 @K1.1
- ✓ Spin-flip B(M1) and in-medium g_{Λ}
  - ${}^{7}_{\Lambda}Li_{\,g.s.}(3/2^{+}\rightarrow 1/2^{+})$ J-PARC E63 @K1.1
  - ${}^{12}_{\Lambda}C_{g.s.}(2^{-}\rightarrow 1^{-})$ J-PARC future plan

E1(p_{Λ}->s_{Λ}) for B_{Λ} (-> ΛNN force) and ΛS splitting

Light hypernuclei

$^{4}_{\Lambda}He(1^{+} \rightarrow 0^{+})$ E13 in 2015

$^{4}_{\Lambda}H\ (1^{+} \rightarrow 0^{+})$ E63

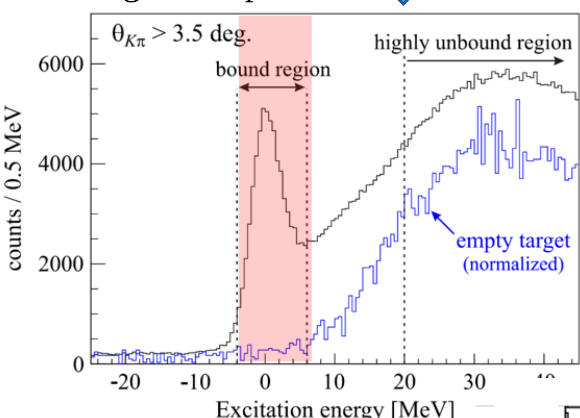
$^{3}_{\Lambda}H$ gamma-ray search E63

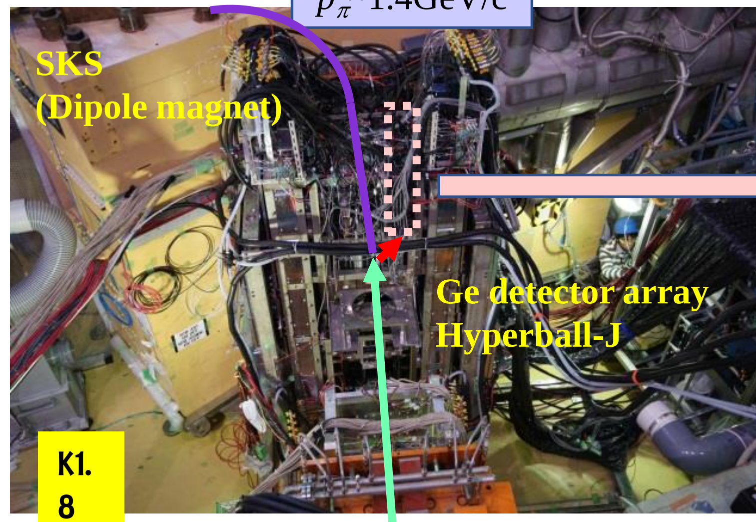
Precise measurement of $^{4}_{\Lambda}$He($1^{+} \rightarrow 0^{+}$) transition

J-PARC E13
K1.8 in 2015

$$^{4}\mathrm{He}\,(K^{-},\pi^{-})\,^{4}_{\Lambda}\mathrm{He}^{*} \rightarrow {}^{4}_{\Lambda}\mathrm{He} + \gamma$$

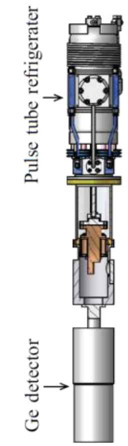
Missing mass spectrum





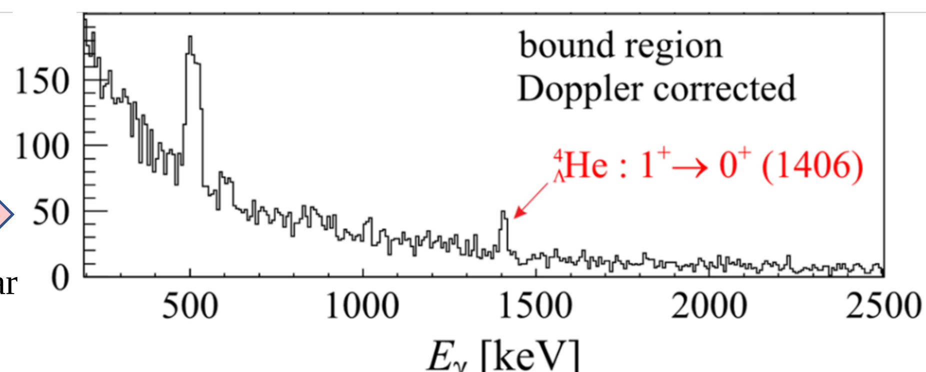
p_{π}~1.4GeV/c

K^{-} beam
p_{K}=1.5GeV/c



Germanium(Ge) detector

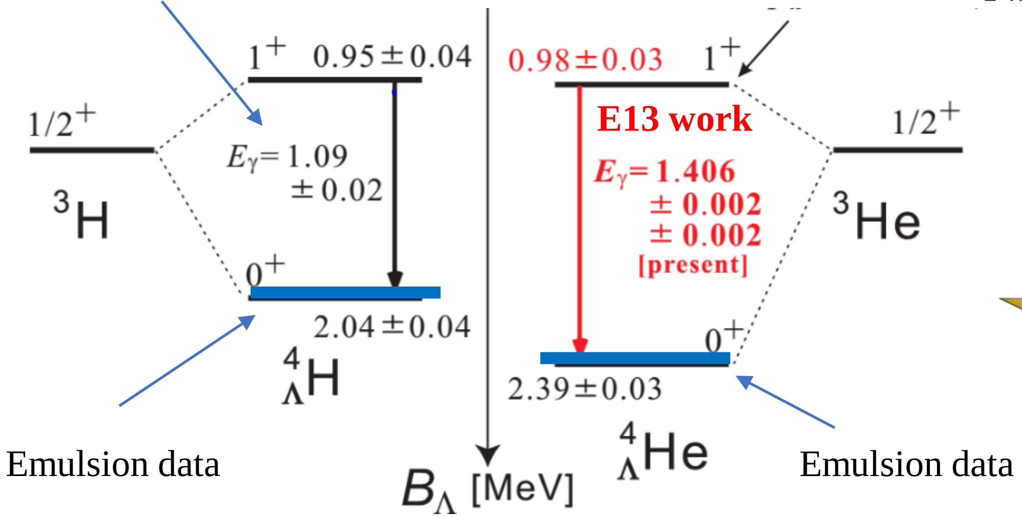
γ-ray energy spectrum



Select hypernuclear production event

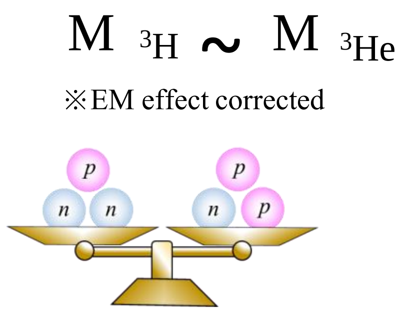
T.O.Yamamoto PRL(2015)

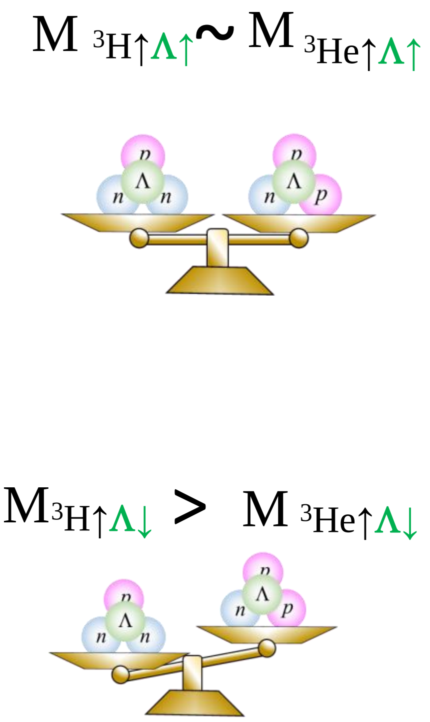
Level structure of 4-body hypernuclei



Level scheme of 4-body mirror hypernucleus

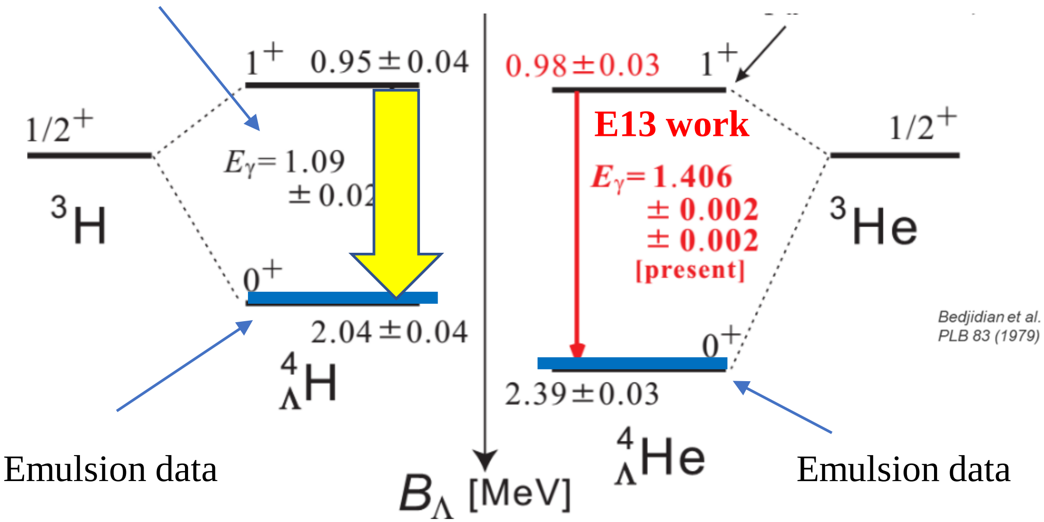
Charge symmetry of NN interaction



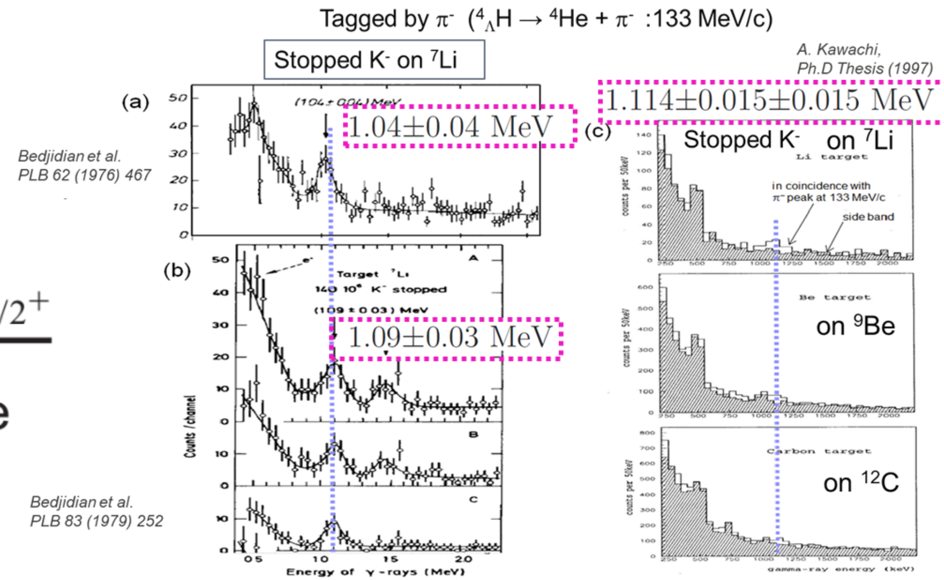


Charge symmetry breaking between Λp and Λn interaction and its spin dependence is confirmed.

Level structure of 4-body hypernuclei



Level scheme of 4-body mirror hypernucleus



Not accurate as the present $^{4}_{\Lambda}$He data

NaI ~ 70 keV(FWHM)@1 MeV
+ large Doppler broad
for large momentum transfer
by stopped K- absorption method

Proposed as E63

Ge ~ a few keV(FWHM)@1 MeV
+ smaller Doppler broad via inflight (K^-,π^-)

Production of $^{4}_{\Lambda}$H(1^{+}) state as secondary hypernuclei at E63

E63 nat. Li target RUN

^{7}Li

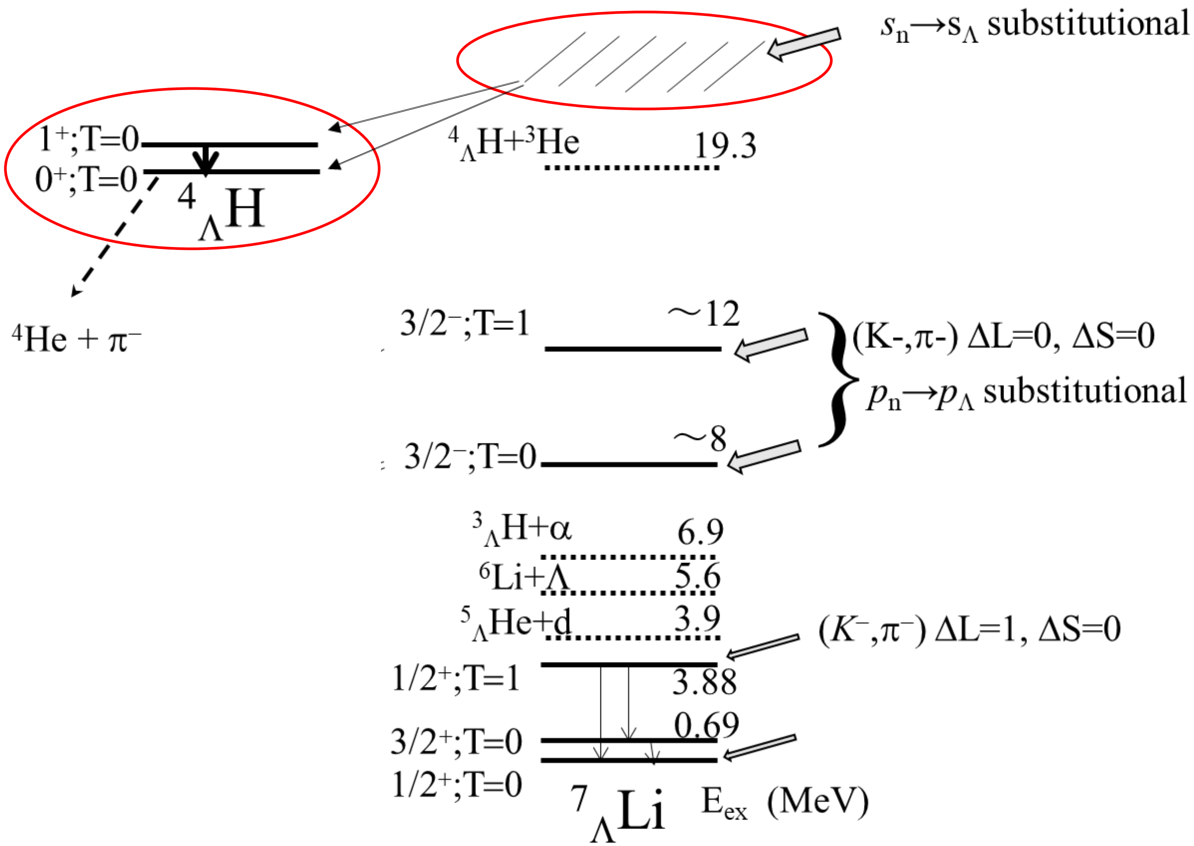
$K^{-} + (\alpha + t) \rightarrow {}^{7}_{\Lambda}\mathrm{Li}^{*} + \pi^{-}$

$^{4}_{\Lambda}$H

$^{7}_{\Lambda}\mathrm{Li}^{*} \rightarrow {}^{3}\mathrm{He} + (\Lambda + t)$

Expected yield ratio

$^{4}_{\Lambda}\mathrm{H}(1^{+}):{}^{4}_{\Lambda}\mathrm{H}(0^{+})$ = 3 : 1



Production of $^{3}_{\Lambda}H(T=1)$ state as secondary hypernuclei at E63

By product of E63

E63 nat. Li target RUN

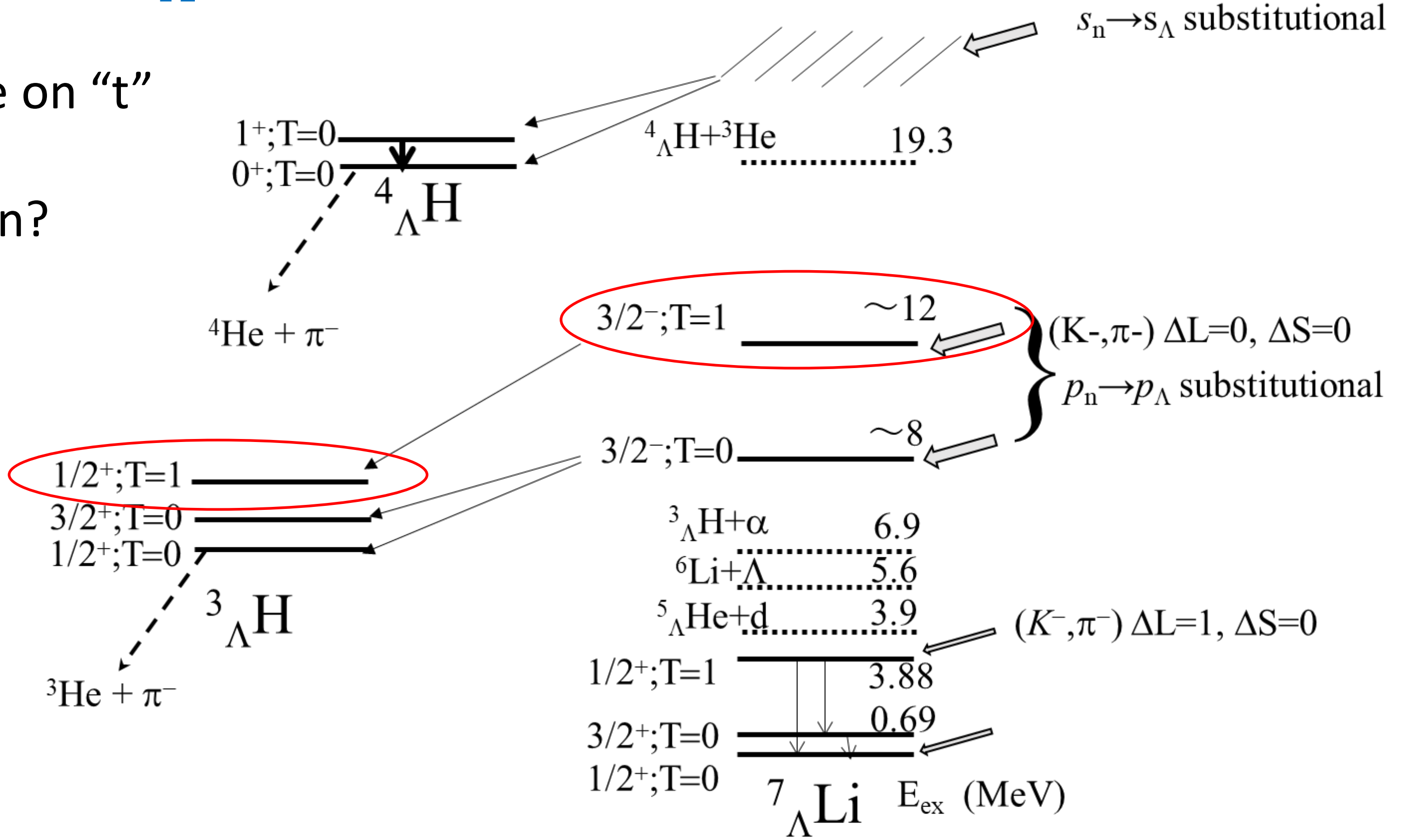
^{7}Li

$K^- + (\alpha + t) \rightarrow {}^{7}_{\Lambda}Li^*(T=1) + \pi^-$

$^{7}_{\Lambda}Li^*(T=1) \rightarrow \alpha + {}^{3}_{\Lambda}H^*(T=1)$

substitutional state on "t"

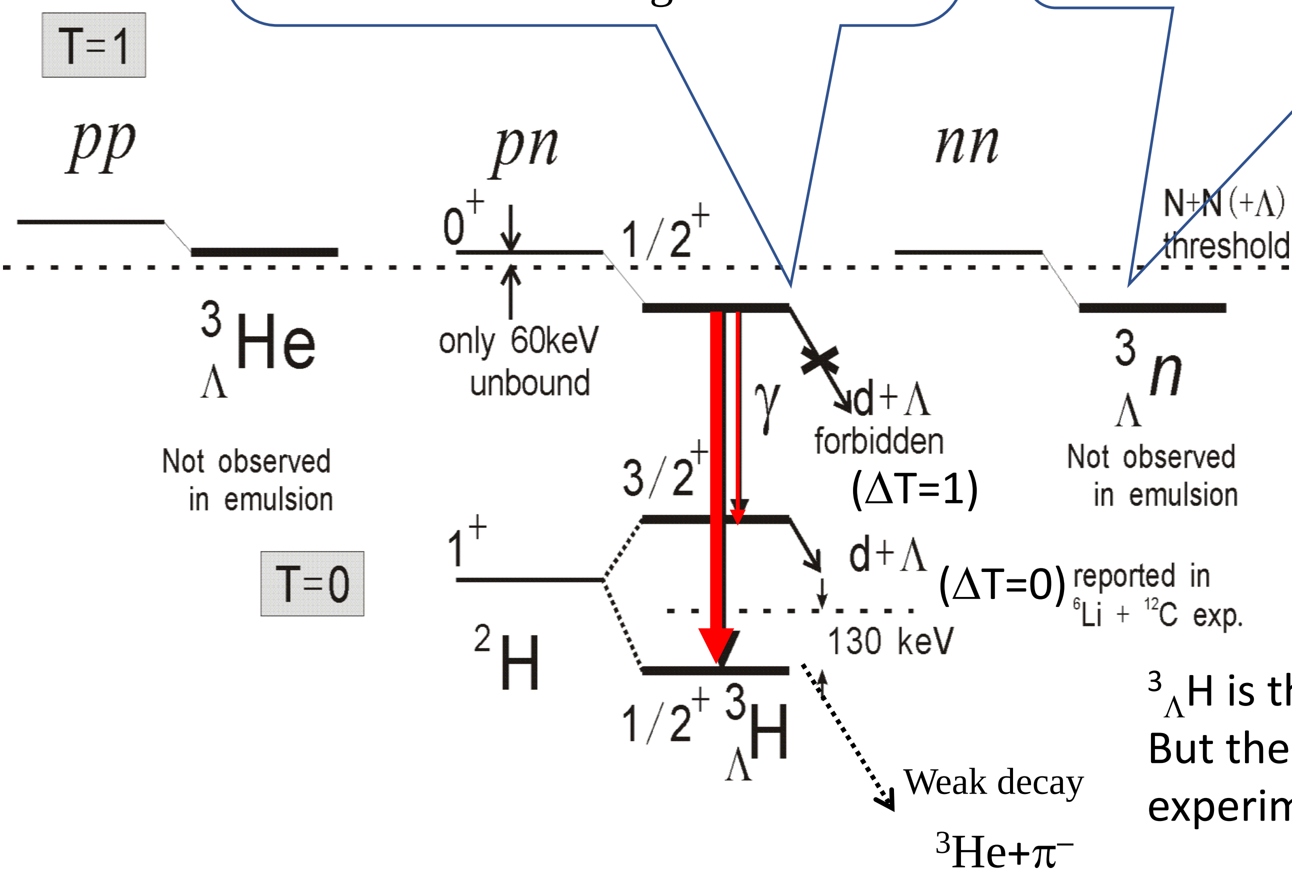
Large cross section?



Expected level scheme of NNΛ systems (if nnΛ is bound)

If $^{3}_{\Lambda}n$ is bound, $^{3}_{\Lambda}H(1/2^{+};T=1)$ is lower than the pnΛ threshold. $^{3}_{\Lambda}H(1/2^{+};T=1)$ state can decay by γ-emission due to the isospin conservation of strong interaction

Bound nnΛ was repoted in GSI Exp.
But negative result from recent J-Lab data



Even if the $1/2^{+};T=1$ state is slightly higher than the threshold, there is a chance to have finite branching ratio of gamma decay.

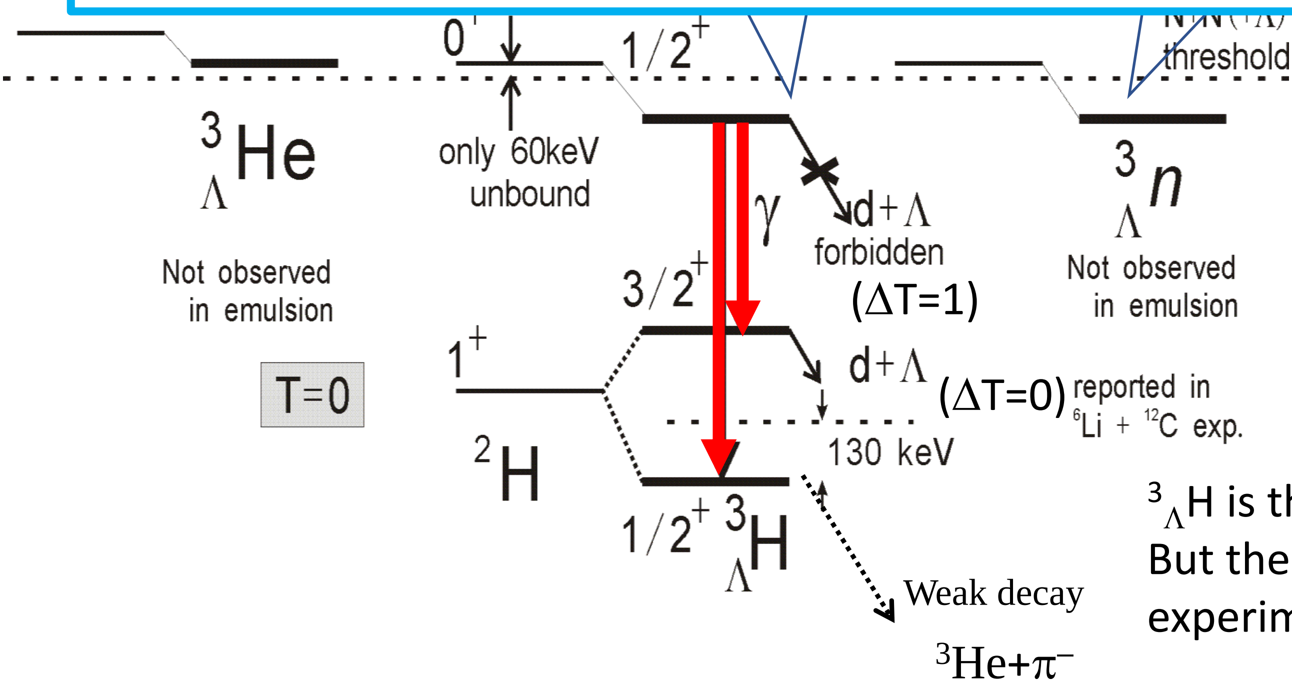
$^{3}_{\Lambda}H$ is the lightest hypernuclei.
But the situation of recent experimental data is becoming chaotic.

Expected level scheme of NNΛ systems (if nnΛ is bound)

Ge detector is well calibrated detector
(systematic error < 1 keV, resolution ~ 3 keV(FWHM)@2 MeV).

If we can observe $^{3}_{\Lambda}$H gamma-ray,
the problems of different experimental values of $^{3}_{\Lambda}$H binding energy and existing of nnΛ would be solved.

branching ratio of gamma decay.



$^{3}_{\Lambda}$H is the lightest hypernuclei.
But the situation of recent experimental data is becoming chaotic.

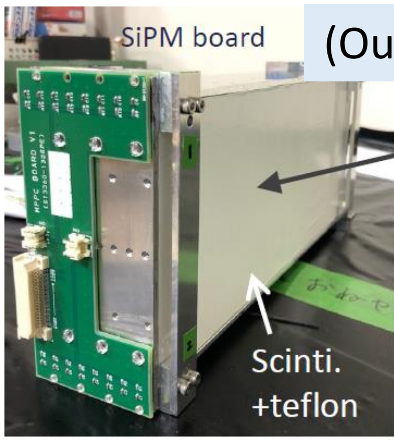
Identification of hypernuclear species (Triple coincidence method)

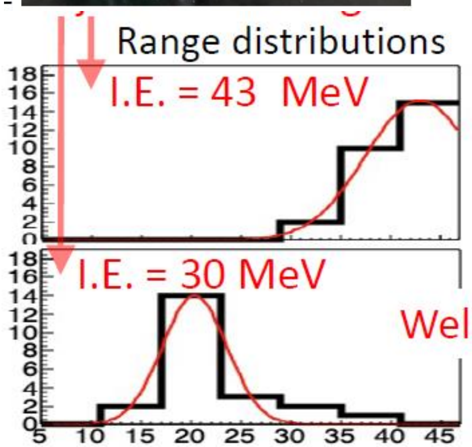
E63 nat. Li target RUN

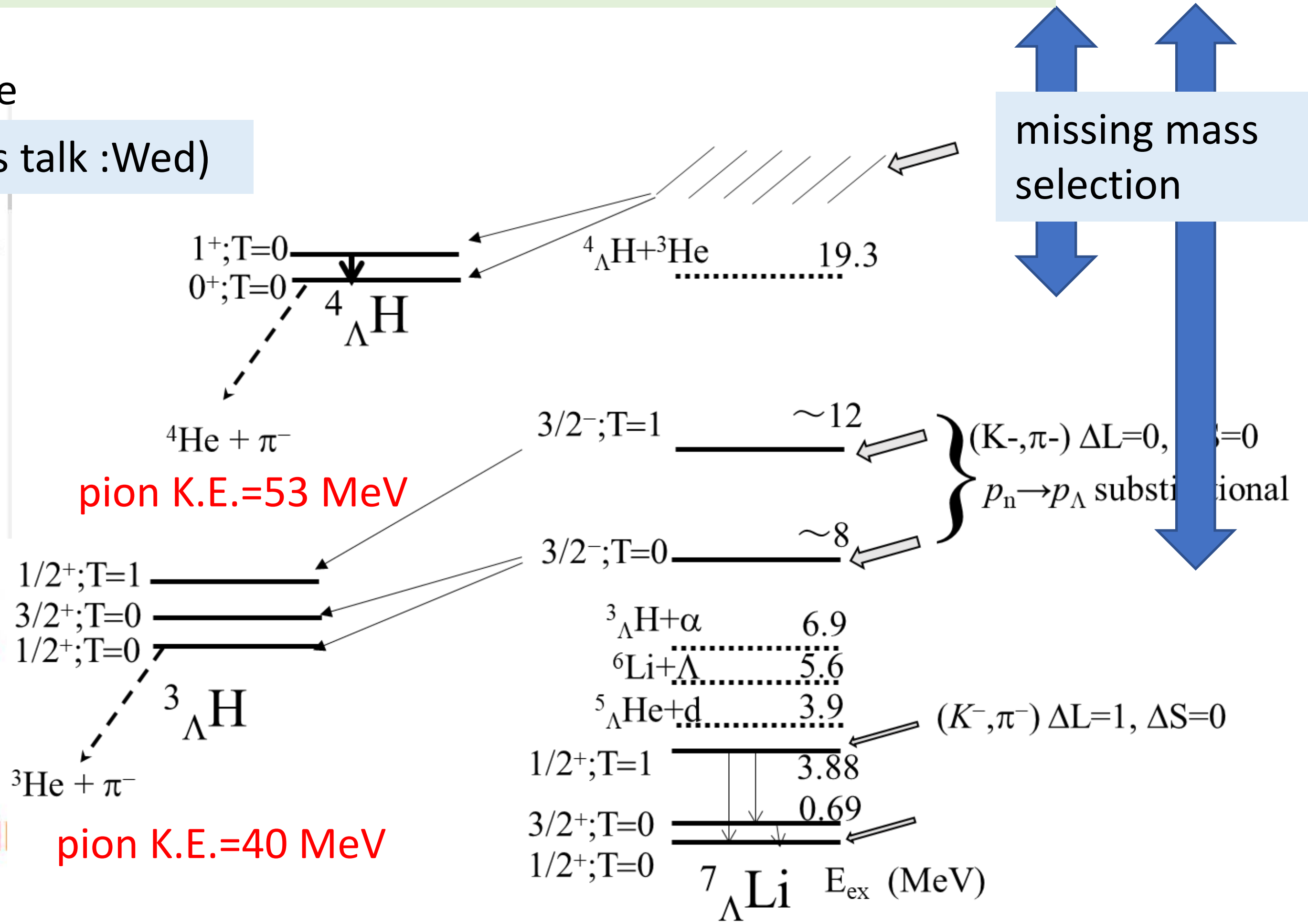
Missing mass (SKS@K1.1) ~ 8 MeV(FWHM) ~10 g thick target
× weak π^- (range counter)
× gamma-ray (Ge: Hyperball-J)

Range counter Prototype

(Oura's talk :Wed)

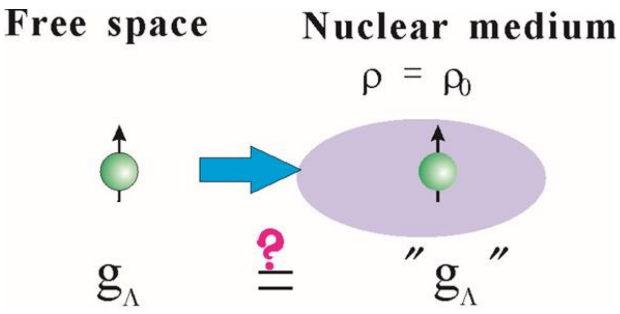


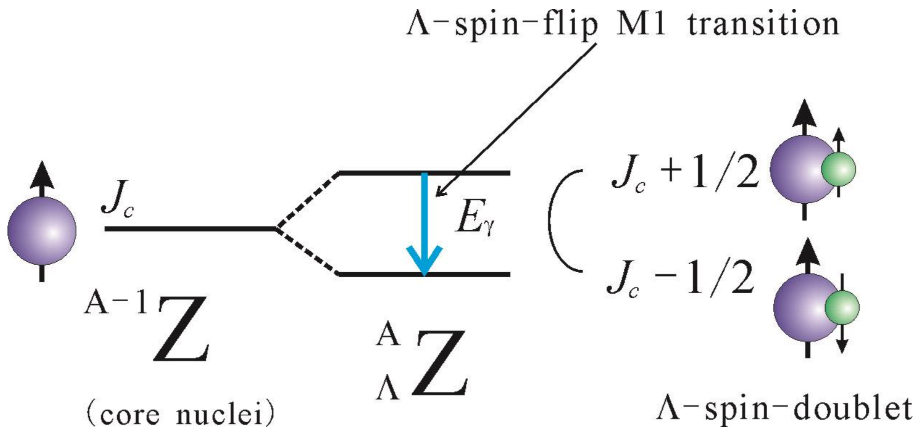




Spin-flip B(M1) and in-medium g_Λ

Λ g-factor and spin-flip M1 transition

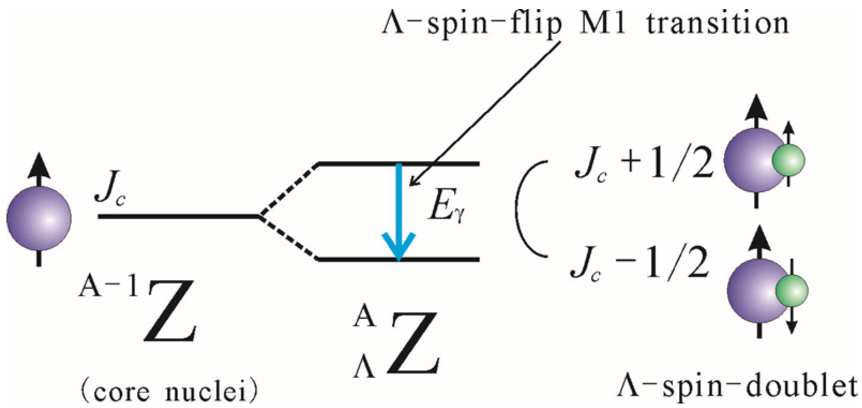




$$B(M1) = \frac{3}{8\pi}\frac{(2J_{low}+1)}{(2J_c+1)}(g_c - g_\Lambda)^2 = \frac{9}{16\pi}\frac{\Gamma_{M1}}{E_\gamma^3}$$

$$\Gamma_{M1} = \text{B.R.(M1)} / \tau$$

Expected $1/\Gamma_{M1}$ values of light hypernuclei

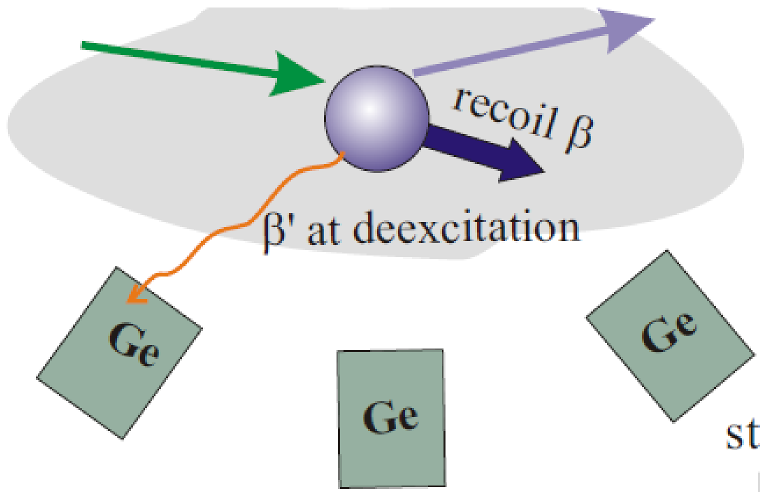


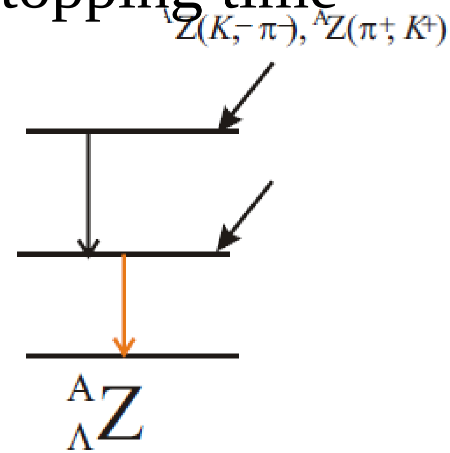
	g.s. doublet J_{up}, J_{low}	E_γ [keV] Exp.	Core g-factor [μN]	Calculated $1/\Gamma_{M1}$ [ps]
$^{4}_{\Lambda}He$	1^+, 0^+	1406	–4.2552	0.1
$^{7}_{\Lambda}Li$	$3/2^+$, $1/2^+$	692	0.8220	0.5
$^{11}_{\Lambda}B$	$7/2^+$, $5/2^+$	262	0.6002	9
$^{12}_{\Lambda}C$	2^-, 1^-	160	–0.643	440
$^{19}_{\Lambda}F$	$3/2^+$, $1/2^+$	316	0.849(calc.)	6

Lifetime measurement -1

Doppler-shift-attenuation-method (γ peak shape analysis)

In case: lifetime is the same order as the stopping time



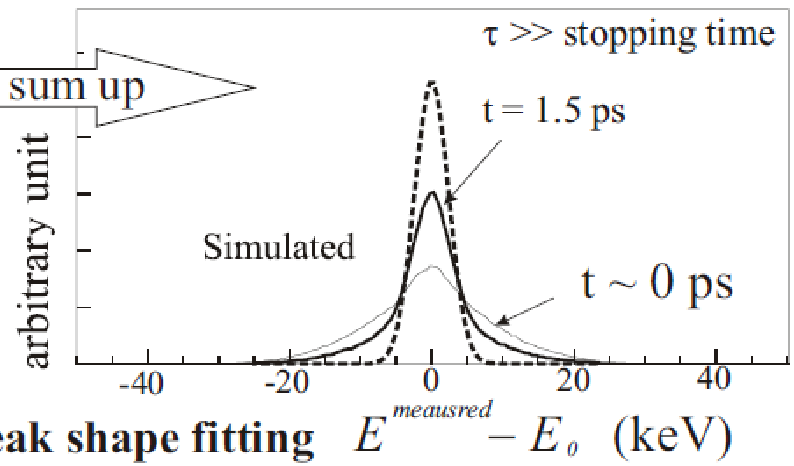


τ=0.5 ps

stopping time ∼2 ps, initial β ~ 3%

$$E^{measured} = E_0 / \gamma(1-\beta' \cos\theta)$$

sum up



lifetime (τ) can be obtained by peak shape fitting

The best sensitivity realize for lifetime ~ stoppint time x 0.5

Lifetime measurement -1

Doppler-shift-attenuation-method (γ peak shape analysis)

In case: the same order of lifetime as stopping time

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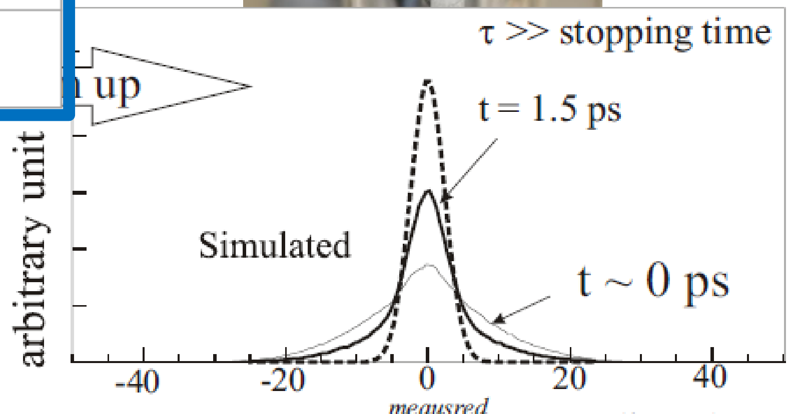
Li_2O single crystal ρ= 2 g/cm^3

stopping time

2 ~ 3 ps via (K^-,π^-)~ 1 GeV/c

τ=0.5 ps

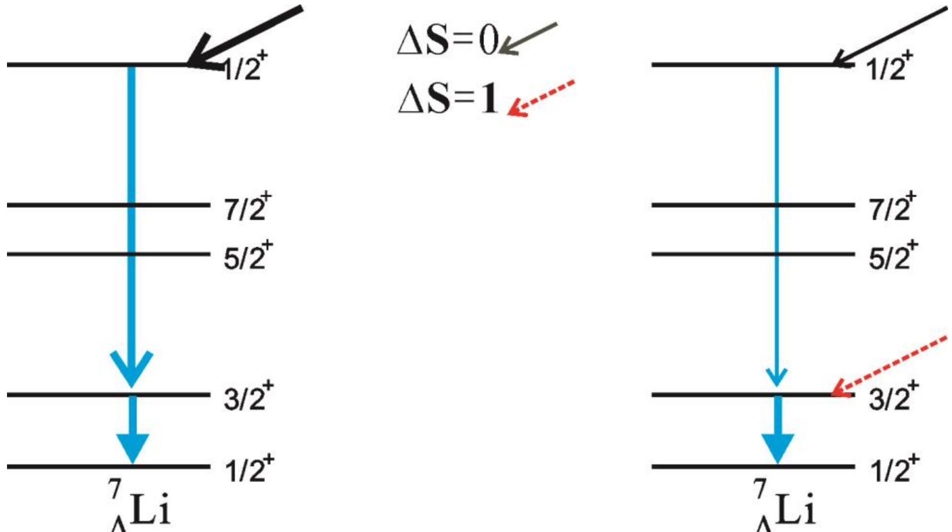


lifetime (τ) can be obtained by peak shape fitting

The best sensitivity realize for lifetime ~ stoppint time x 0.5

Simulation of B(M1) accuracy of $^{7}_{\Lambda}$Li

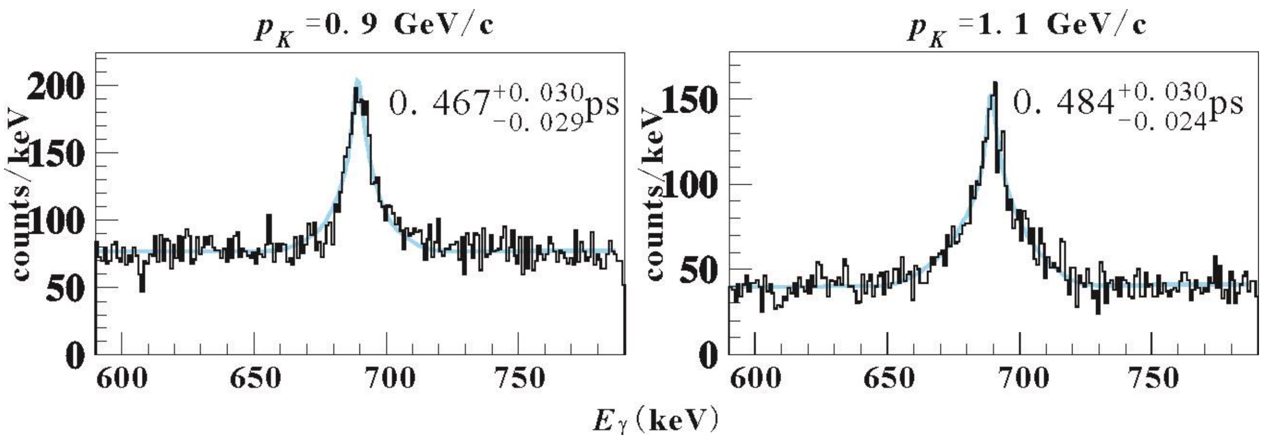
E63 Li_2O target RUN



3/2+→1/2+
2.5 counts/h

3/2+→1/2+
3.0 counts/h

Li_2O (2g/cm3) target



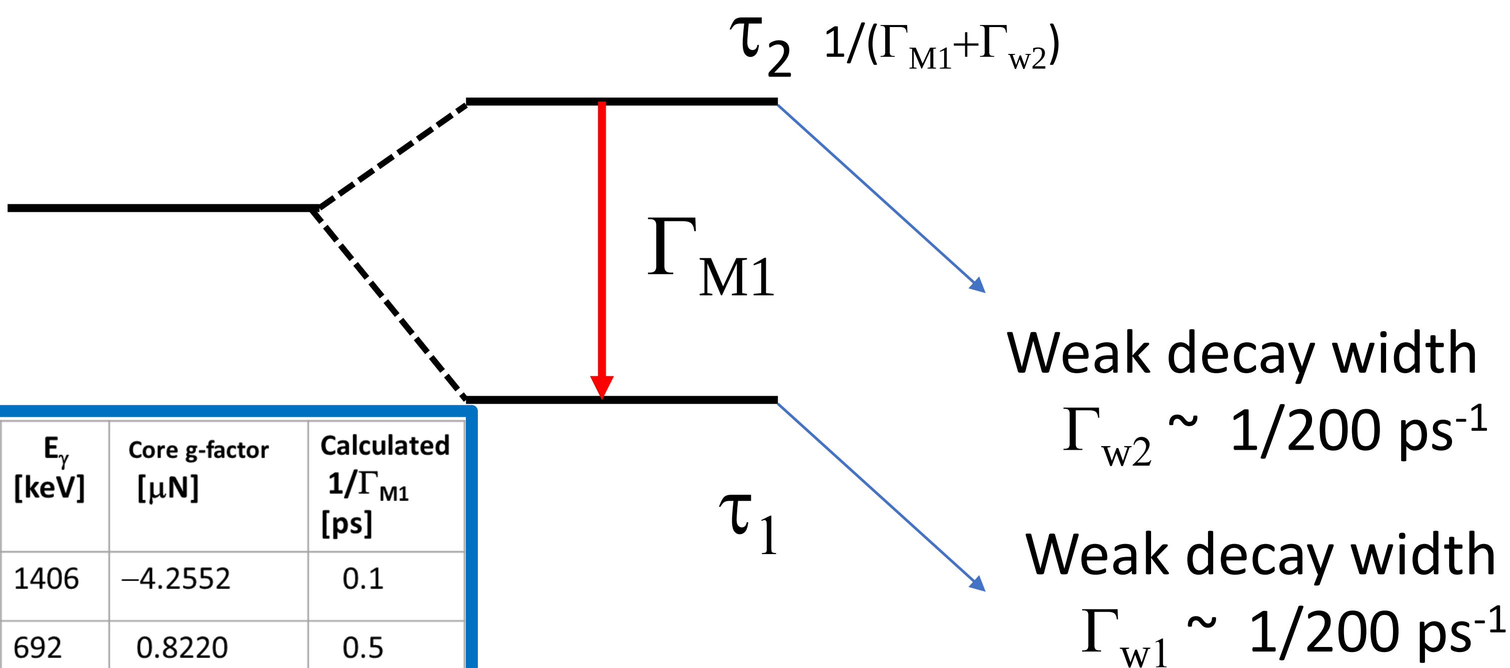
Simulation for
one month beam time

Both case, 6 % B(M1) accuracy , 3 % (g_c-g_Λ) accuracy is expected to be obtained

Beam momentum will be determined by real data for a few days beam time.

Lifetime measurement -2
Direct measurement
In case: lifetime is the same order of weak decay

$$\Gamma_{M1} = \text{B.R.(M1)} / \tau_2$$



	g.s. doublet J_{up}, J_{low}	E_γ [keV]	Core g-factor [μN]	Calculated $1/\Gamma_{M1}$ [ps]
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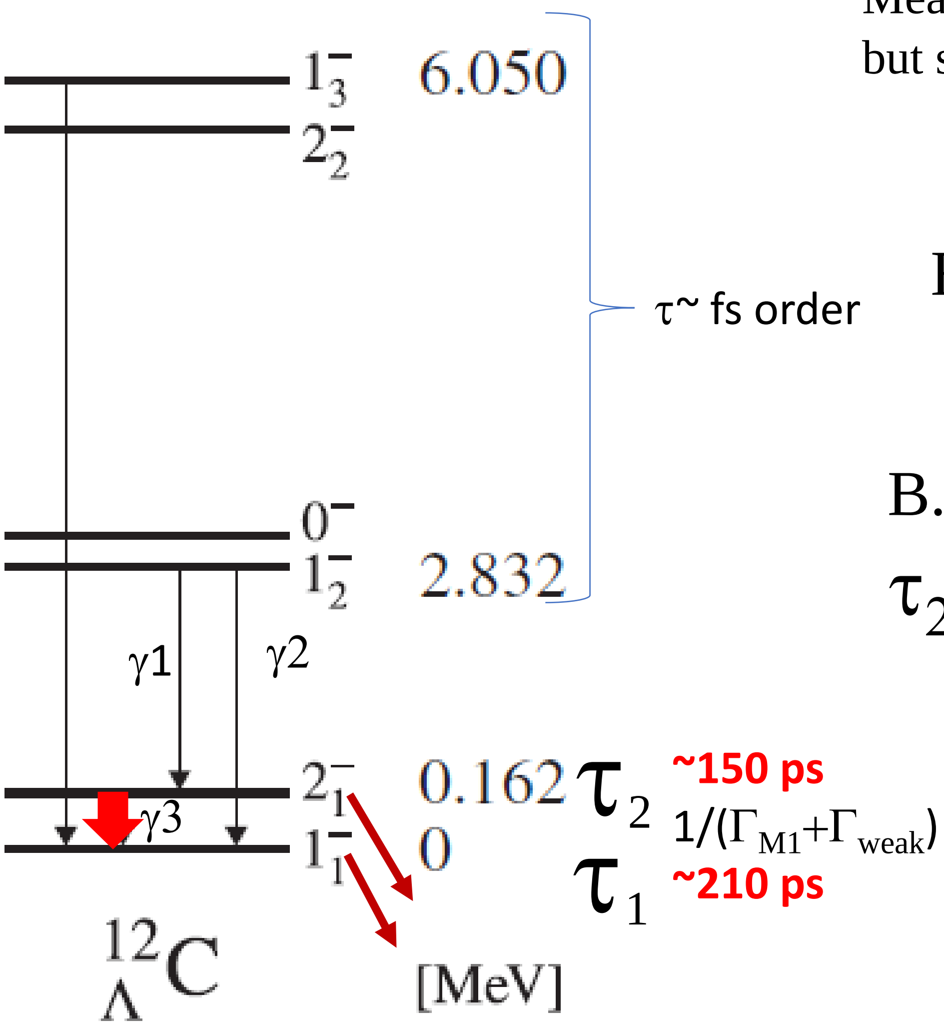
B(M1) measurement between ${}^{12}_{\Lambda}C$ g.s. spin doublet

$$\Gamma_{M1} = B.R.(M1) / \tau_2 \propto (g_\Lambda - g_C)^2$$



KEK E566

Measured weak lifetime of ${}^{12}_{\Lambda}C$ 212^{+7}_{-6} ps $\neq \tau_1$
but slightly affected from 2^- lifetime
~5% via M1($2^- \rightarrow 1^-$) and ~10% weak from 2^-
(K. Hosomi doctoral thesis)

Expected τ_2 ~ 150 ps
(assumed $1/\Gamma_{M1}$ ~ 440 ps, $1/\Gamma_{weak}$ ~ 210 ps)

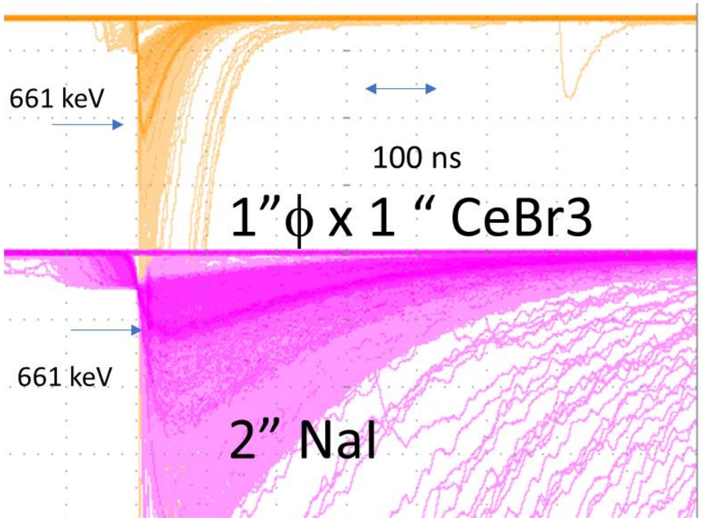
$B.R.(M1) = Y_{\gamma 3} / Y_{\gamma 1}$ (gamma-ray yield ratio)

τ_2 (1) lifetime by weak decay particle detector
τ_2 from γ3 & γ1 x weak coin.
=> timing counter = plastic scintillator
< 100 ps resolution achievable

(2) lifetime by gamma ray detector
τ_2 from γ3
=> timing counter = gamma detector
∼100 ps resolution required

Candidate of gamma detector: $CeBr_3$ scintillator

1”ϕ x 1 “ CeBr3

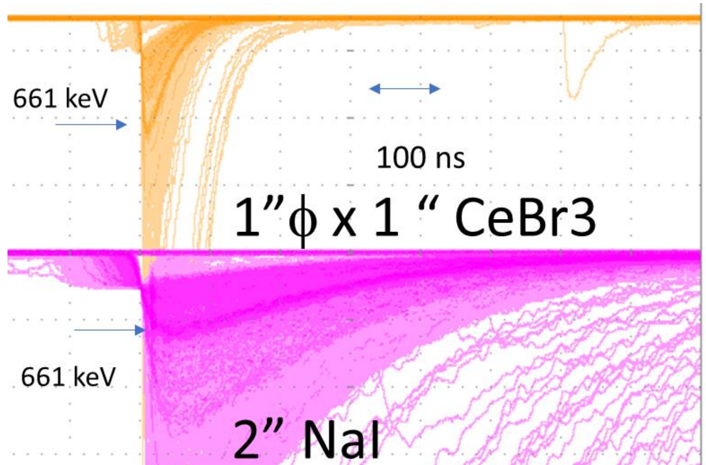


PMT output

	CeBr3	LaBr3(Ce)	NaI(Tl)	Ge
Resolution (FWHM) 661 keV	~ 4%	~3.5%	~7%	~0.3% Hyperball
density (g/cm3)	5.10	5.29	3.67	5.3
Z eff	45.9	45.2	49.7	32
Decay constant (ns)	17	30	245	(3 μs Shaping time)
Light yield (%)	122	130	100	-
Wave length (ns)	371	356	410	-

Candidate of gamma detector: $CeBr_3$ scintillator

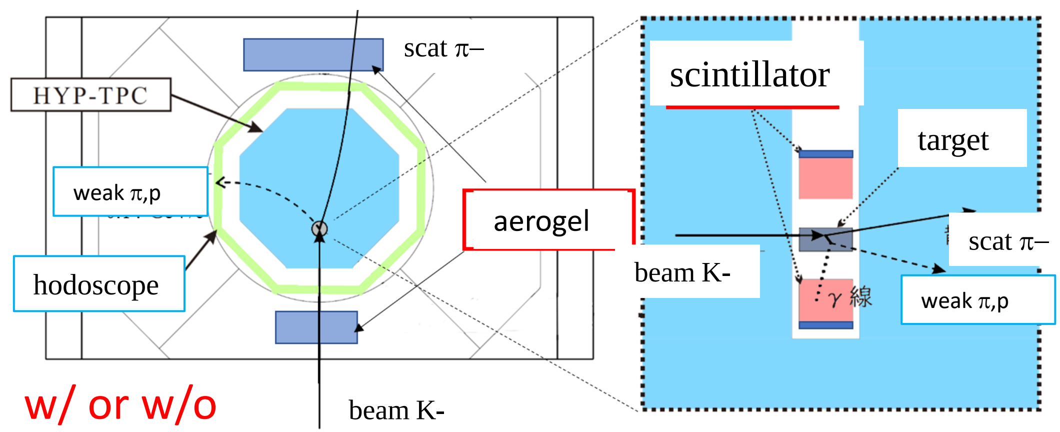
1”ϕ x 1 “ CeBr3



PMT output

	CeBr3	L
Resolution (FWHM) 661 keV	~ 4%	
density (g/cm3)	5.10	5
Z eff	45.9	4
Decay constant (ns)	17	3
Light yield (%)	122	1
Wave length (ns)	371	3

Conceptual design around target
w/ existing HYP-TPC &HS magnet (J-PRC E42)



w/ or w/o
HS magnet

Realistic yield estimation is now under going

Summary

- s-shell to sd-shell hypernuclear gamma-ray spectroscopies were carried out at KEK, BNL and J-PARC

- Observation of 1.4 MeV $^{4}_{\Lambda}$He ($1^{+} \rightarrow 0^{+}$) gamma-ray (J-PARC E13)confirmed the large charge symmetry breaking in ΛN interaction.
- Further study of CSB, precise measurement of $^{4}_{\Lambda}$H gamma-ray is planned as J-PARC E63 (nat. Li target RUN).
- As E63(nat. Li) by product, search for the $^{3}_{\Lambda}$H gamma-ray will be performed.

- B(M1) of the L spin-flip M1 transition has information of the g_{Λ} in nuclei.
- B(M1) measurement of $^{7}_{\Lambda}$Li($3/2^{+} \rightarrow 1/2^{+}$) is planned as J-PARC E63(Li2O target RUN) with Doppler-shift attenuation method (gamm-peak shape analysis).
- a new B(M1) measurement of $^{12}_{\Lambda}$C($2^{-} \rightarrow 1^{-}$) is suggested using fast scintillation counter as gamma-ray detector for gamma-weak competing state.