# Study of charge symmetry breaking in A=4 hypernuclear system

## via the gamma-ray spectroscopy experiment at J-PARC

## J-PARCにおけるガンマ線分光実験で調べる A=4ハイパー核構造の荷電対称性の破れ

2017/2/7


T. O. Yamamoto

KEK IPNS (Japan)

and the J-PARC E13/E63 collaboration

# J-PARC E13 collaboration

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(J-PARC E13-1st Collaboration)

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# Contents

- Hypernuclear gamma-ray spectroscopy
- Charge symmetry breaking (CSB) in $\Lambda$N interaction studied via A=4 hypernuclei
  - Gamma-ray spectroscopy of $^{4}_{\Lambda}$He (J-PARC E13, 2015) : new result
  - Gamma-ray spectroscopy of $^{4}_{\Lambda}$H (J-PARC E63, 2018) : near future plan
- Far future possibility
- Summary

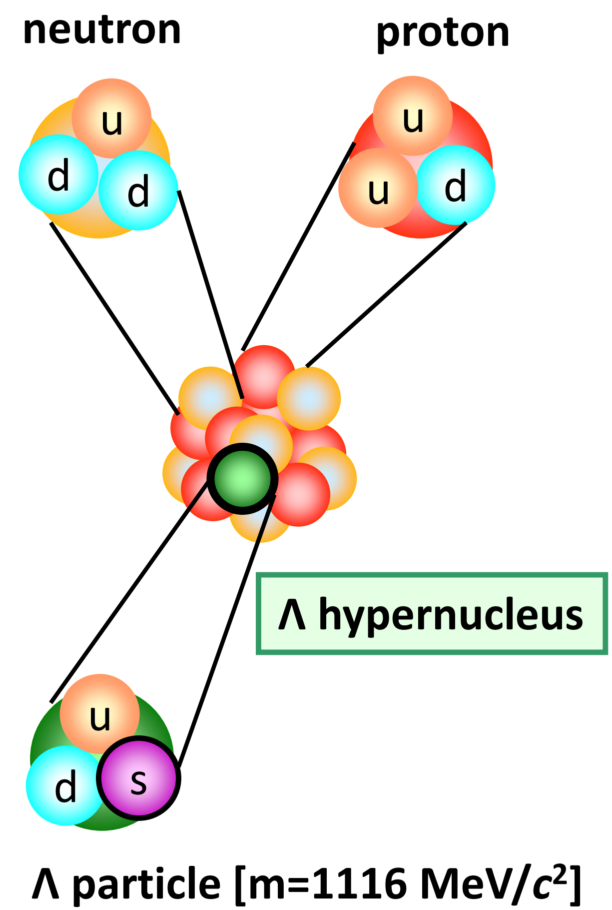
# Λ hyper nucleus

**Ordinal nuclei**

**+ Λ (bound due to ΛN attractive force)**

***< Physics motivations >***

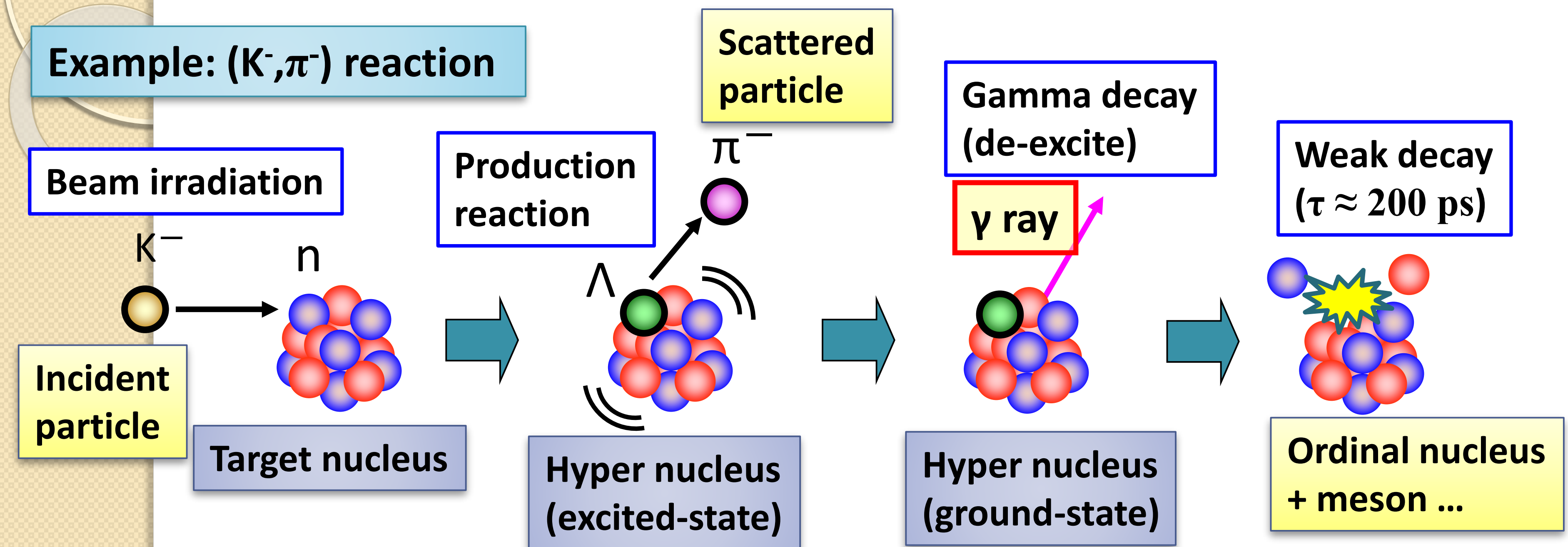
- **Hyperon(Y)-Nucleon(N) interaction**
  - ***Difficulty in YN scattering experiment due to short life time (~260 ps)***
    - → Studied via hypernuclear structure
- **Property change of baryon in nuclear density**
  - ***No Pauli effect between Λ and N***
    - → Λ (in 0s orbit) as probe
- **Impurity effect by introducing Λ**
  - ***structure change of "core" nuclei***
    - e.g. shrinking, deformation

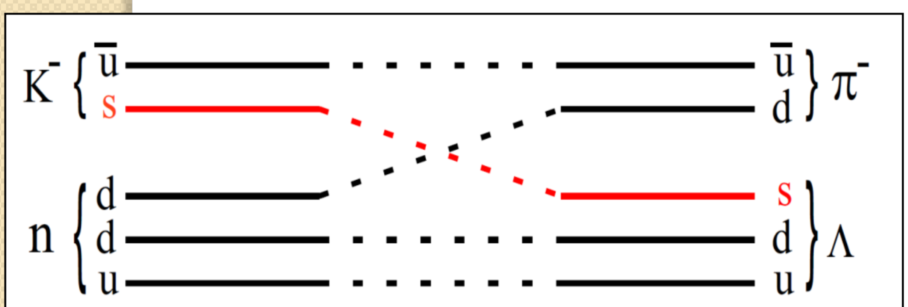



**Lightest hyperon (others: Σ, Ξ, Ω)**

# Production and decay of hypernuclei

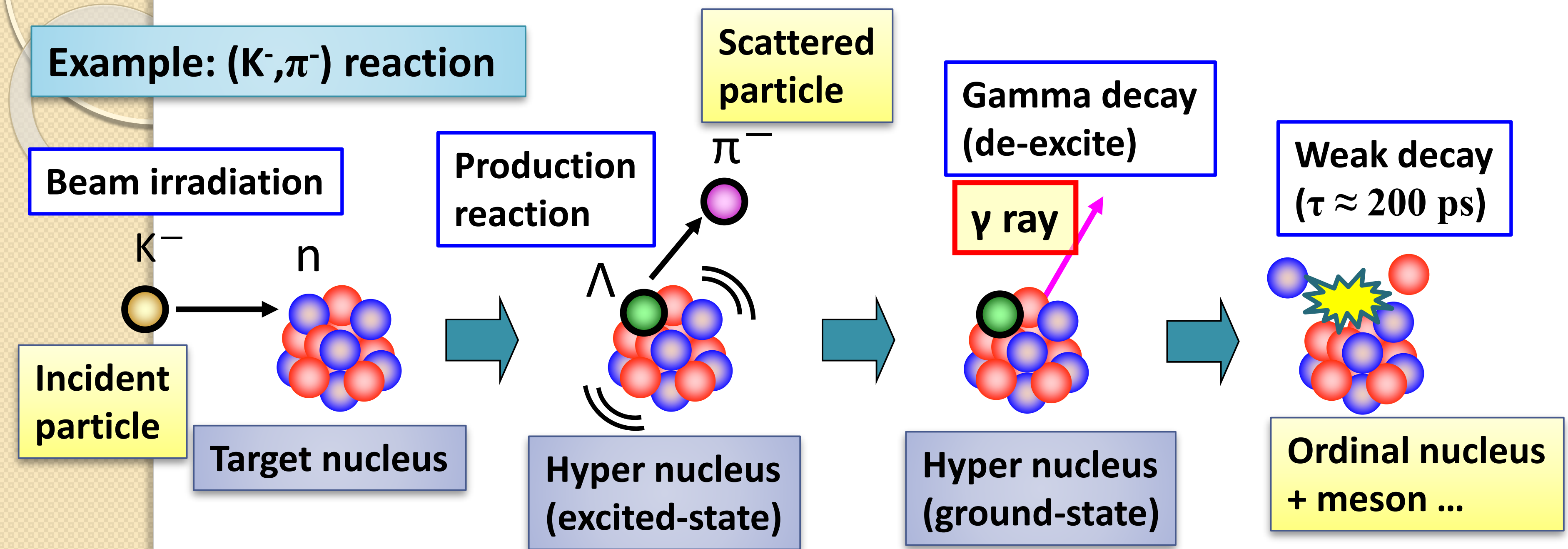
Example: $(K^-,\pi^-)$ reaction




Elementary process:
s quark exchange reaction

# Production and decay of hypernuclei



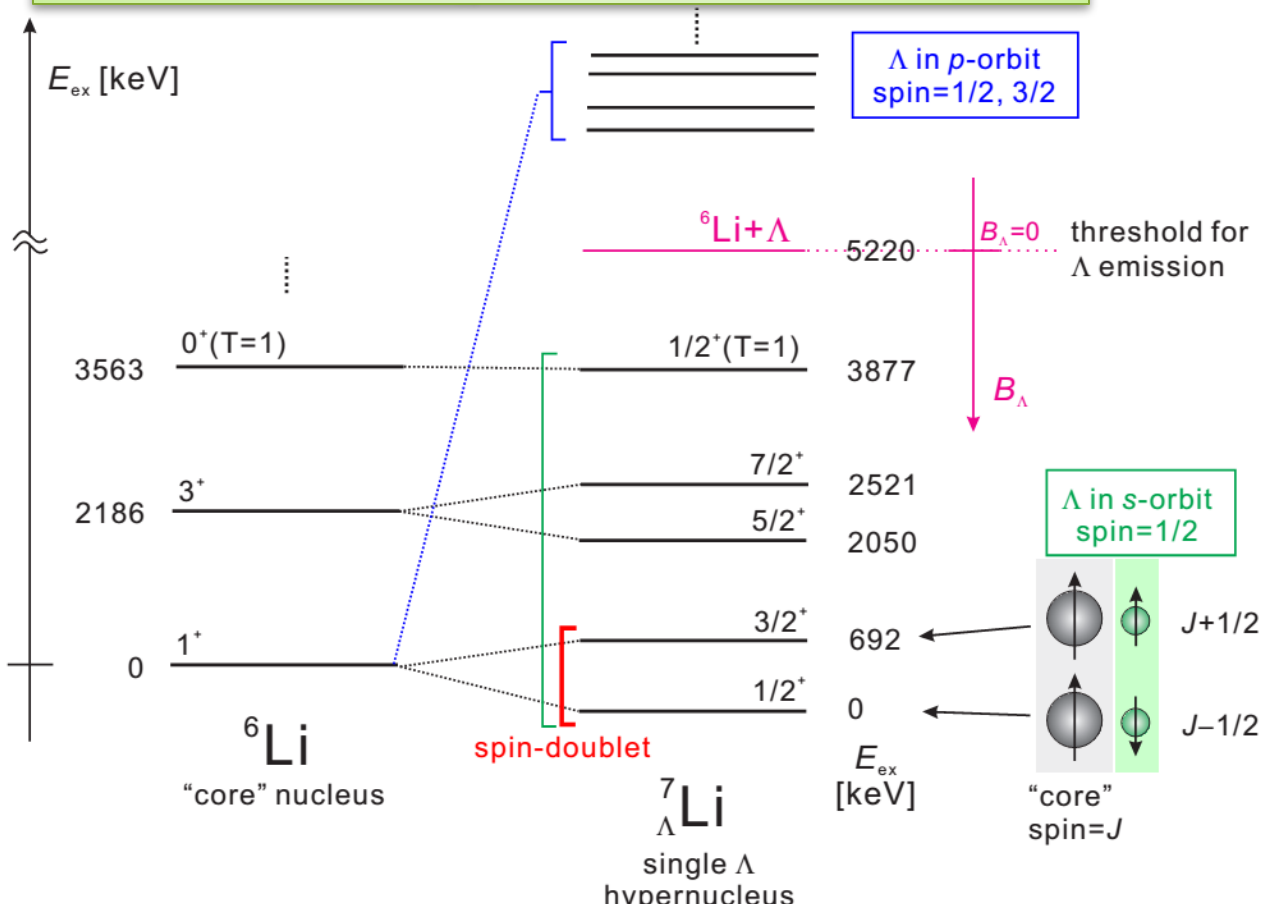

< Experimental methods >

- Incident and scattered particle

  -> Reaction spectroscopy — Absolute mass, $\sigma_E$=500~2000 keV
- Gamma-ray spectroscopy — Excitation energy, $\sigma_E$=5 keV
- Decay particle spectroscopy — Absolute mass, $\sigma_E$=150 keV

# ΛN interaction and structure of hypernuclei

**Level schema of $^{7}_{\Lambda}$Li and its "core" nucleus**




**Spin dependent**
**ΛN interaction**
**+**
**Combination of $S_{core}$ and $S_{\Lambda}$**

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

**Gamma-ray spectroscopy using Ge detectors**
*(2 keV energy resolution)*

**Many p-shell hypernuclei are already studied. (Hyperball project)**

# Previous Hyperball project ：Hypernuclear γ-ray spectroscopy

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

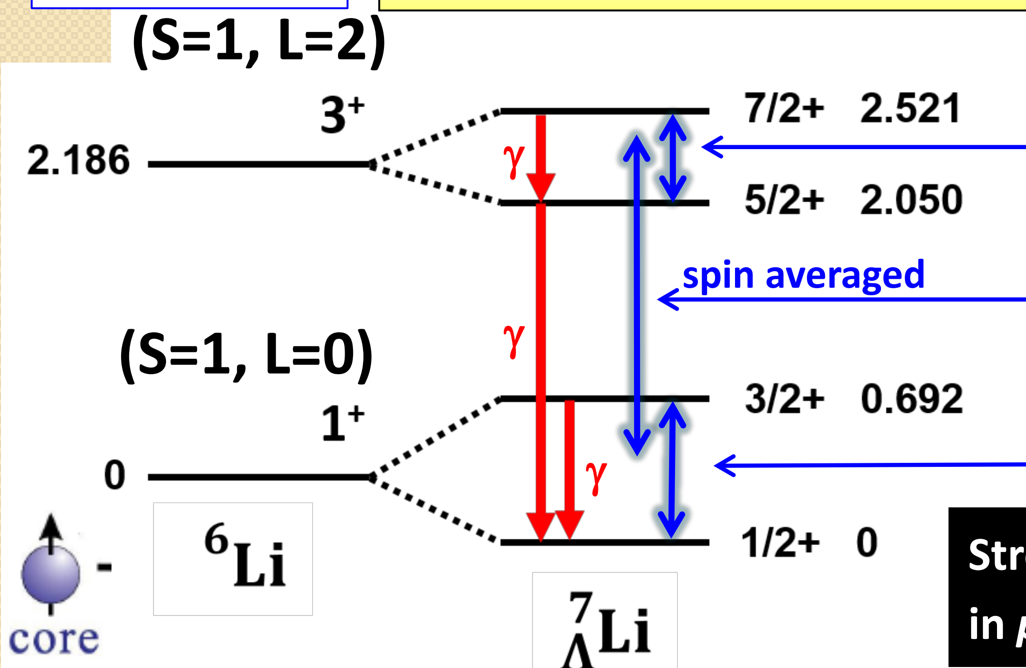
${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B, ${}^{12}_{\Lambda}$C, ${}^{15}_{\Lambda}$N, ${}^{16}_{\Lambda}$O

→ **Level schemes of these *p*-shell hypernuclei were determined with energy resolution of a few keV (using Ge detector array)**

**LS coupling scheme**

**Level scheme of ${}^{7}_{\Lambda}$Li (KEK-E419 & BNL-E930)**

**(Λ in s state)**




**0.471 MeV = spin-spin + spin-orbit ($s_\Lambda$) + tensor**

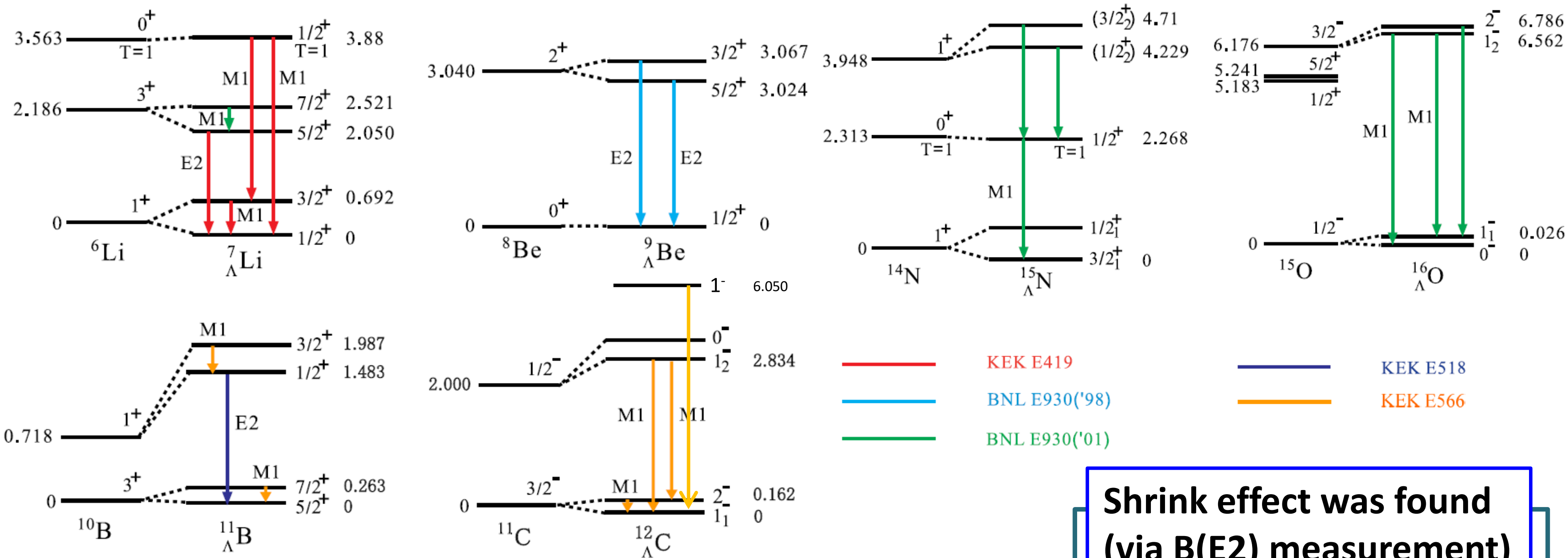
**1.858 MeV = $E_{core}$(2.186 MeV) + spin-orbit ($s_N$)**

**0.692 MeV = spin-spin**

**Strengths of each spin-dependent part in *p*-shell were determined.**

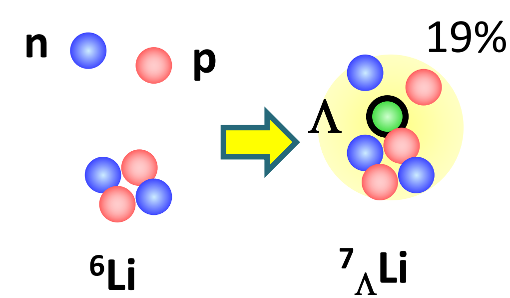
# Level scheme of *p*-shell hypernuclei

**Studied by Hyperball project (only with non-charge exchange reaction)**




**Strength of spin-dependent term of ΛN interaction were determined (in *p*-shell)**

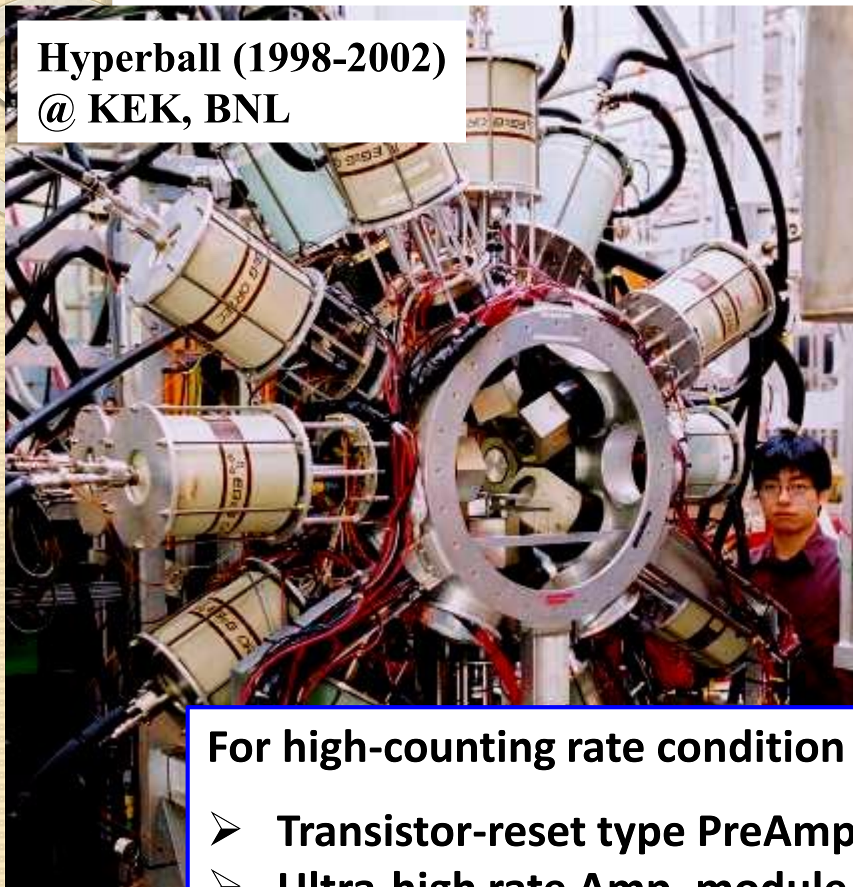
**Shrink effect was found (via B(E2) measurement)**




**< Next step >**

- ***s*-shell, *sd*-shell hypernuclei**
- **Mirror hypernuclei**

# Ge array: Hyperball & Hyperball2

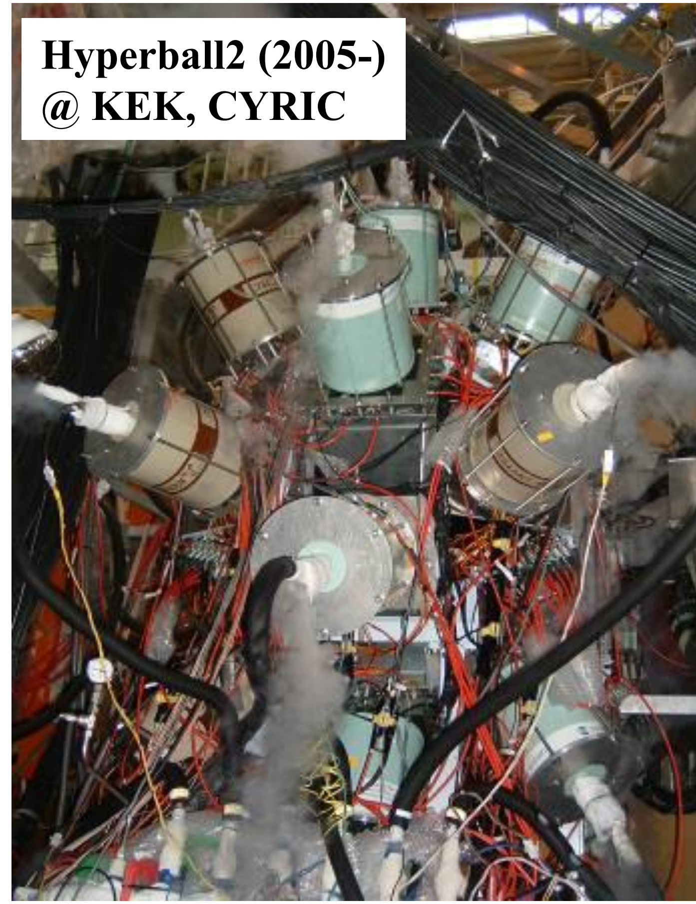


Hyperball (1998-2002)
@ KEK, BNL

**For high-counting rate condition**

- Transistor-reset type PreAmp.
- Ultra-high rate Amp. module

14 single type Ge detectors (60%)
+ BGO counter
$\varepsilon_\gamma$~2.5%



Hyperball2 (2005-)
@ KEK, CYRIC

14 single type Ge detectors (60%)
6 clover type Ge detector (120%)
+ BGO counter
$\varepsilon_\gamma$ ~4%

# Charge symmetry breaking in hypernuclear structure

# Charge symmetry in NN interaction

**Charge symmetry :**

identical under iso-spin reversal
(180 deg. rotation)

u quark ↔ d quark

⇨ $\Sigma^+_{uus}\ (T_z=+1) = \Sigma^-_{dds}\ (T_z=-1)$

**Charge independence :**

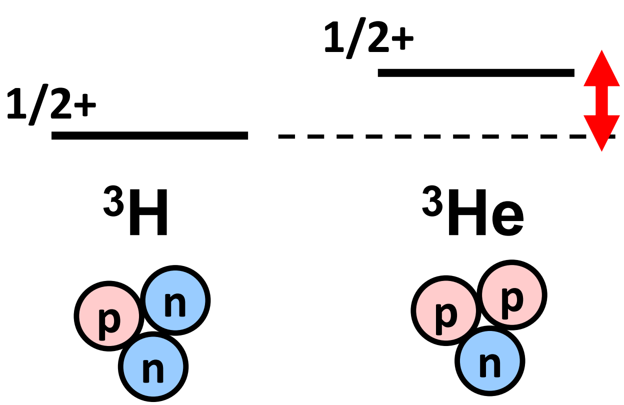
identical under iso-spin rotation

⇨ $\Sigma^+ = \Sigma^0_{uds} = \Sigma^-$

**holds almost exactly In NN interaction**
***(only small effect was known)***

*G. A. Miller, A. K. Opper, and E. J. Stephenson, Ann. Rev. Nucl. Part. Sci. 56, 253 (2006).*

**Level schema of $^3$H / $^3$He mirror nuclei**



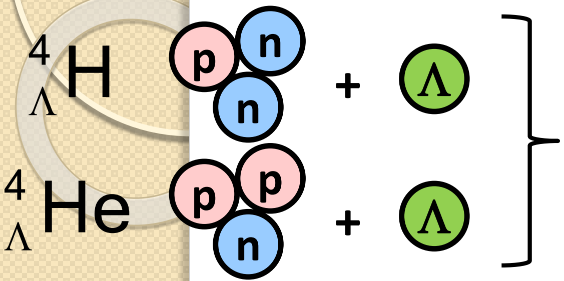

$\Delta$ Binding energy = 764 keV

Coulomb effect is dominant

CSB effect from hadronic interaction : 71 keV

$\rho^0$-$\omega$ mixing effect
due to u,d quark mass difference
(explained with meson-exchange model)

# CSB effect in A=4 hypernuclear structure



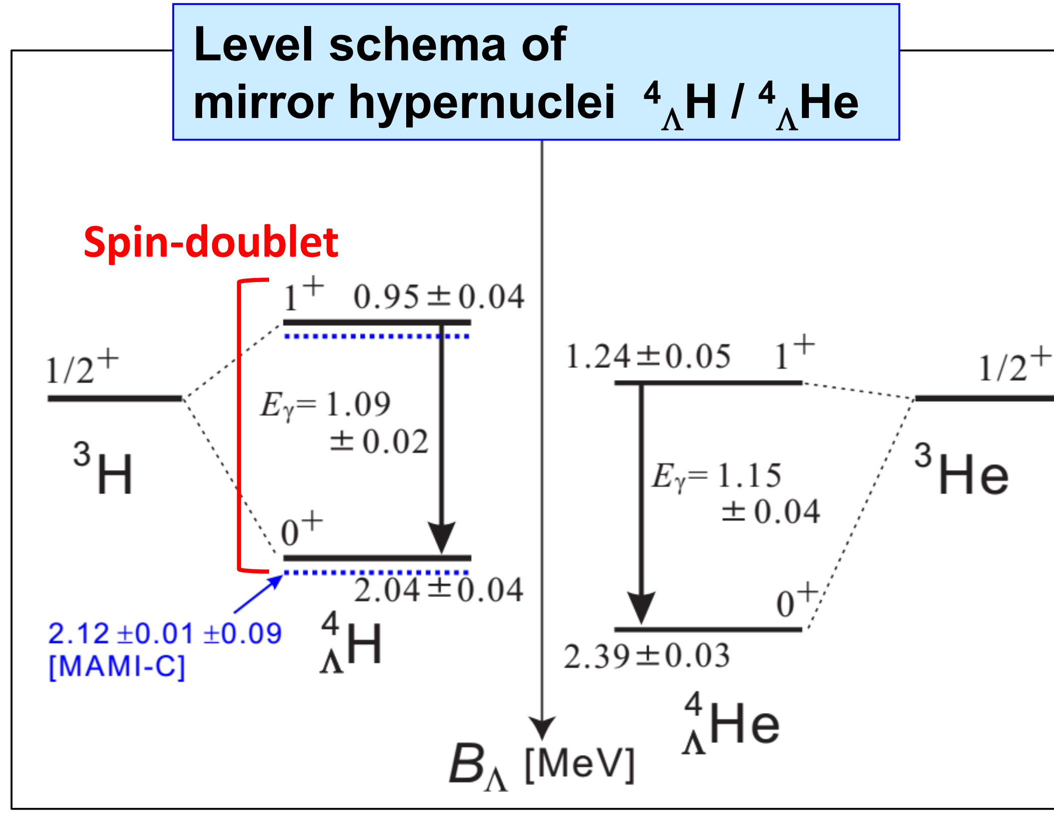

Λp ≠ Λn ?

**Λ binding energy($B_\Lambda$) :**

No direct electromagnetic effect

**$B_\Lambda$ difference in mirror hypernuclei: good test of CSB effect.**

**A=4 system is suitable w/ theoretical *ab initio* calc.**




**$\Delta B_\Lambda$ ($0^+$) = 0.35 MeV**
**$\Delta B_\Lambda$ ($1^+$) = 0.28 MeV**

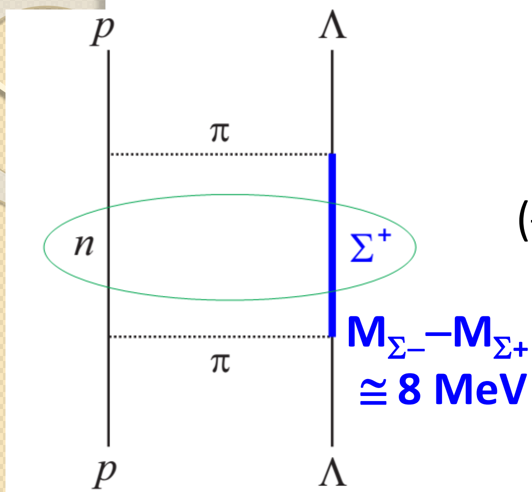
$B_\Lambda(0^+)$ : emulsion technique

$E_x(1^+)$ : γ-ray spectroscopy (NaI)

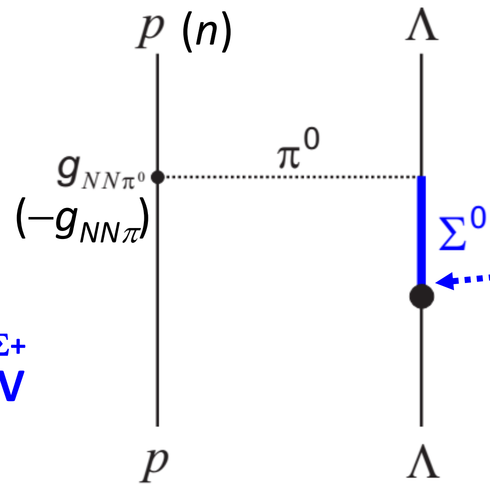
**Un expectedly large difference ( Long standing problem since 1960's )**

**while many theoretical studies based on widely accepted NSC interaction model**

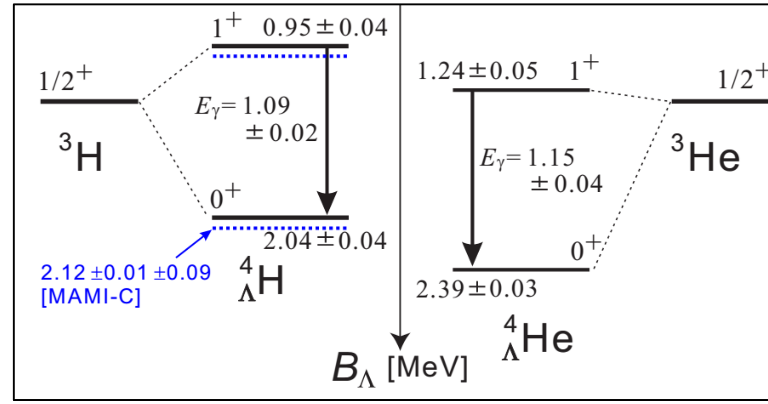
# Candidate of CSB source




ΛN-ΣN mixing
- Σmass difference
- pΣ coulomb force

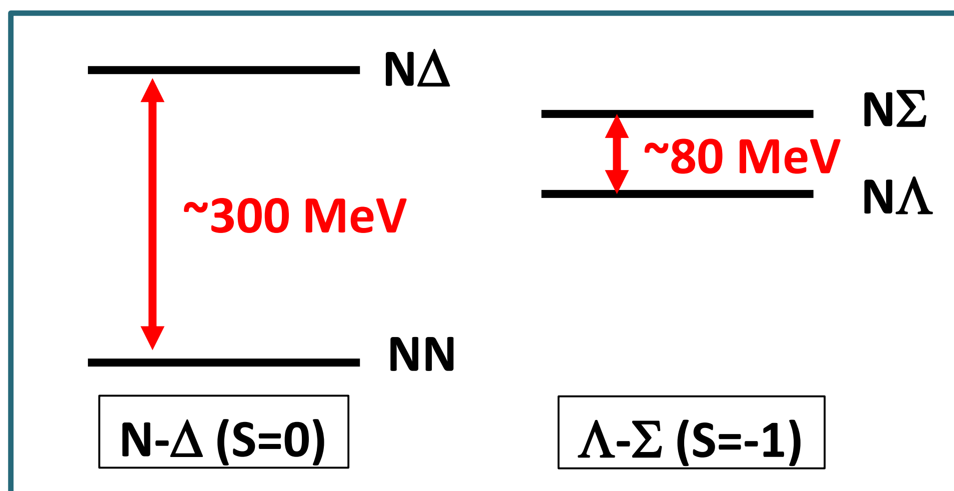



$\Lambda\Sigma^0$ mixing
- CSB interaction

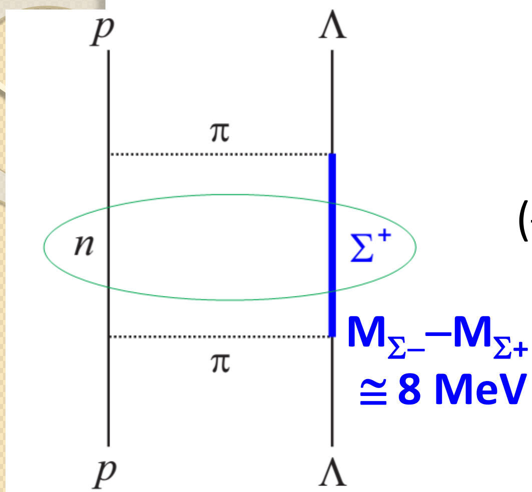


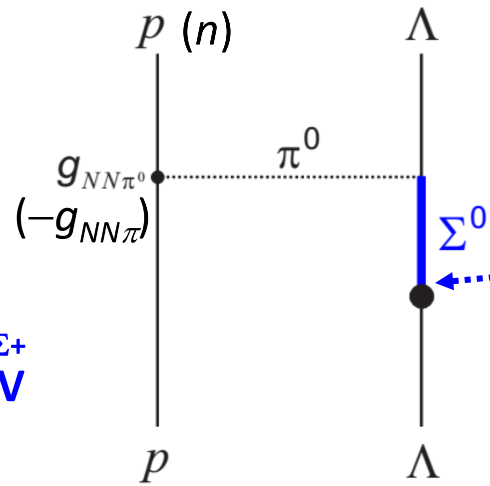

*ΛN-ΣN mixing have important roll for CSB effect ?*

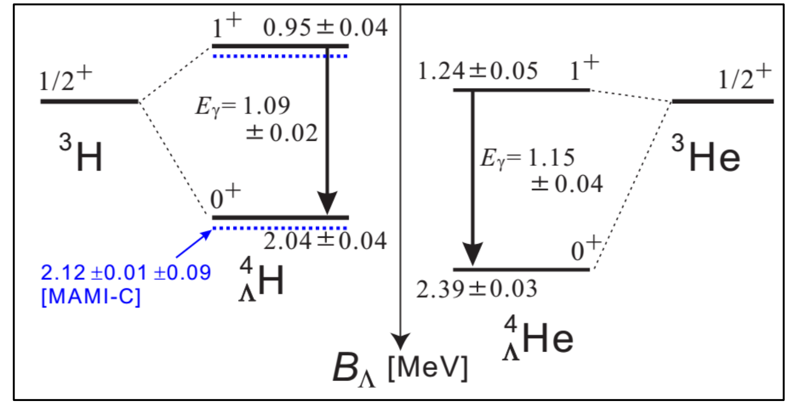
ΛΣ Mixing effect can be larger than NΛ system



# Candidate of CSB source




**$\Lambda$-$\Sigma^0$ mixing**

***ΛN-ΣN mixing have important roll for CSB effect ?***

ΛN-ΣN mixing
- Σmass difference
- pΣ coulomb force

$\Lambda\Sigma^0$ mixing
- CSB interaction

**Theoretical calc.** (unit : MeV)

| | Exp. | Calc. Nogga |
|---|---|---|
| $\Delta B_\Lambda(1^+)$ | 0.28(5) | -0.01 |
| $\Delta B_\Lambda(0^+)$ | 0.35(5) | 0.07 |

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

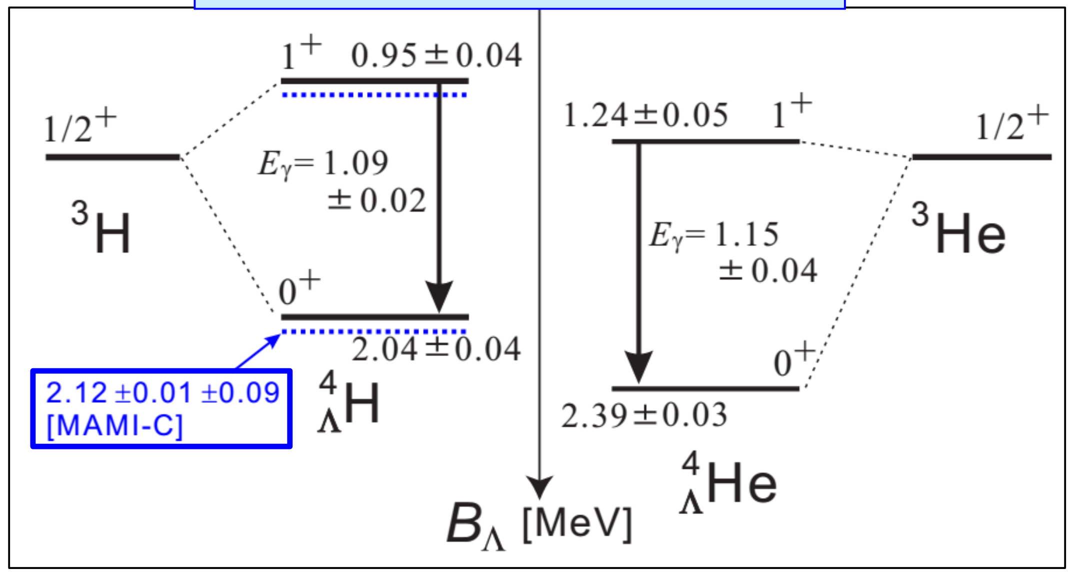
Including all possible sources
- ΛΣ mixing effect
- Change in “core” Coulomb effect

**Only 70 keV CSB difference ( ≠ 350 keV)**

**Need to check old experimental data ?**

# Test of previous experimental data

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




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

*M. Juri ´c et al., Nucl. Phys. B 52, 1 (1973).*

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

*M. Bedjidian et al., Phys. Lett. B 62, 467 (1976).*
*M. Bedjidian et al., Phys. Lett. B 83, 252 (1979).*
*A. Kawachi, Doctoral Thesis, University of Tokyo (1997), unpublished.*

# Test of previous experimental data

**$B_\Lambda(^4_\Lambda H(0^+))$, 2015**

Decay $\pi^-$ spectroscopy (MAMI-A1)

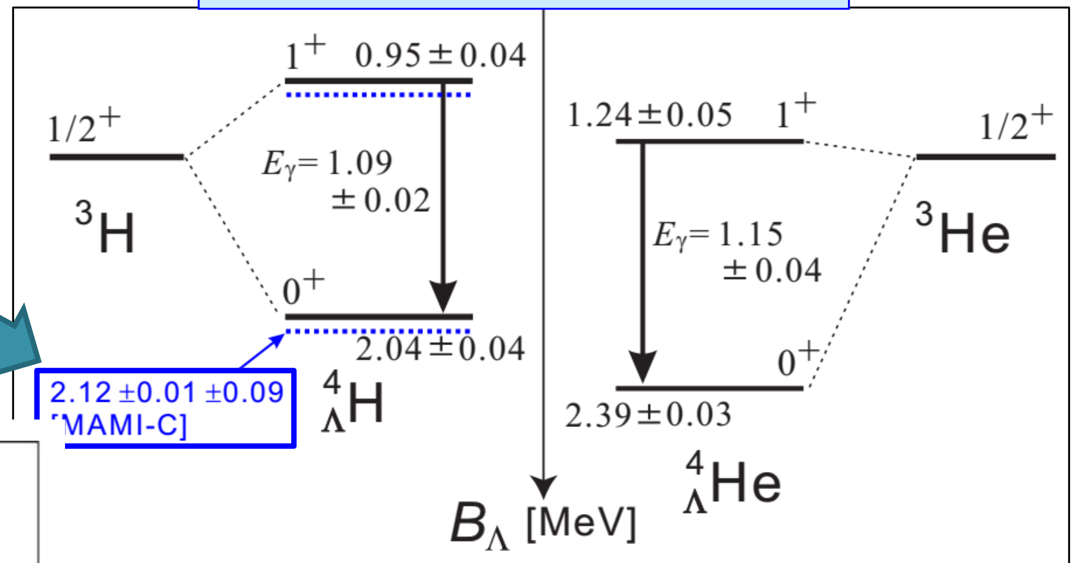
**2.157 ± 0.077 MeV**

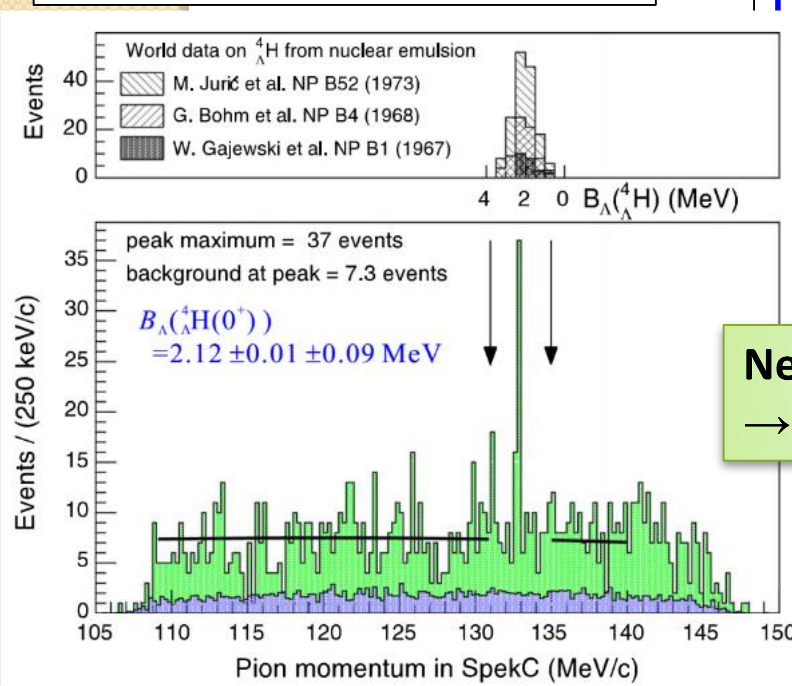
**w/ better systematic errors**

*A. Esser, S. Nagao et al.,*
*Phys. Rev. Lett. 114, 232501 (2015)*

*A1 collaboration., NPA 954 (2016) 149*

**Level schema of $^4_\Lambda H$ / $^4_\Lambda He$**




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

*M. Juri ´c et al., Nucl. Phys. B 52, 1 (1973).*

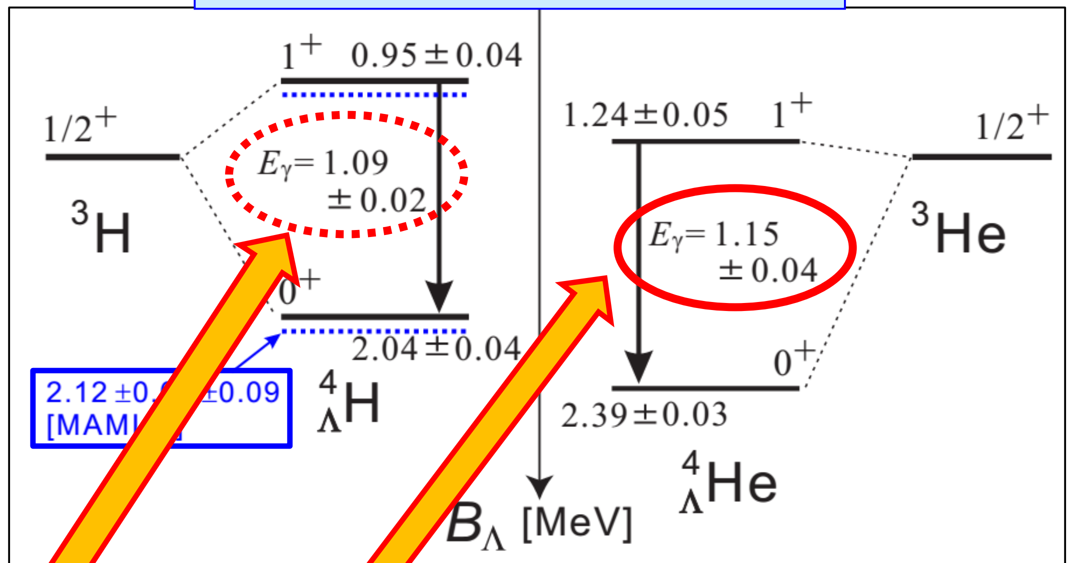
**Near to old data**
**→ 230 keV CSB effect**

**ray spectroscopy (NaI)**

*jidian et al., Phys. Lett. B 62, 467 (1976).*
*M. Bedjidian et al., Phys. Lett. B 83, 252 (1979).*
*A. Kawachi, Doctoral Thesis,*
*University of Tokyo (1997), unpublished.*

# Test of previous experimental data

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




**$E_x$ measurement in 1970's**
**($\gamma$-ray spectroscopy)**
stopped K⁻ reaction + NaI detectors

| | ${}^{4}_{\Lambda}$H($1^+ \to 0^+$) | ${}^{4}_{\Lambda}$He($1^+ \to 0^+$) |
|---|---|---|
| M. Bedjidian *et al.* (1976) [12] | 1.09 ±0.03 | - |
| M. Bedjidian *et al.* (1979) [13] | 1.04 ±0.04 | 1.15 ±0.04 |
| A. Kawachi (1997) [14] | 1.114 ±0.030 | - |
| Weighted average | 1.09 ±0.02 | 1.15 ±0.04 |

**Need solid experimental data**

**We performed J-PARC E13 (2015)**

**Need high quality experimental data**

**We are aiming for J-PARC E63 (near future)**

# Old experiment for $E_\gamma(^4_\Lambda He)$

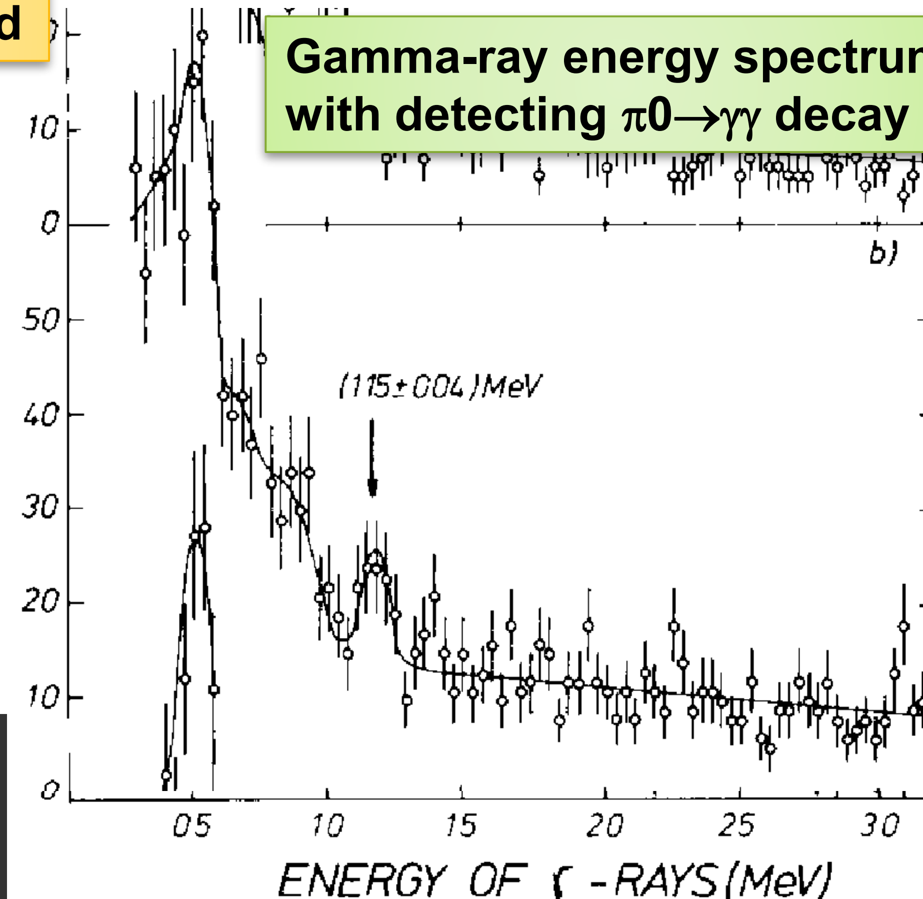
**Only one experiment was performed**

- **Stopped K- reaction (Li target)**
  - **detecting $\pi^0 \rightarrow \gamma\gamma$**
    (with Pb + scinti. sandwich)
    **for tagging hypernuclei**
  - **Doppler broaden $\gamma$ peak**
- **NaI detector**
  - **Energy resolution : 12%**
- **Limited statistics**

**Higher sensitivity and statistics can be achieved by**

- In-flight $^4He(K^-,\pi^-)^4_\Lambda He$ reaction
- Ge detector (Energy resolution : 0.2%)
- High intensity K beam
  + large acceptance spectrometers

**Gamma-ray energy spectrum with detecting $\pi 0 \rightarrow \gamma\gamma$ decay**




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

**reported value : 1.15 (0.04) MeV**

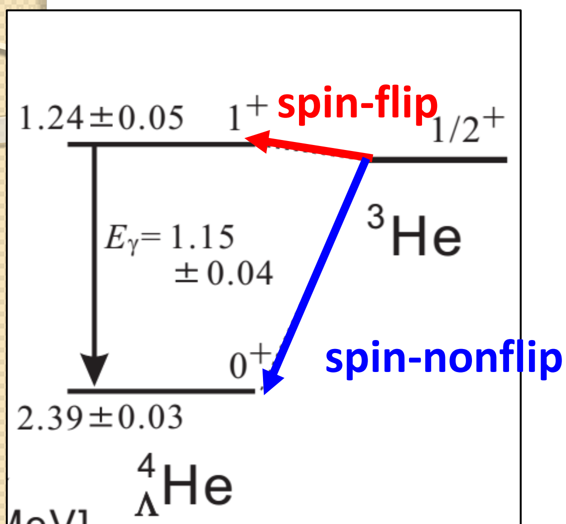
J-PARC E13

# Gamma-ray spectroscopy of ${}^{4}_{\Lambda}$He (performed in 2015)

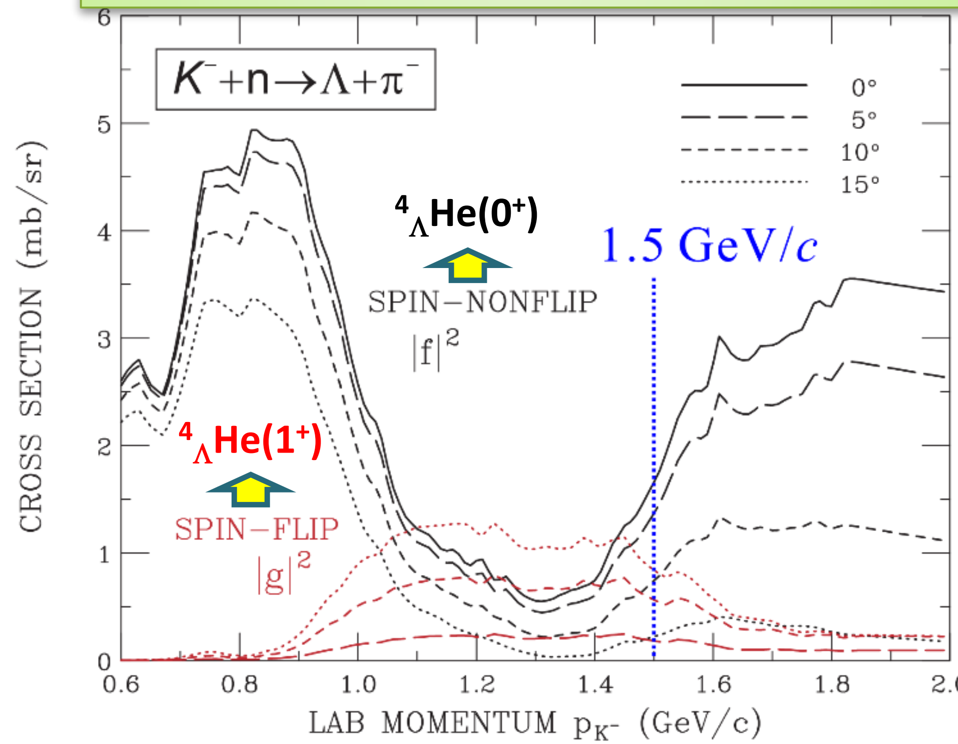
# $^{4}_{\Lambda}$He production

*T. Harada, private communication (2006)*

**Need to produce 1⁺ excited state**




**Cross section of elementary n(K⁻,π⁻)Λ**




**(K⁻,π⁻) reaction @$p_K$=1.5 GeV/c**

**s quark exchange reaction**

○ **Large cross section**
enough yield with
reasonable beam intensity

***Good for Ge detector***

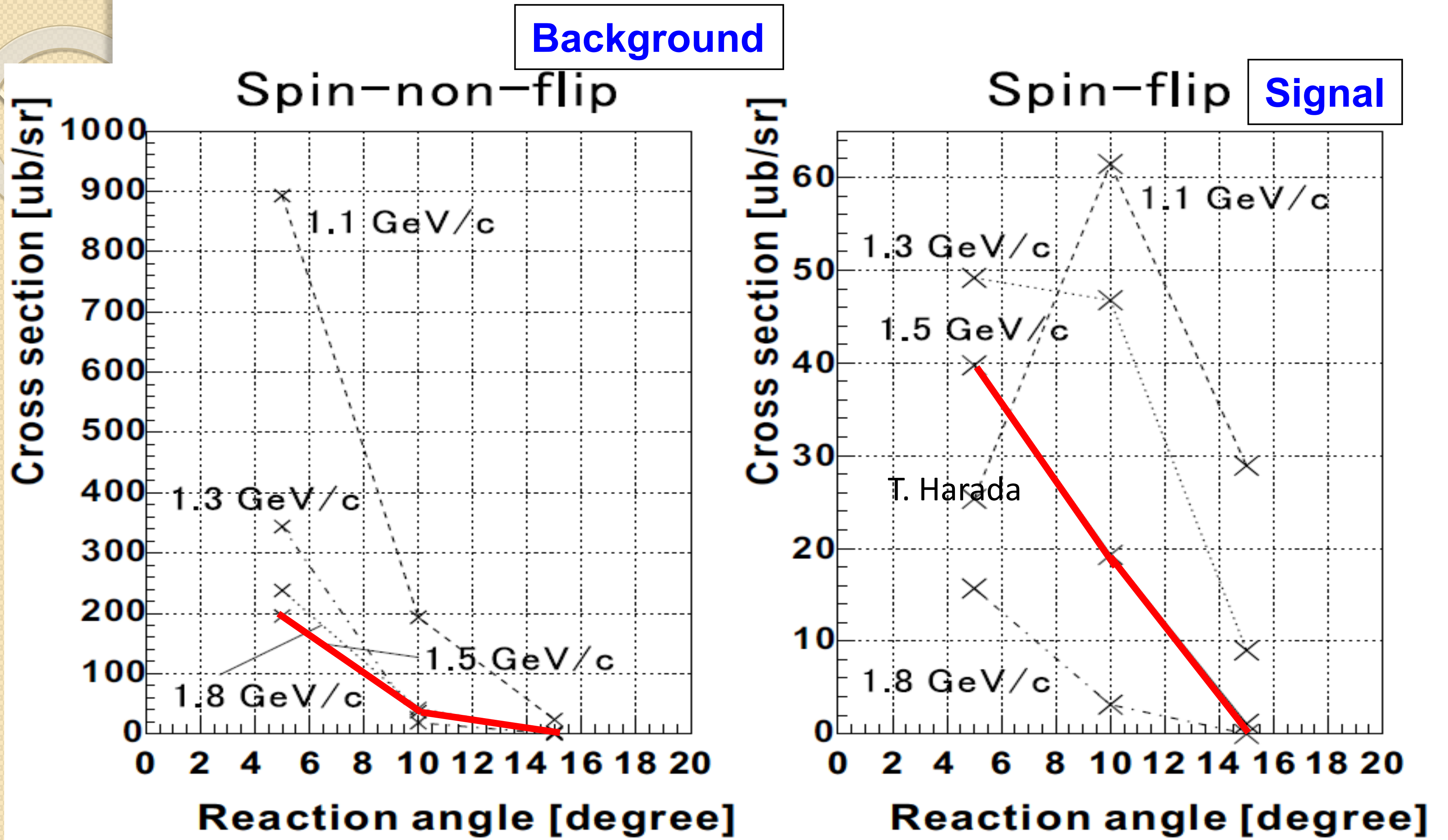
× **Huge background**
**due to beam K⁻ decay**

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

**Reaction-γ coincidence measurement**

as performed for *p*-shell
gamma-ray spectroscopy

# $^{4}{}_{\Lambda}He$ cross section (theoretical prediction)




- High intensity beam : ~2 x $10^8$ kaons/h
- Long target : liq. $^4$He 22 cm ( 2.75 g/cm$^2$ )

**Necessary for reaction-γ coincidence**

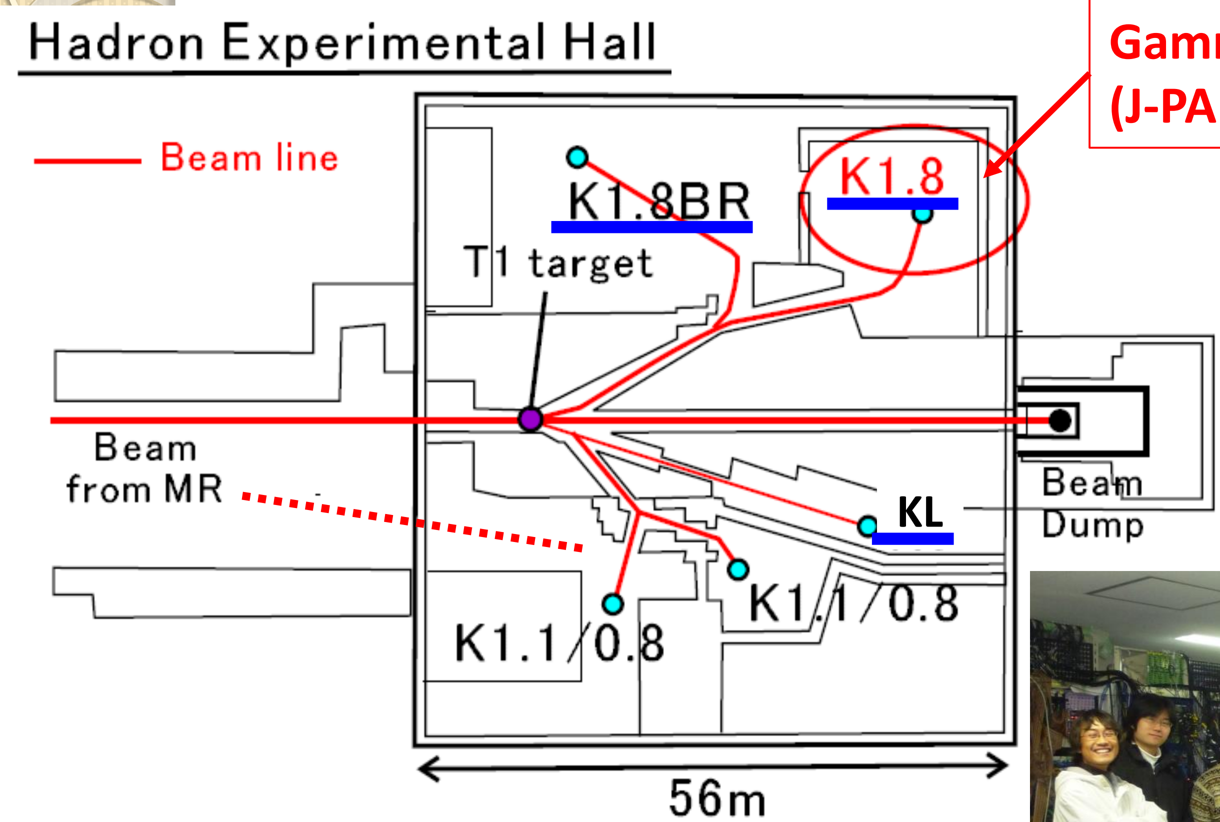
# J-PARC (Japan Proton Accelerator Research Complex)



**Primary intensity is increasing (so far $3 \times 10^{16}$ protons/h)**
**→ >4 times higher in future**

**High intensity secondary meson beam (p<2 GeV/c)**
**→ suitable for study of hypernuclei**

# J-PARC Hadron Experimental Hall




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

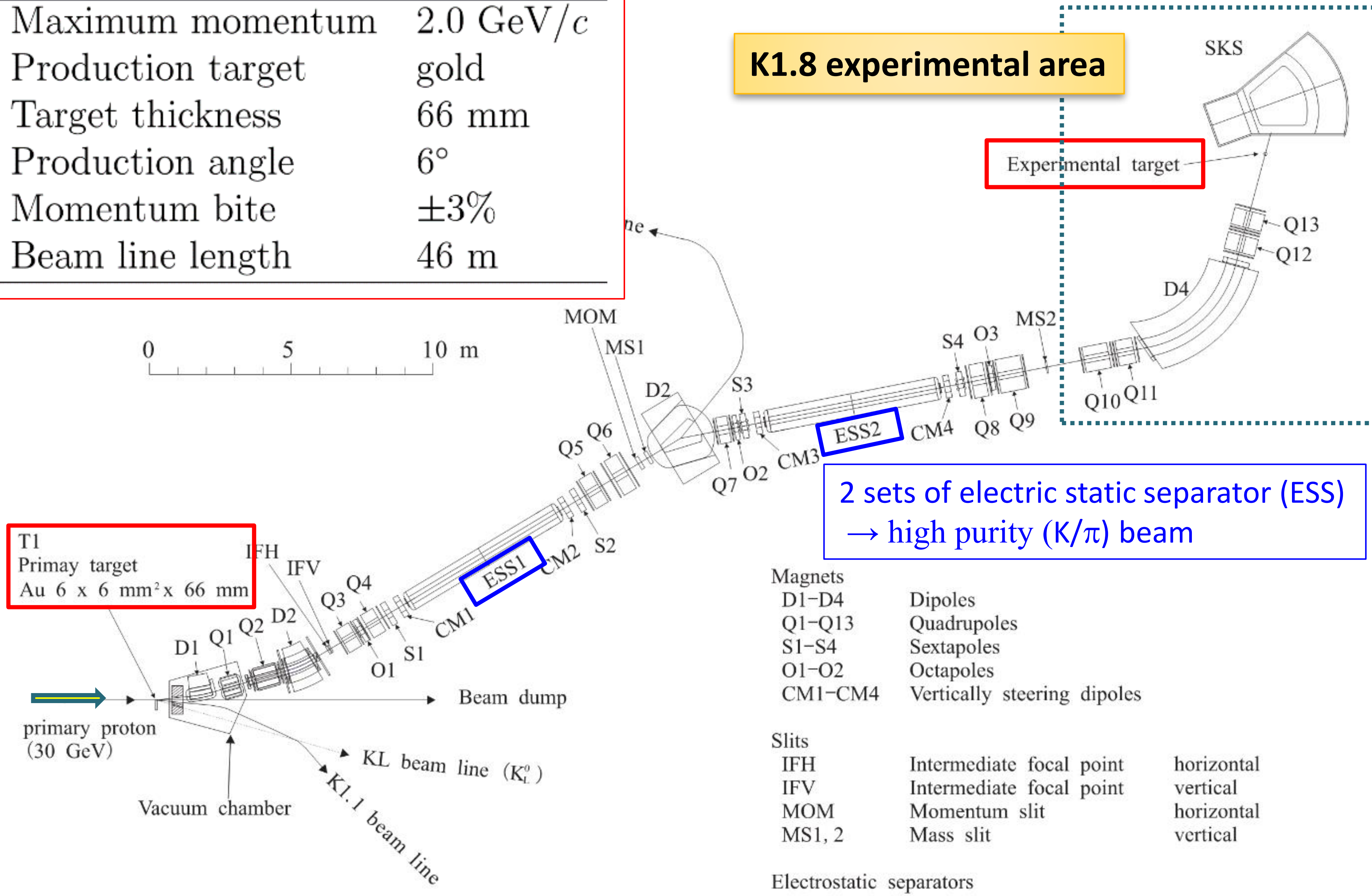
First beam at K1.8 beam line (2009)

- 3 beam lines are now available (K1.8, K1.8BR, KL)
- New beam lines are constructing (K1.1, high-p, COMET)

# J-PARC K1.8 beam line

**For high intensity and high purity K beam**

| | |
|---|---|
| Maximum momentum | 2.0 GeV/$c$ |
| Production target | gold |
| Target thickness | 66 mm |
| Production angle | 6° |
| Momentum bite | ±3% |
| Beam line length | 46 m |



# Experimental setup (E13)

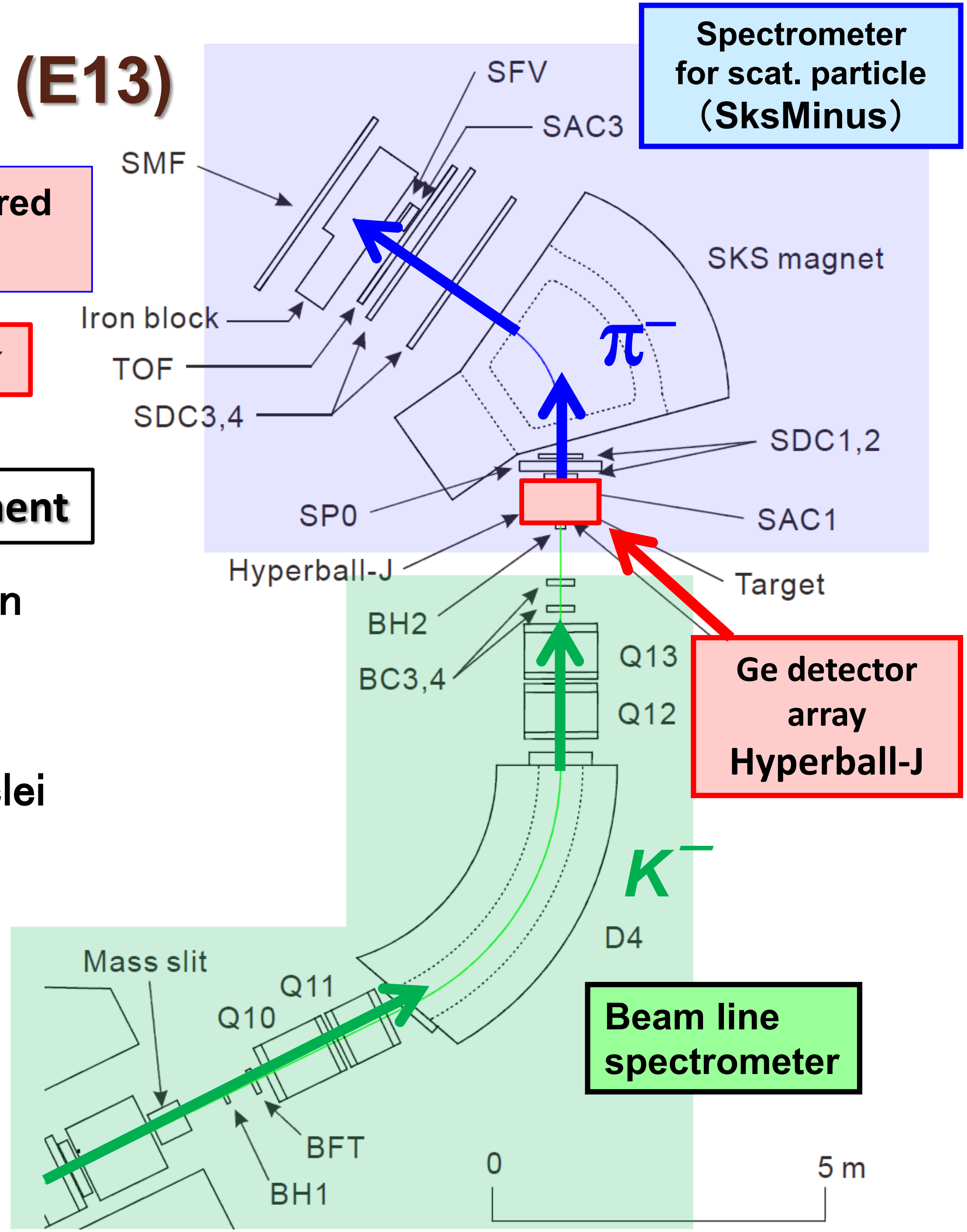
**Use high intensity K- beam delivered from J-PARC K1.8 beam line**

$^{A}Z\,(K^{-},\pi^{-})\,{}^{A}_{\Lambda}Z^{*} \rightarrow {}^{A}_{\Lambda}Z + \gamma$

**reaction-γ coincidence experiment**

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

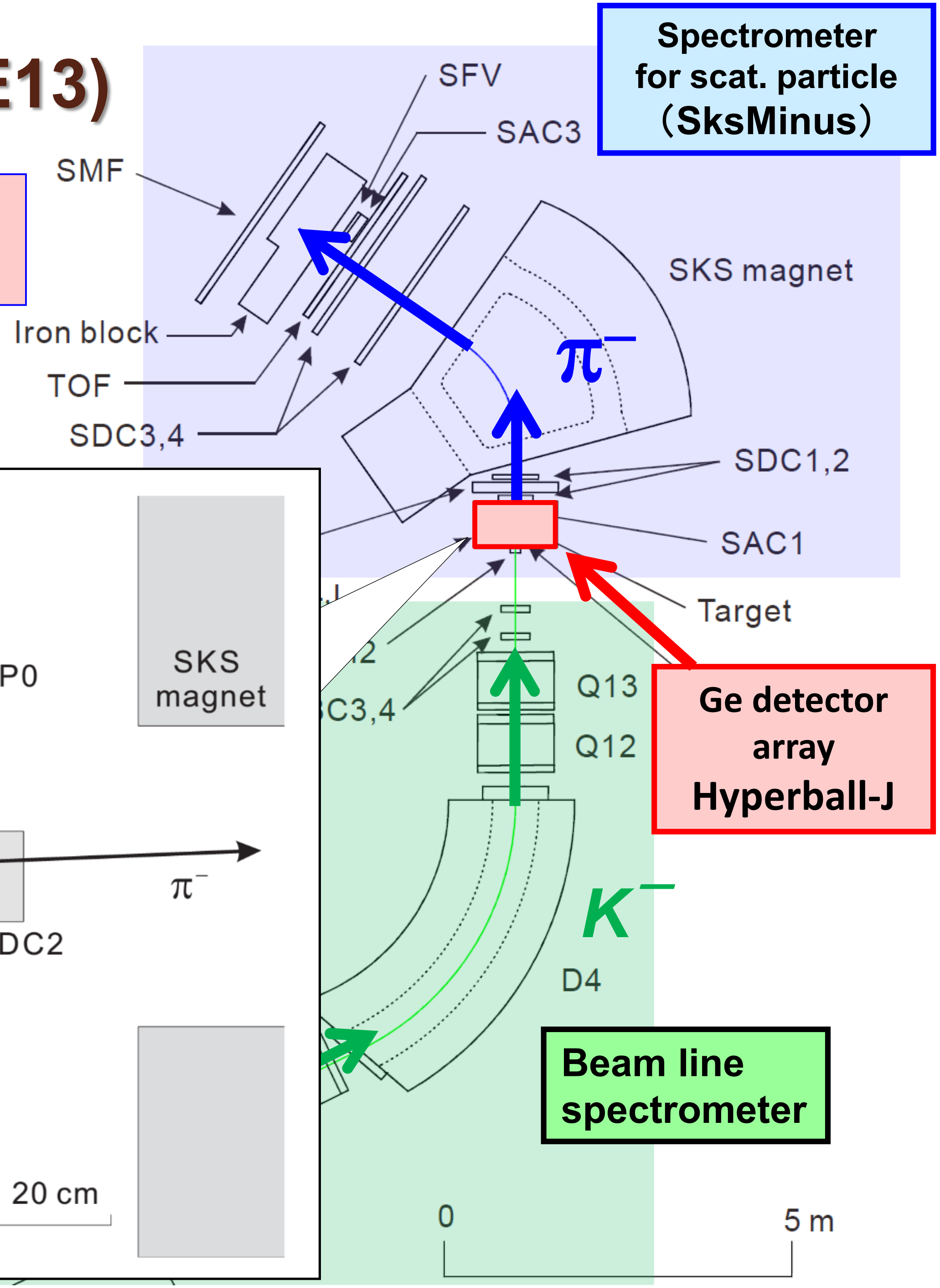
$^{4}_{\Lambda}$He : liq.He target (2.7 g/cm$^2$)
length : ~23 cm
size : 12cmϕ
$p_K$ = 1.5 GeV/c

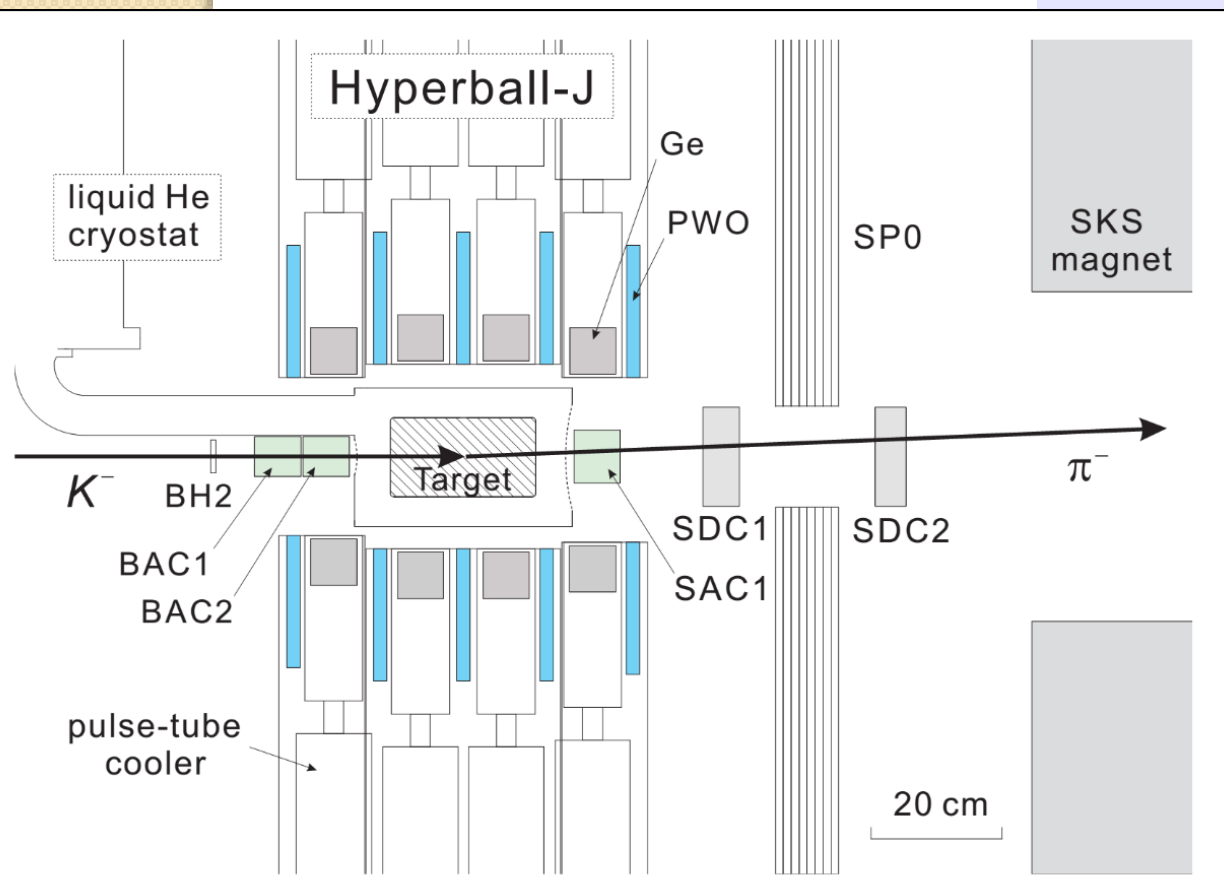


# Experimental setup (E13)

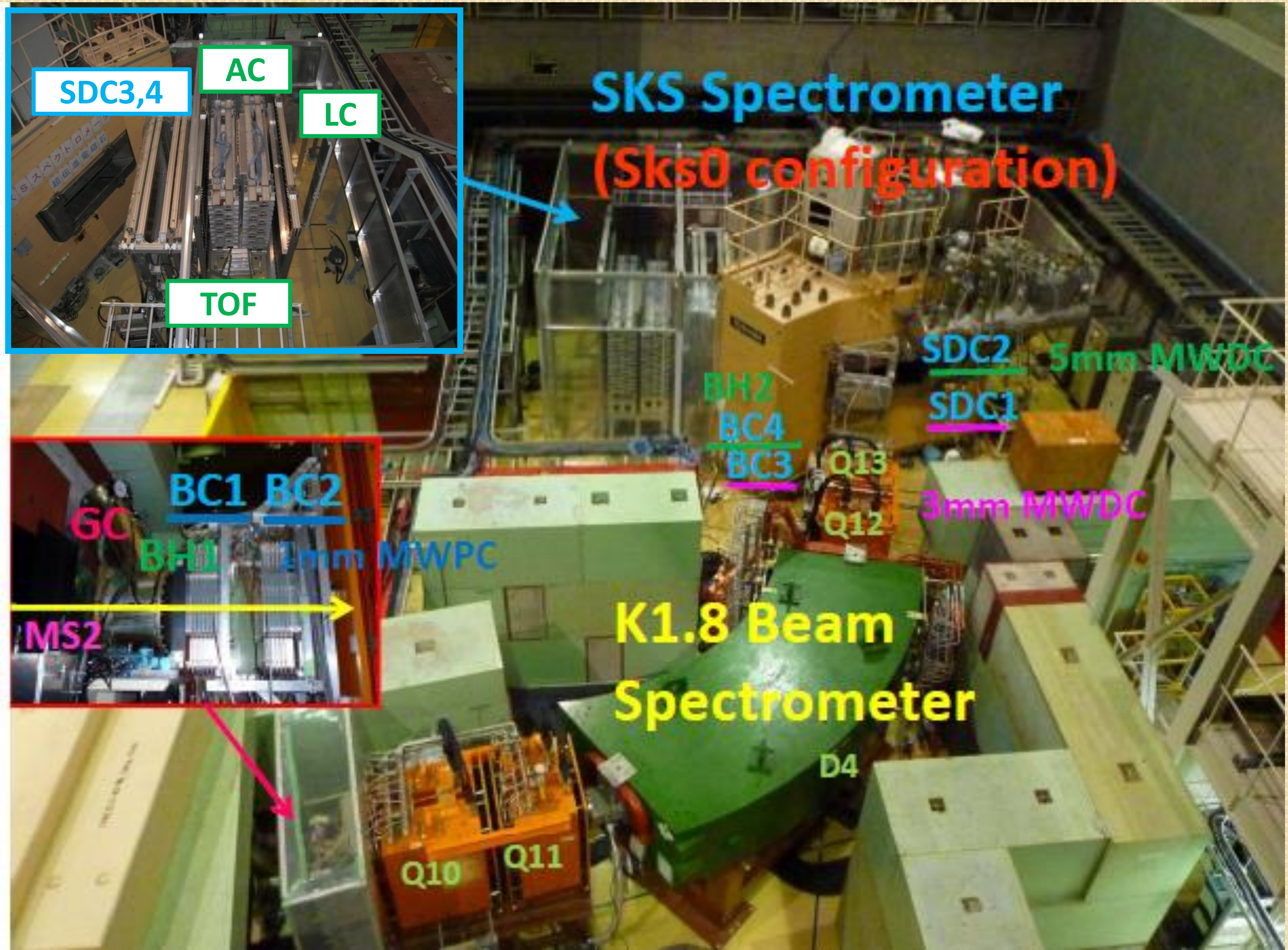
Use high intensity K- beam delivered from J-PARC K1.8 beam line

$$ {}^{A}Z(K^-,\pi^-)\,{}^{A}_{\Lambda}Z^* \rightarrow {}^{A}_{\Lambda}Z+\gamma $$

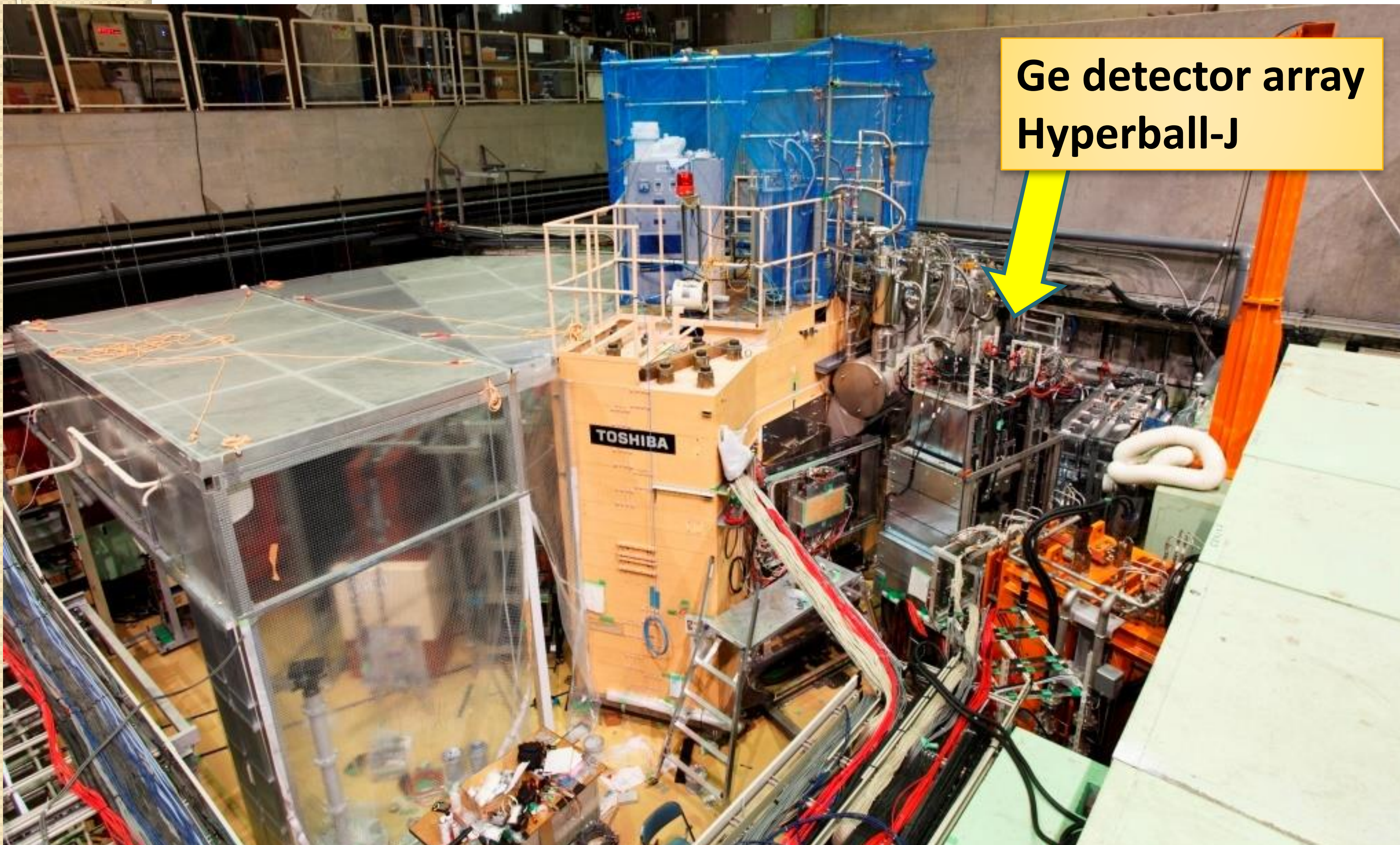


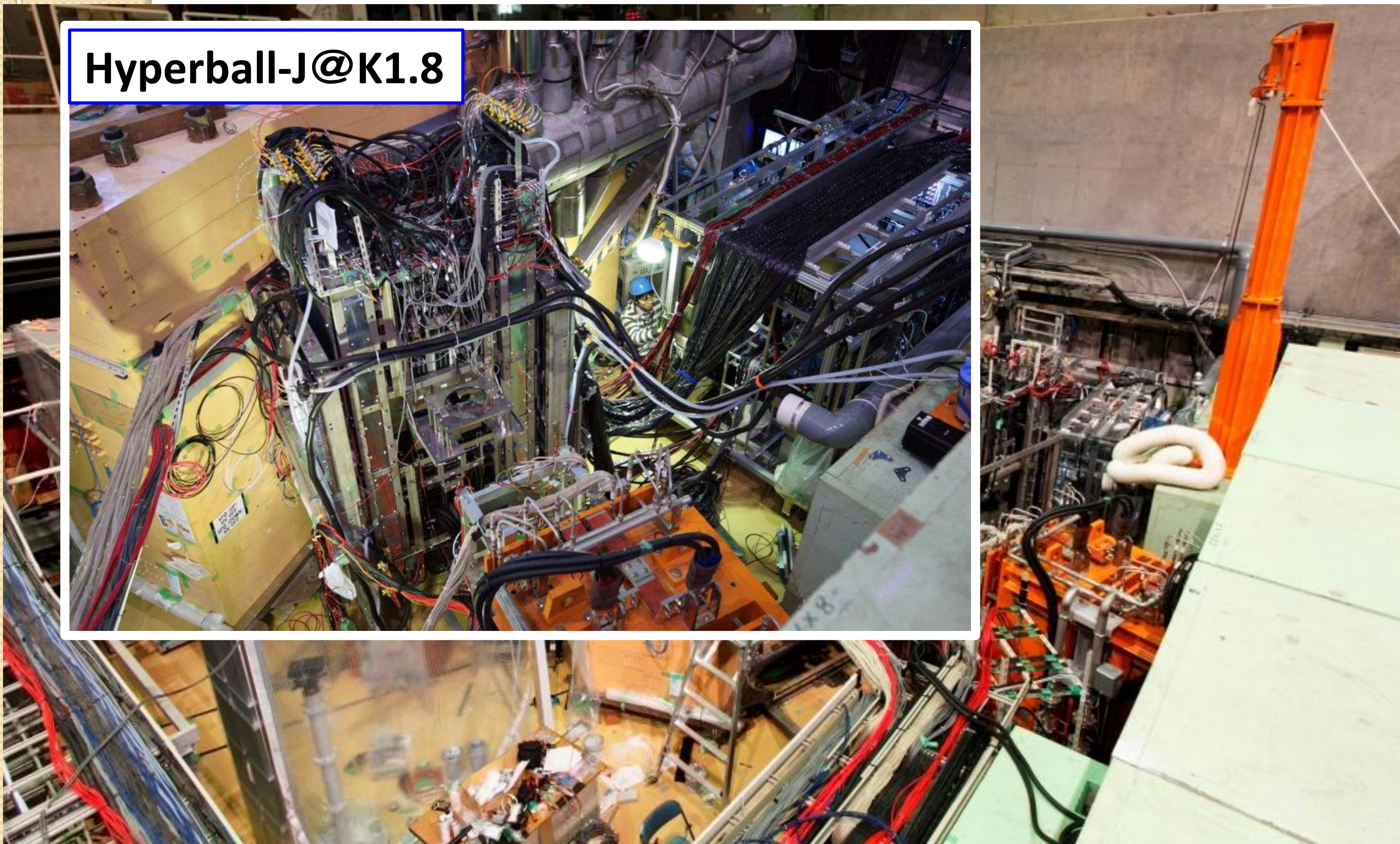
# J-PARC K1.8 beam line + SKS



# E13 setup (2013.5 )



# E13 setup (2013.5 )



# Beam line spectrometer

## ＜Functions＞

- **PID with Time-of-flight**

  Timing counter： BH1—BH2 (Flight length = 11 m)

- **Momentum reconstruction**

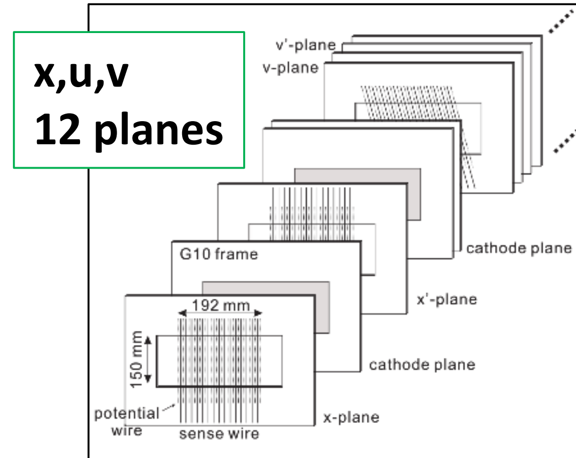
  Upstream： Fiber tracker (BFT)

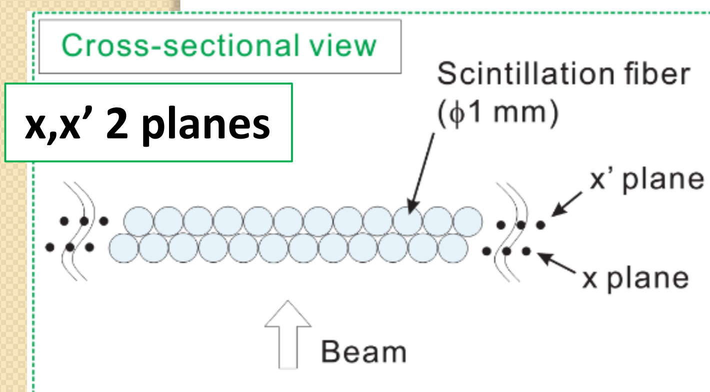
  Downstream： Drift chambers (BC3,4)

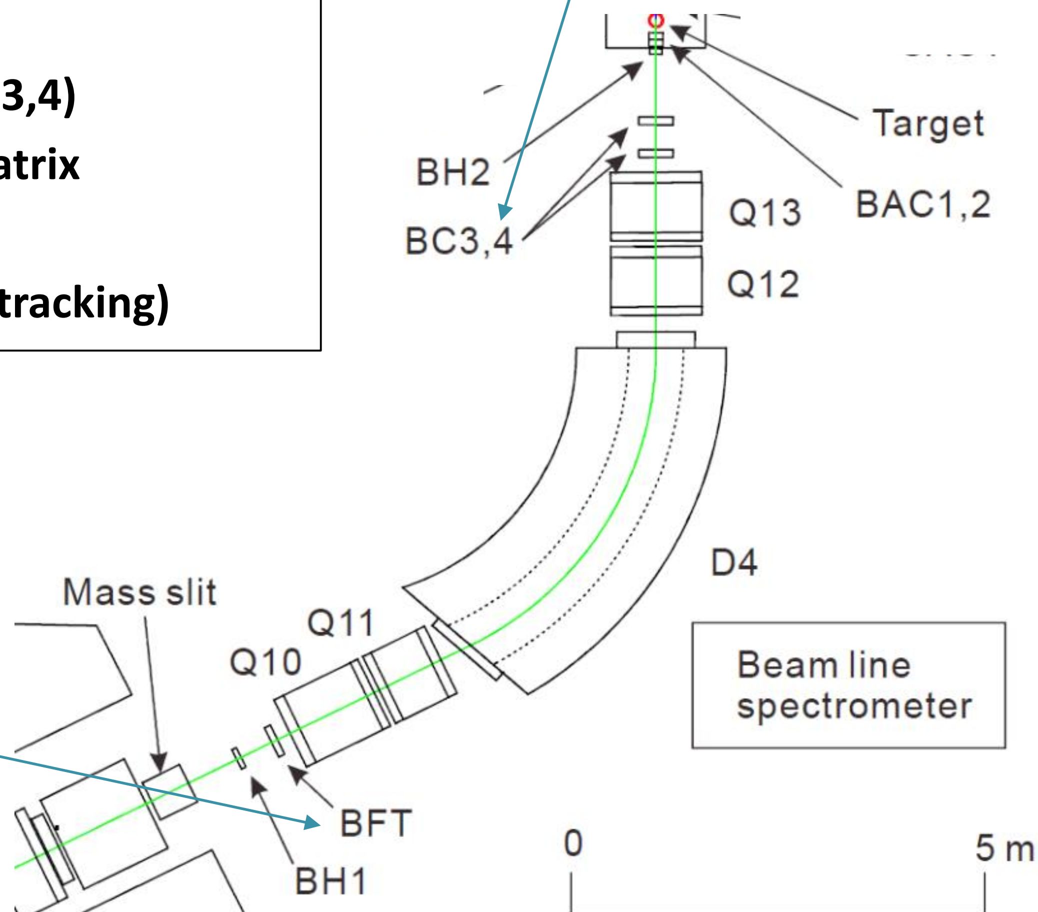
  → 3rd-order QQDQQ transfer matrix

- **Reaction vertex reconstruction**

  (combined with scattered particle tracking)

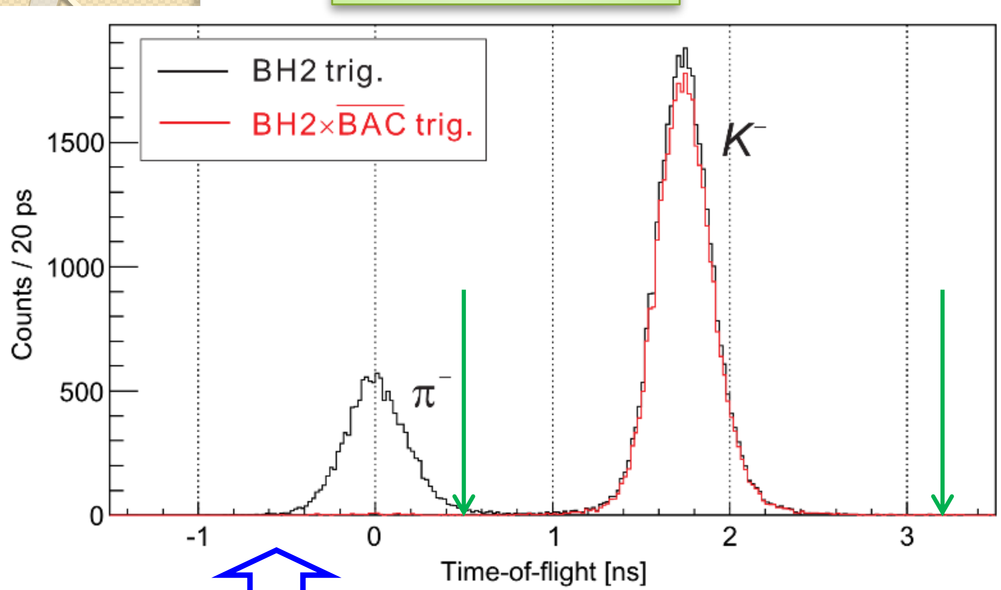


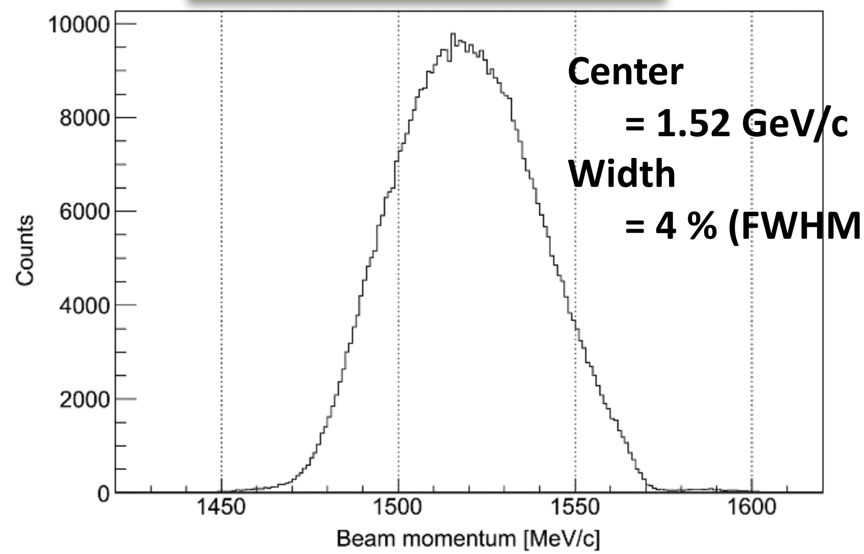
# Analysis for beam particle

**Time-of-flight**

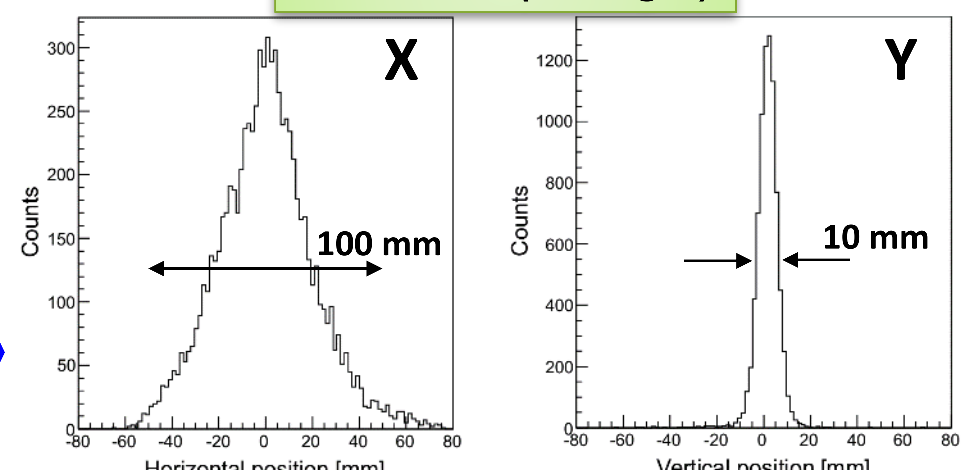



**Good PID performance with aerogel Cherenkov counter**

**Momentum (K⁻ beam)**




**Beam size (at target)**



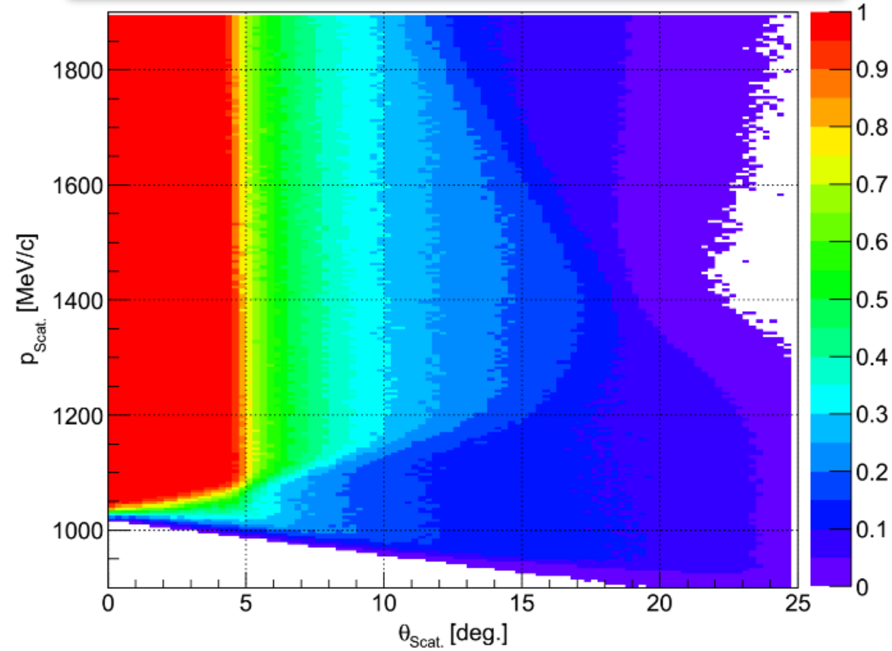

**Horizontally wide beam**
**→ Need large size target**

# Scattered particle spectrometer (SksMinus)

**Wide acceptance magnet [Superconducting Kaon Spectrometer (SKS) ] with modified detector configuration**

- **Wide angular acceptance (0-20 deg.)**
  - **Large yield**
  - **Angular distribution -> populated state identification**
- **Wide momentum acceptance (1.1-2.0 GeV/c)**
  - **Wide beam momentum can be chosen with same setup e.g. 1.8 GeV/c for $^{19}_{\Lambda}F$ run**
- **Enough momentum resolution (~5 MeV/c)**
  - **Hypernuclear production can be tagged by selecting missing mass**

**SksMinus acceptance (momentum and angle dependence)**



# Functions of SksMinus

- **PID with Time-of-flight**

  **Timing counter : BH2—TOF**

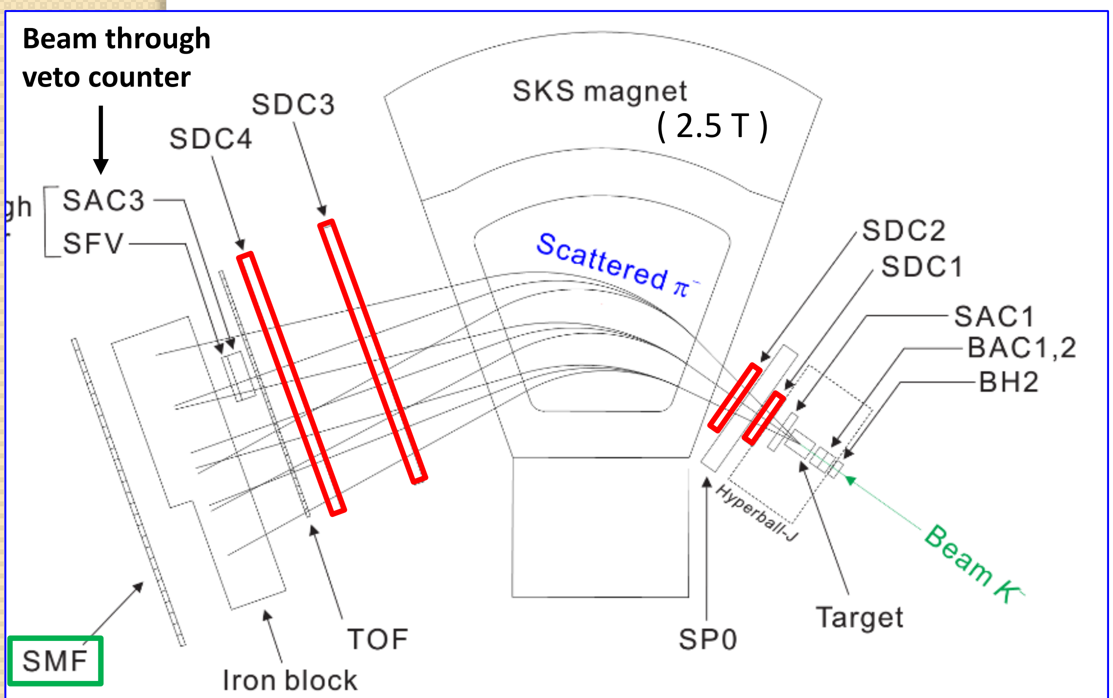
- **Momentum reconstruction**

  **Up and Down stream : Wide size drift chambers SDC1,2,3,4**

  **x, u, v total 22 planes → Runge-Kutta method**

- **Reaction vertex reconstruction**

  **(combined with beam particle tracking)**




< Other detectors >

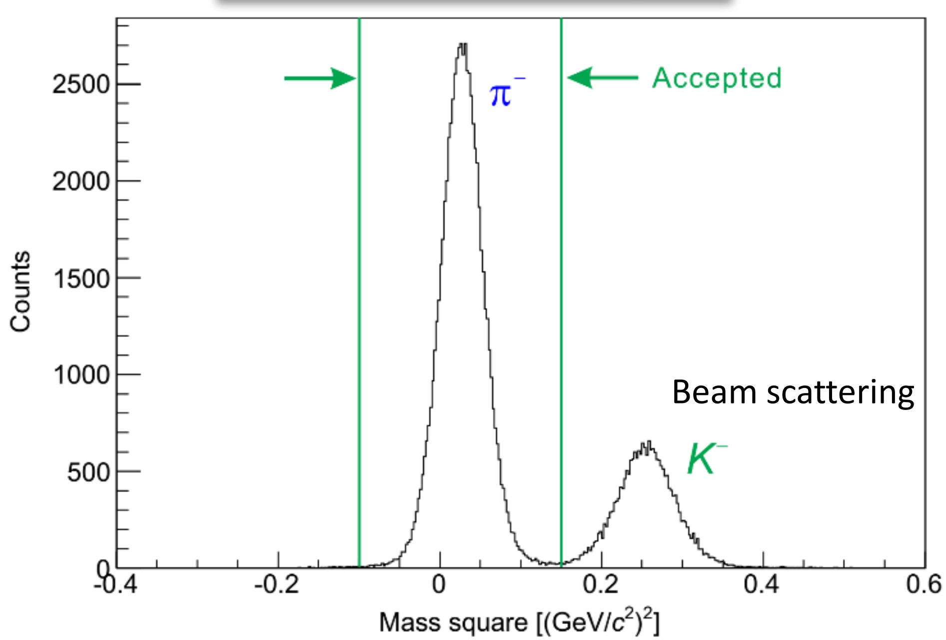
- Beam through veto counter

  Timing counter + aerogel Cherenkov

- Beam $K^-$ decay veto counter
  - **SMF** $K^- \to \mu^- + \nu_\mu$ (64%)
  - **SP0** $K^- \to \pi^- + \pi^0$ (21%)

# Analysis for scattered particle

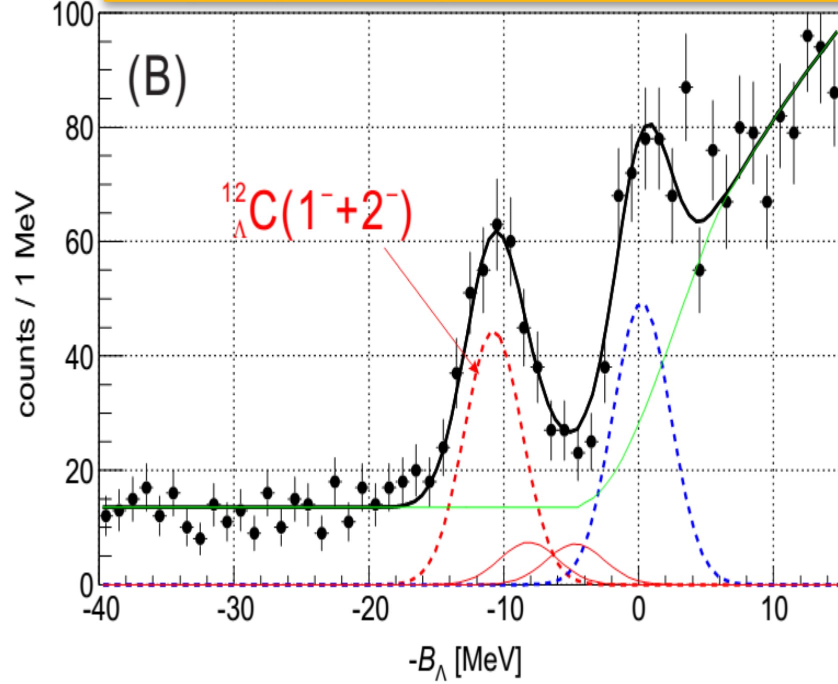
**mass^2 distribution**
**(PID with time-of-flight)**




$$M_{\mathrm{scat}} = \frac{p}{\beta}\sqrt{1-\beta^2}, \quad \beta = \frac{L}{c\Delta t}$$

**Enough PID performance**

**$^{12}_{\Lambda}C$ Missing mass spectrum**
**$CH_2$ target (2.9 g/cm$^2$) data**

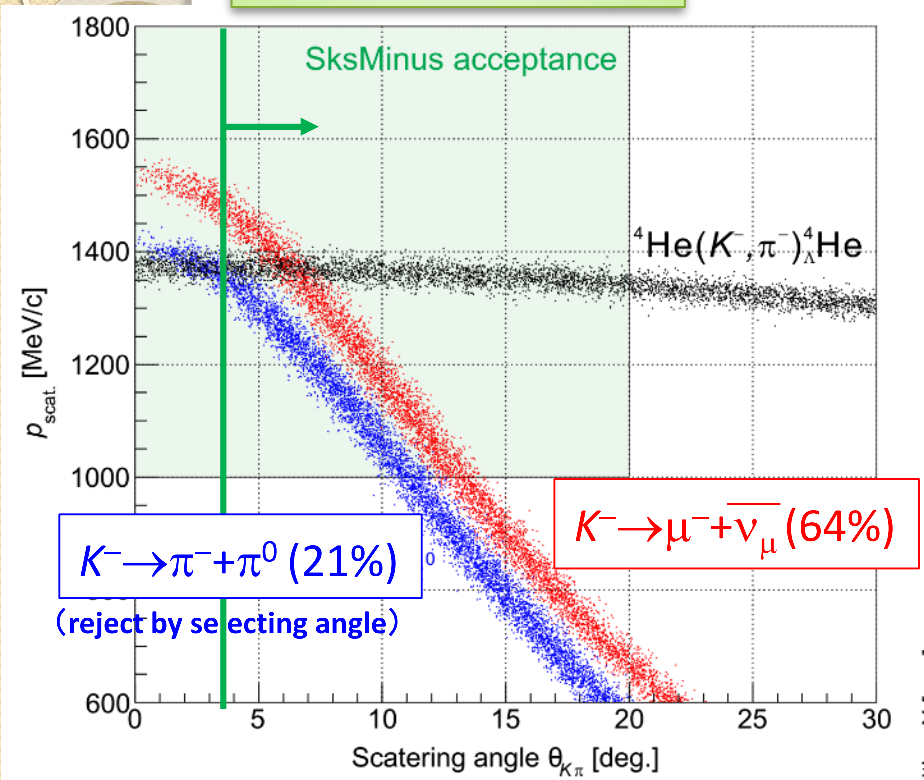



**Mass resolution = 4.8(3) MeV**

**Enough missing mass resolution**
**(combined with beam spectrometer)**

# Beam $K^-$ decay veto counter (SMF)

**Momentum vs angle**

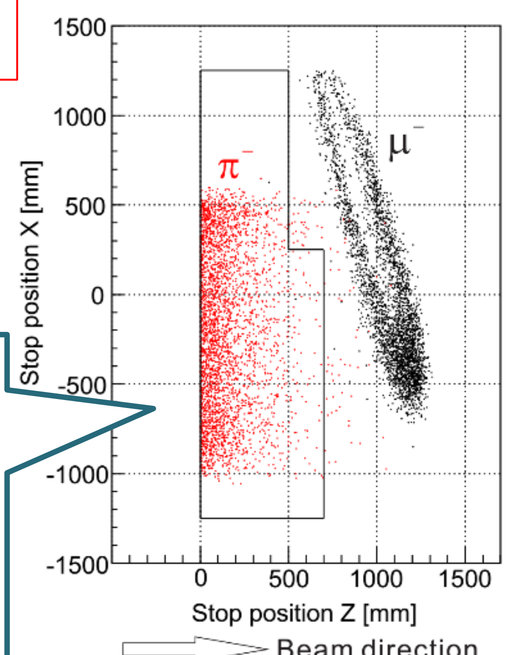


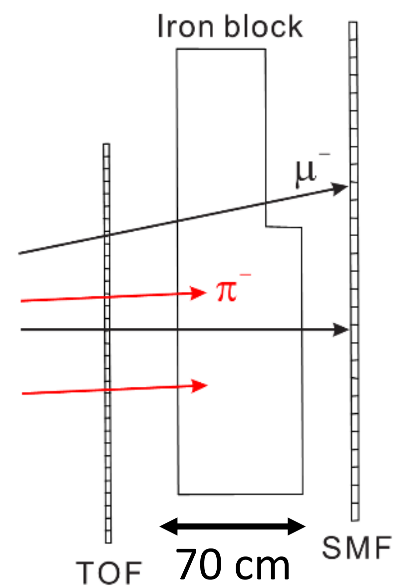

**Beam $K^-$ 2 body decays cause huge background**

- **Cannot distinguish by aerogel Cherenkov**
- **Kinematically overlap with hypernuclear production**

**Introduce SMF**

**~95% rejection power**
**(trigger rate : decrease to 43%)**




**$K^- \to \mu^- + \overline{\nu_\mu}$ rejection by distiguish**
**$\pi^-/\mu^-$ with iron block**

$\mu^-$ : electro magnetic

$\pi^-$ : electromagnetic + hadronic

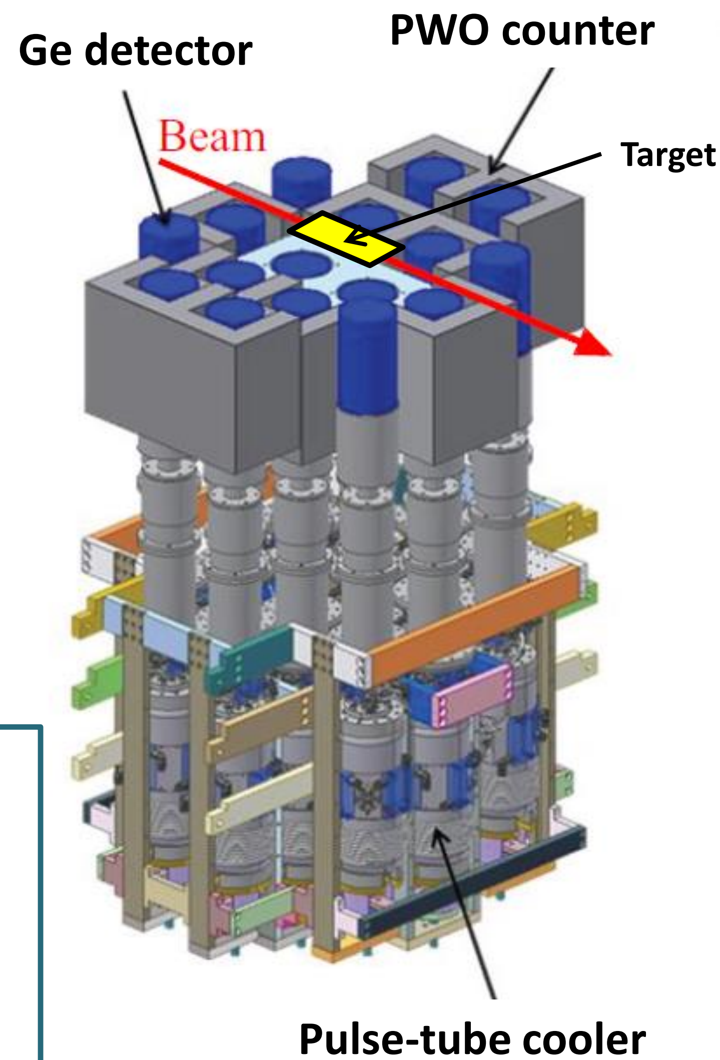
# Hyperball-J new Ge detector array

## Features

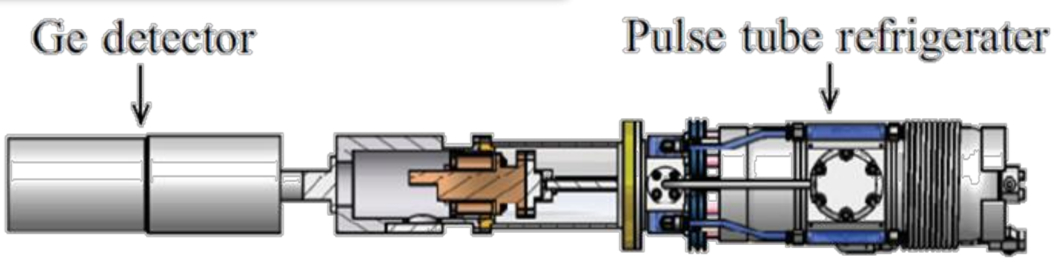
- **Large photo-peak efficiency**
  → ε ~6 % @1 MeV with 32 Ge detectors
- **Fast readout system**
- **Low temp. Ge detector**
  for radiation hardness
  → Mechanical cooling
- **Fast background suppressor**
  → PWO counter

(Fast readout system, Low temp. Ge detector, Fast background suppressor: for high intensity hadron beam)

## Lower half of Hyperball-J




## Developed Ge detector

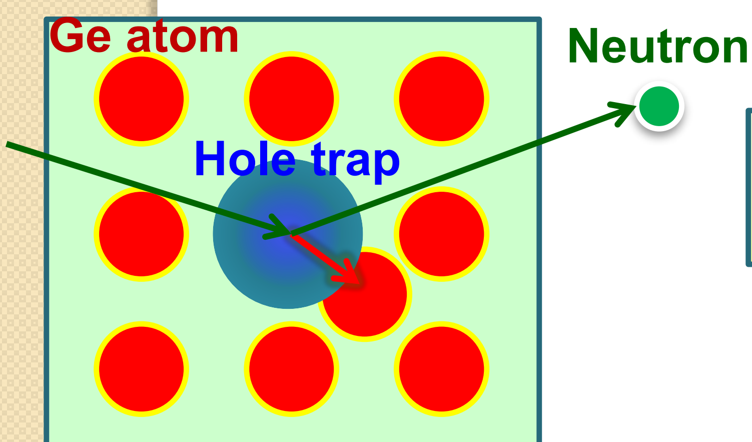


# Radiation hardness (neutron damage)

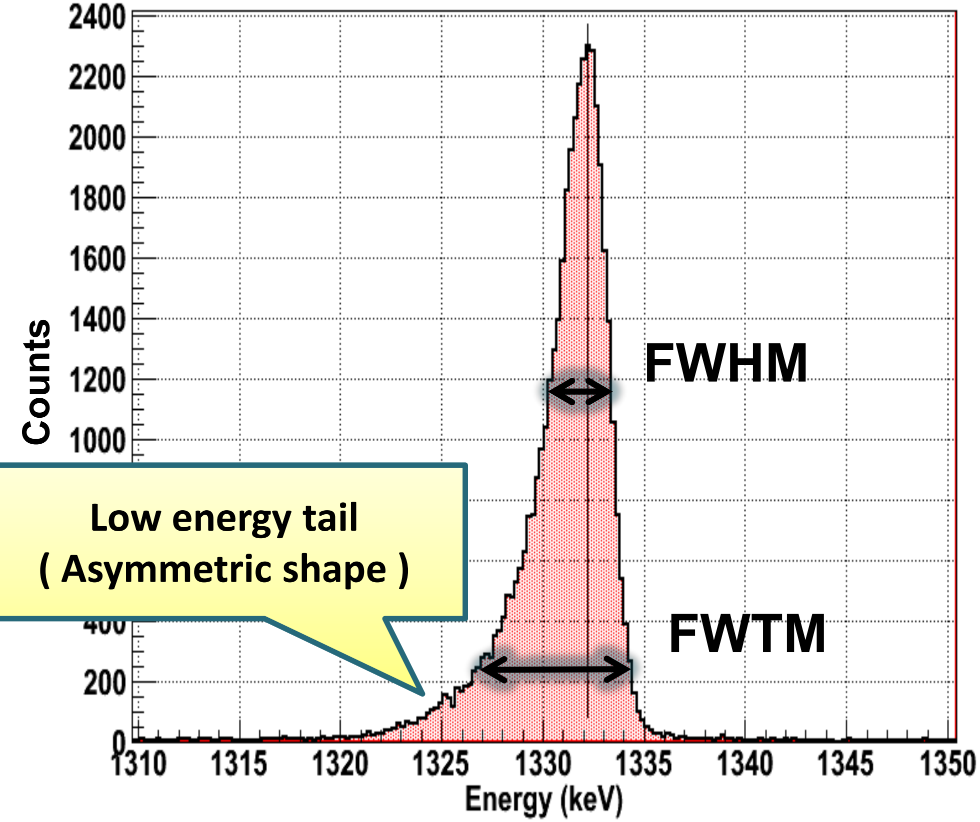
**Energy resolution of Ge detector becomes worse with radiation damage.**

Scattering of fast neutrons with Ge atoms

**Creation of lattice defect**
**( creation of hole trap )**




**Energy peak of a damaged Ge detector**




**Incomplete hole collection due to lattice defection**

# Radiation hardness (neutron damage)

**Energy resolution of Ge detector becomes worse with radiation damage.**

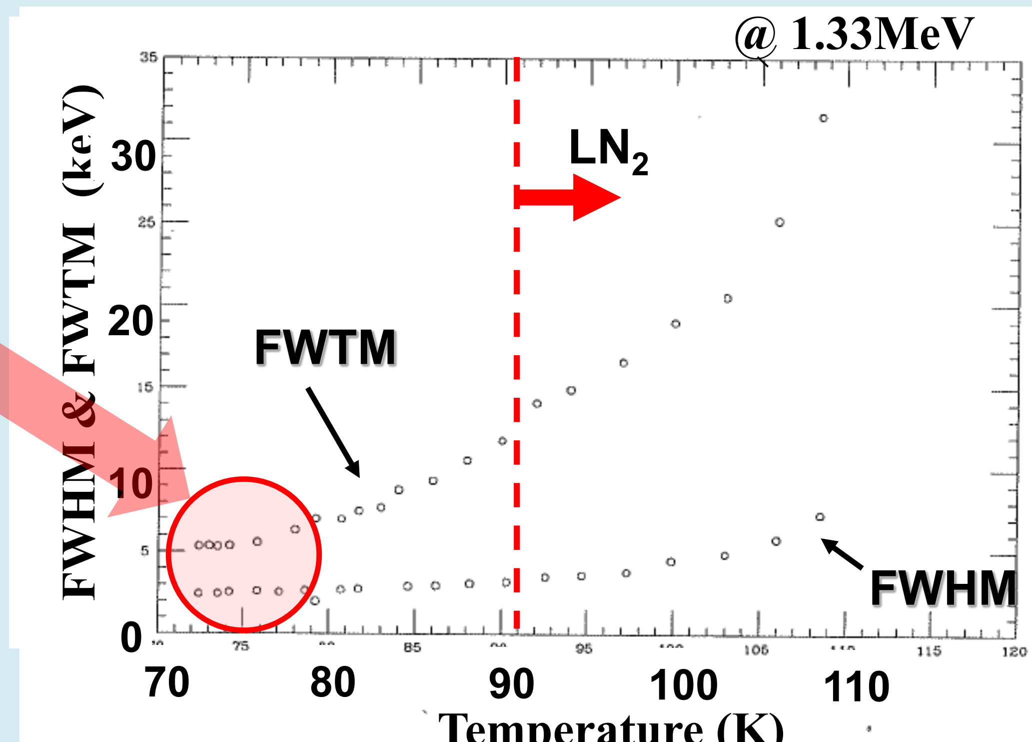
Scattering of fast neutrons
with Ge atoms

**Energy peak of a damaged Ge detector**


**Effect of radiation damage can be suppressed at lower temp.**

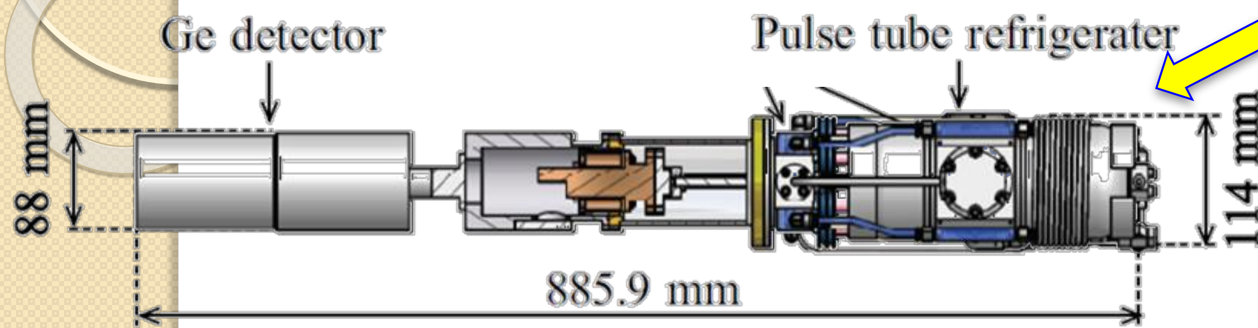
*E. Hull and R. H. Pehl et al.*
*IUCF Ann. Rep. 143, (1993)*

**Use mechanical cooler to obtain lower temp.**




183MeV neutron $3.2\times10^{8}$ n/cm$^{2}$ @ IUCF

# Ge detector for Hyperball-J



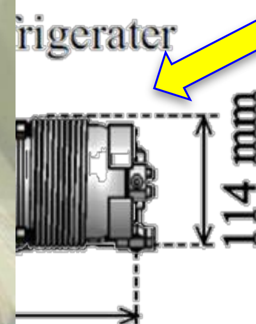

**Pulse-tube refrigerator**
**(Fuji electric, Co.)**

**Weight : ~11 kg**
**Cooling power:**
**2.5 W @77K**

- **Mechanical cooling (Pulse-tube cooler)**
  - **- High cooling power**
    Crystal temp. : **67 K** ($LN_2$ : 92 K)
    ***Enough low for radiation hardness***
  - **- Low mechanical vibration**
    Energy resolution(FWHM) **3.1 keV** @1.33 MeV ($LN_2$ : 3.1 keV)
- **Slim and compact design**
  → **dense placement of detectors**
- **Transistor-reset Pre. Amp. (+Low gain)**
  Expected condition : **Single rate ≅ 100 kHz**
  **Energy deposit rate ≅ 100,000 MeV/s**

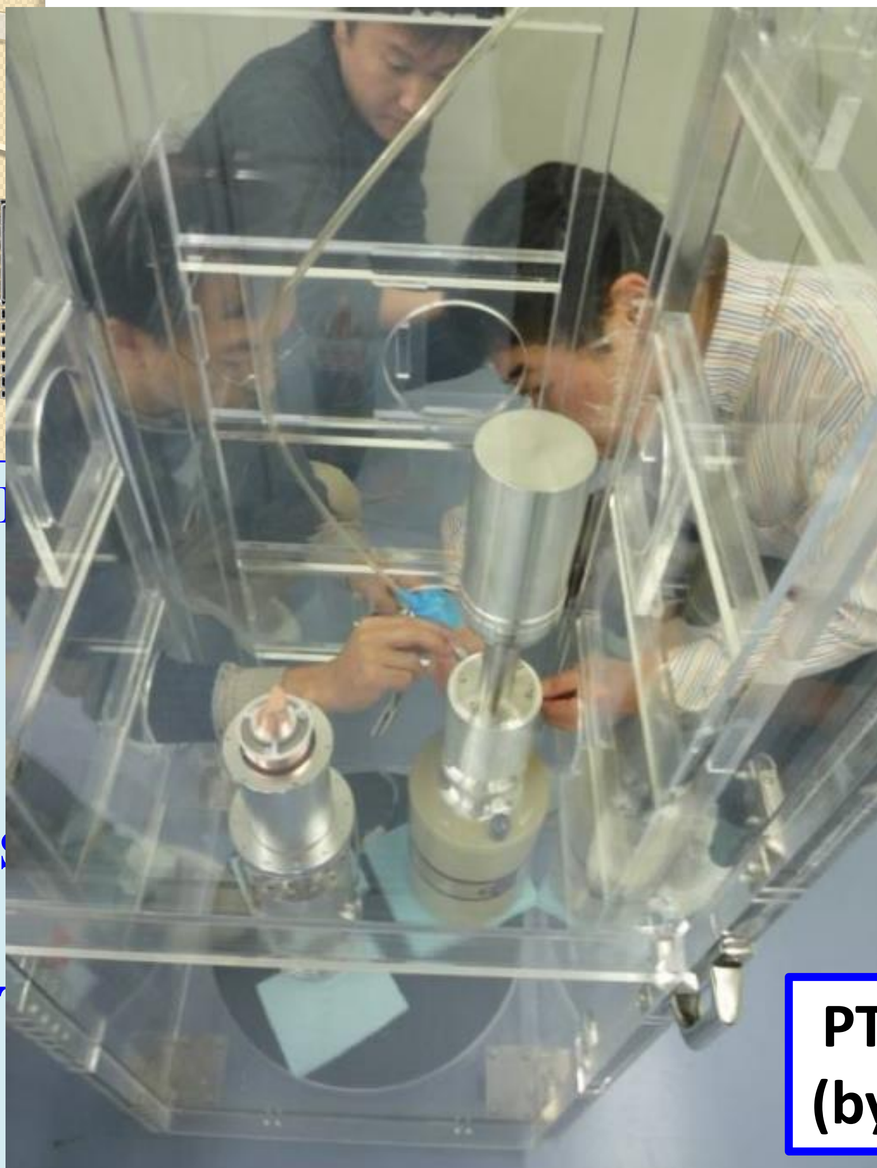
***Gain : 150 MeV/reset***
***→ Reset rate < 1kHz***

# Ge detector for Hyperball-J




**Pulse-tube refrigerator**
(Fuji electric, Co.)

**Weight : ~11 kg**
**Cooling power:**
**2.5 W @77K**



***Enough low for radiation hardness***

V @1.33 MeV (LN$_2$ : 3.1 keV)

***Gain : 150 MeV/reset***
***et rate < 1kHz***

**PTR mounting work (by ourselves) @KEK**

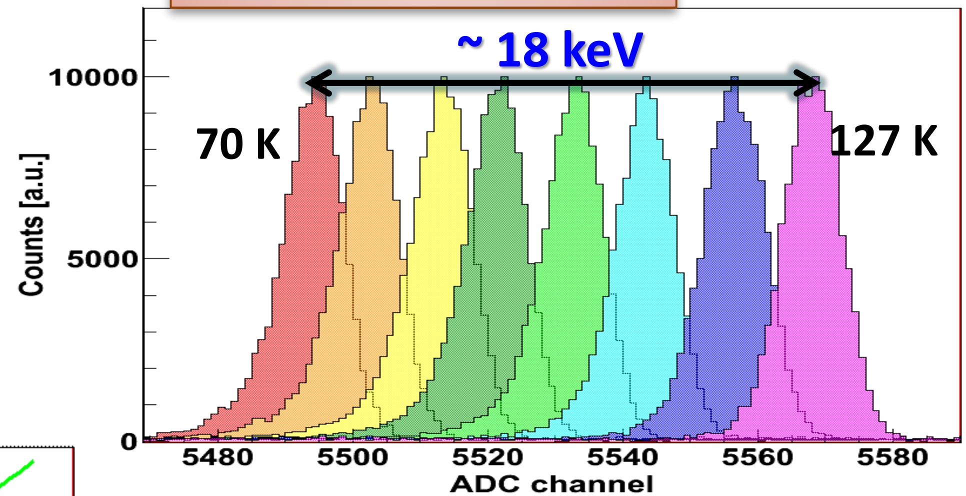
# Gain drift of Ge detector

Worth stability of crystal temp.
by introducing mechanical cooling

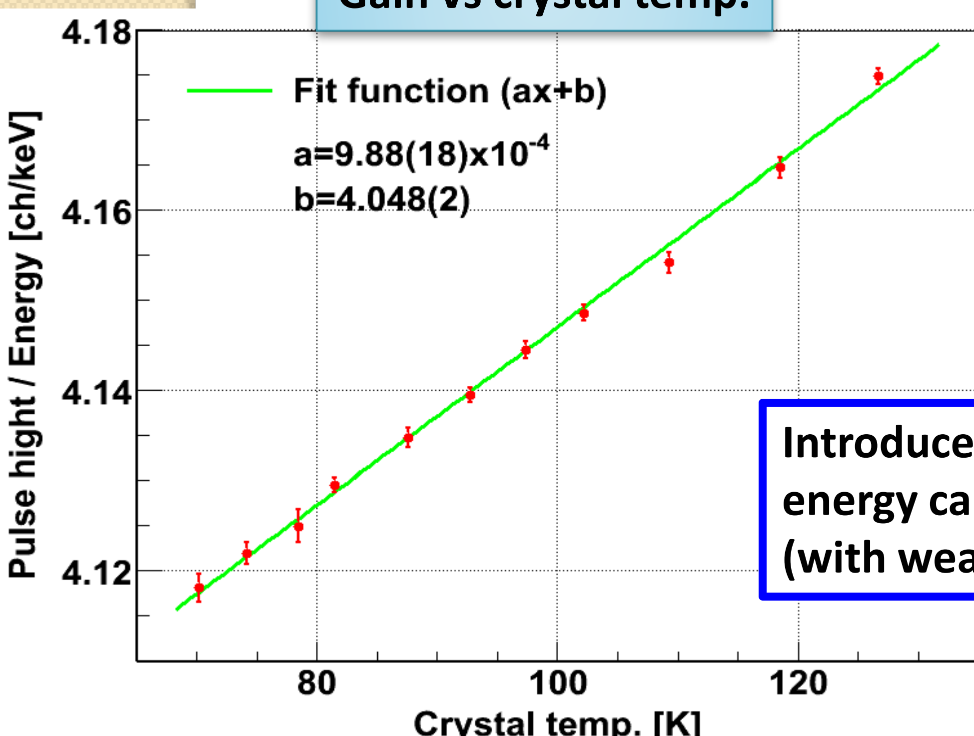
$LN_2$ cooling : < 1 K

Mechanical cooling : ~ 5 K

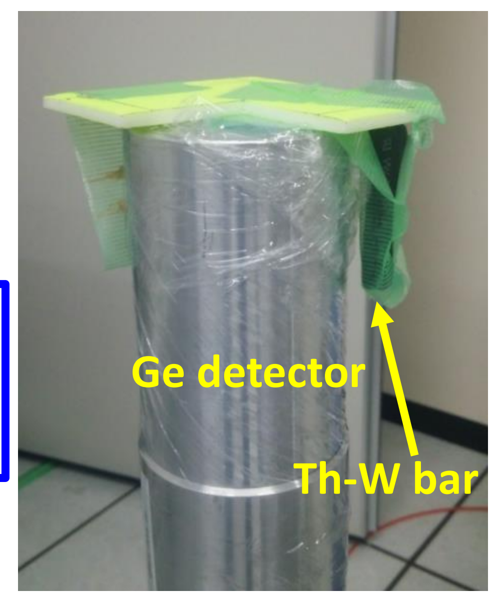
1333 keV peak position




Gain vs crystal temp.




Introduce continuous energy calibration (with weak Th-series source)



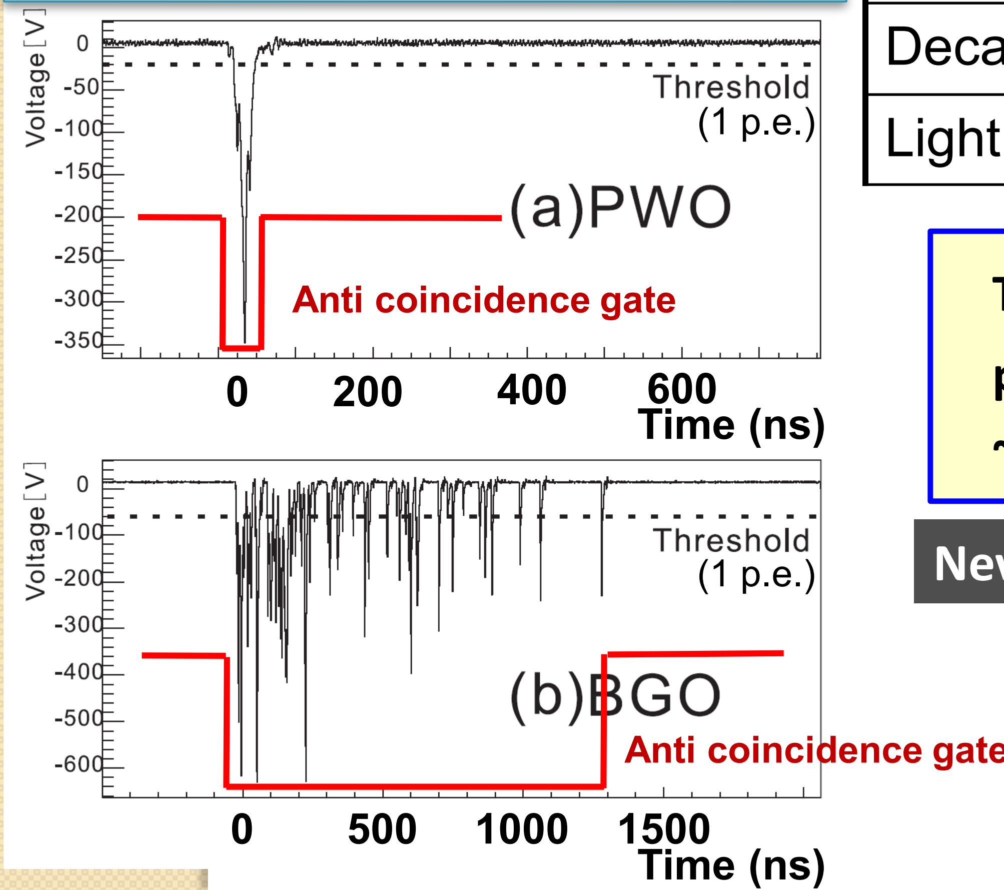
# Fast background suppressor

Conventional BGO counters

↓

**PWO($PbWO_4$) counters**

**Typical pulse shape for 661 keV**




| Crystal | BGO | **PWO** |
|---|---|---|
| Effective atomic number | 75 | **76** |
| Density[g/cm$^3$ ] | 7.23 | **8.28** |
| Decay constant [ns] | 300 | **~6** |
| Light yield [NaI=100] | 15 | **~1** |

**The lower light yield becomes a problem for low energy γ rays of ~ 100 keV.**

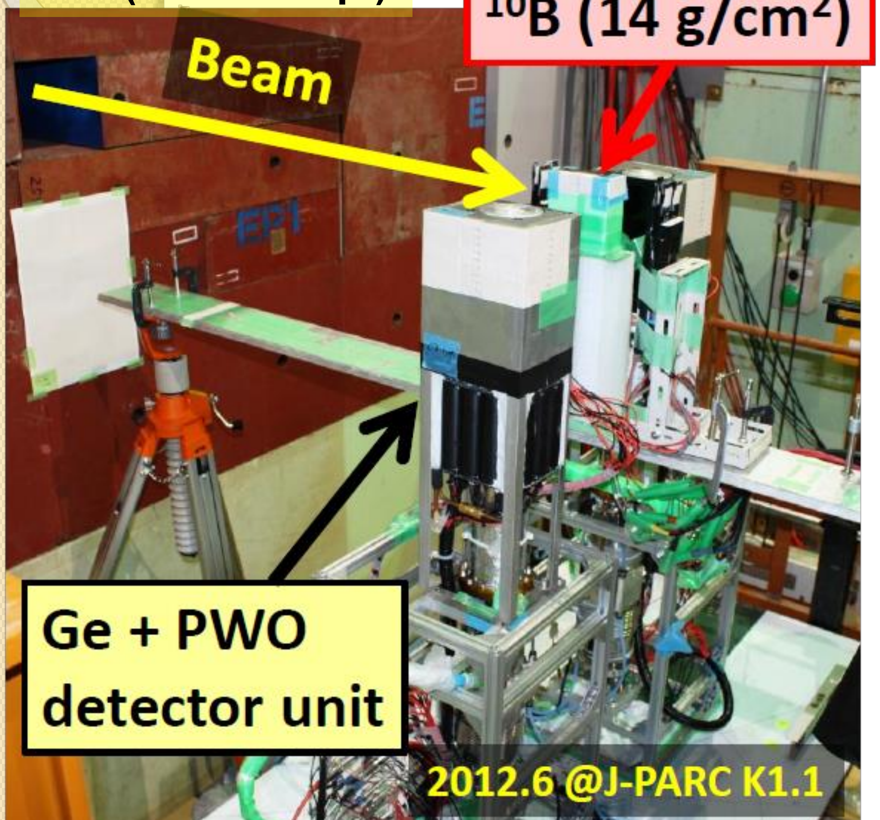
**Never used for low energy nuclear γ**

Increase light yield (4 times)

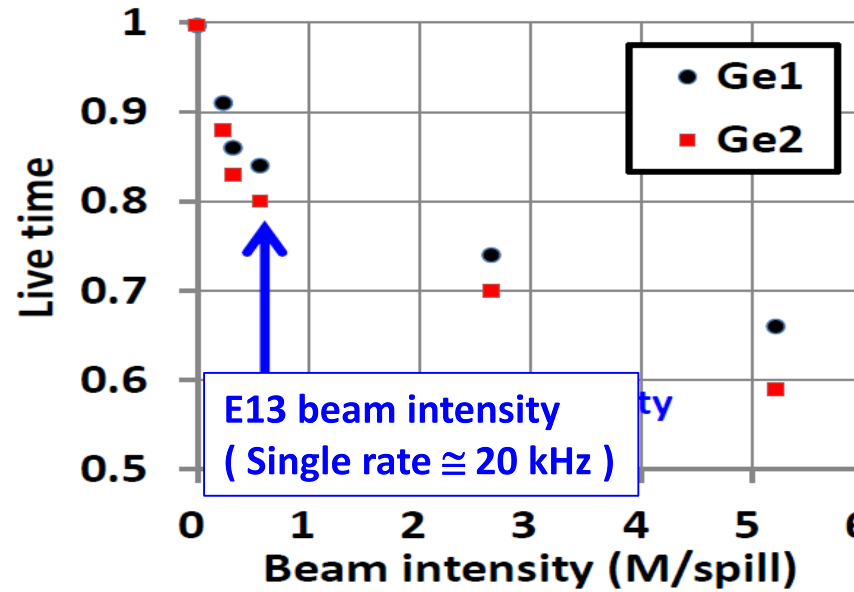
- Doping
- Cooling

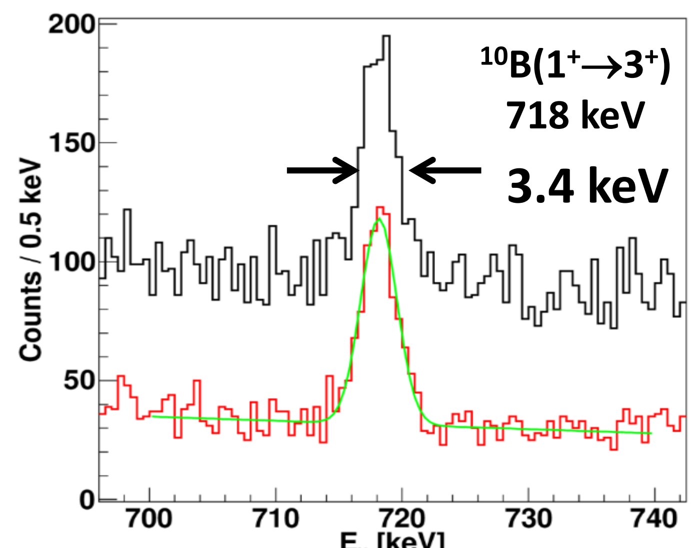
# In-beam performance

$\pi$ intensity
= 0.2~5 M/spill
( 2 s flat top )




**Live time vs beam intensity**

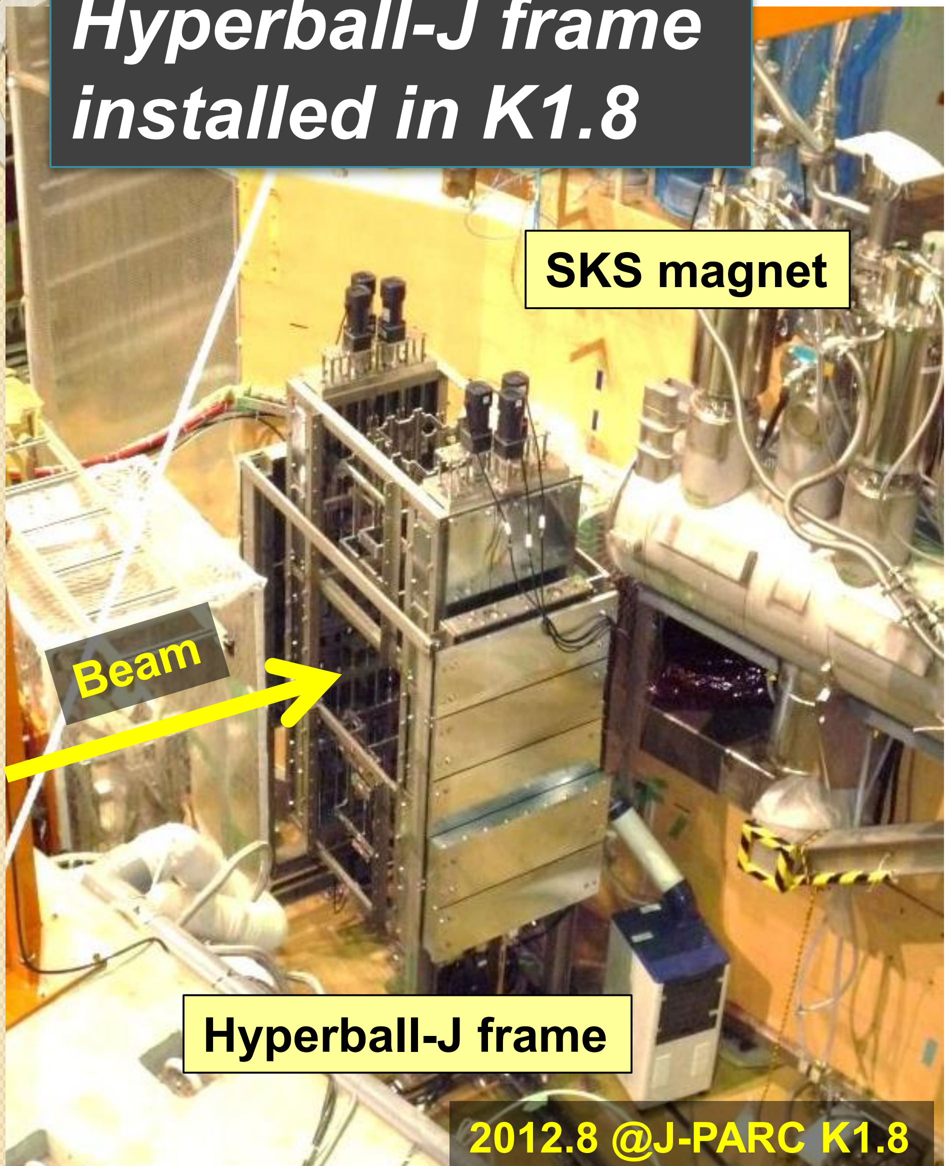


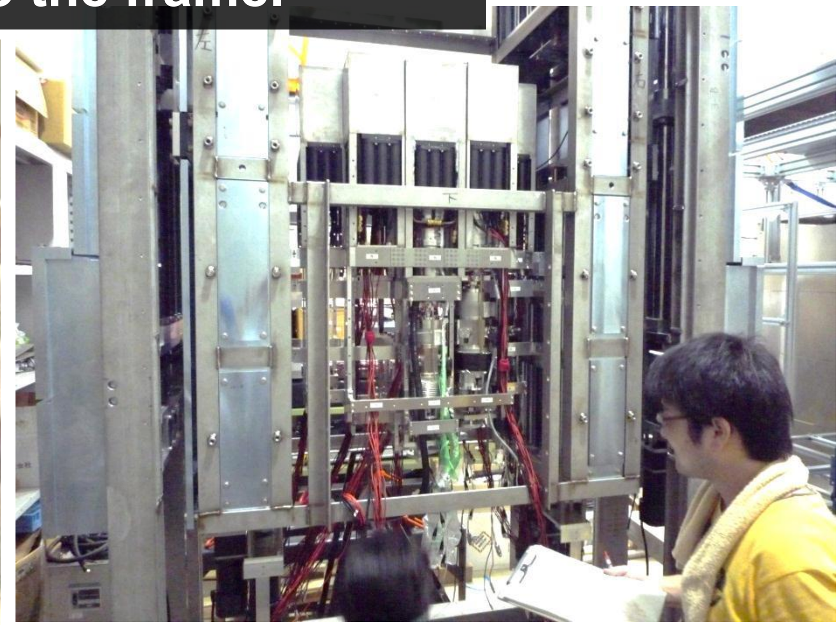

w/ PWO
suppression

# Hyperball-J

***Hyperball-J frame installed in K1.8***




**mounting detectors to the frame.**



# Time line of the E13 experiment

**2012.8** **Installation of Hyperball-J**

**2013.1** **Installation of SksMinus detectors**

**2013.3-5** **Commissioning beam time**

whole system was checked

*( suspend just before physics run )*

**2015.4** **Physics run with a $^{4}$He target**

This talk

- $\gamma$-ray spectroscopy of $^{4}_{\Lambda}$He
- missing mass spectroscopy of $^{4}_{\Sigma}$He

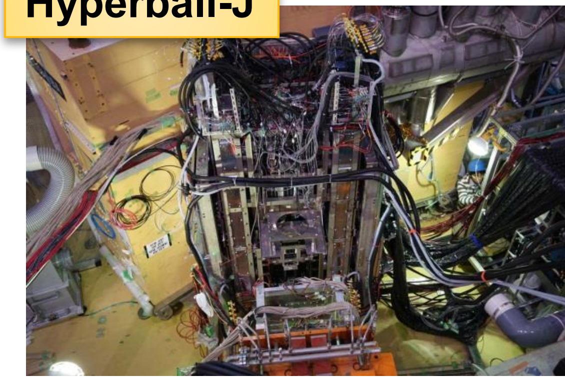
Irradiated K-beam : 23 G

*( Total beam time = ~5 days )*

**2015.6** **Physics run with a CF$_4$ target**

- $\gamma$-ray spectroscopy of $^{19}_{\Lambda}$F

Hyperball-J

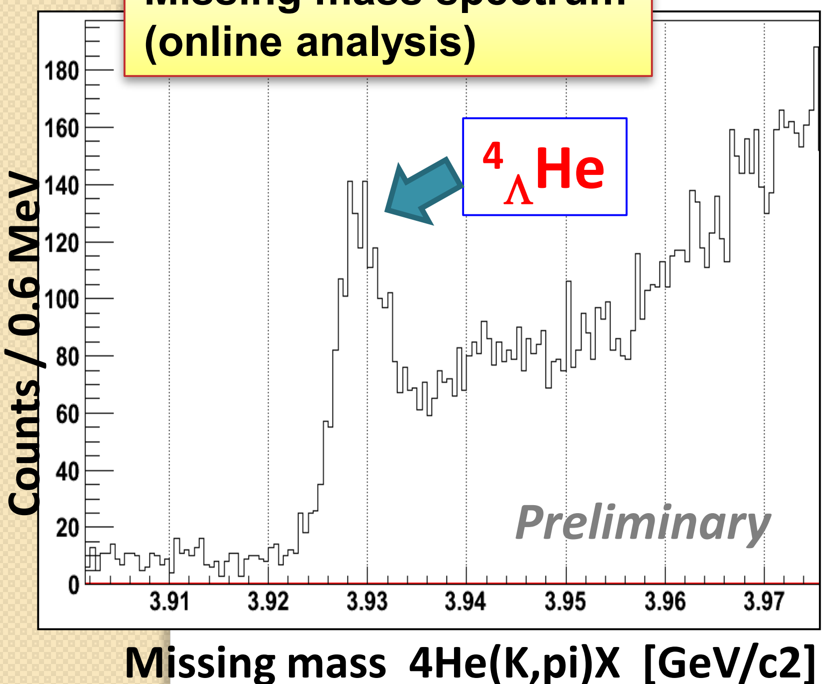


SksMinus(downstream)

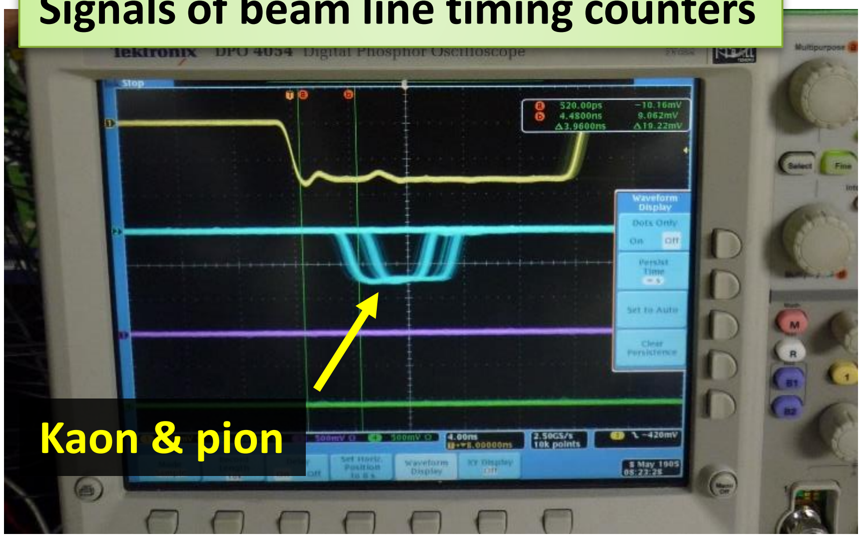
# First K beam experiment @ K1.8

J-PARC E13 was first experiment which use K beam
We tuned beam line parameters (~3 years)
-> Reasonable kaon intensity !

Missing mass spectrum
(online analysis)




Signals of beam line timing counters




*待ちに待ったビームタイム！*
*Kaon実験が始まり感動しました。*

# End run photo


(2015.04)

KEK,
JAEA,
Tohoku univ.,
Kyoto univ.,
Osaka univ.,
Seoul national univ.


(2015.06)

# $^{4}_{\Lambda}$He identification

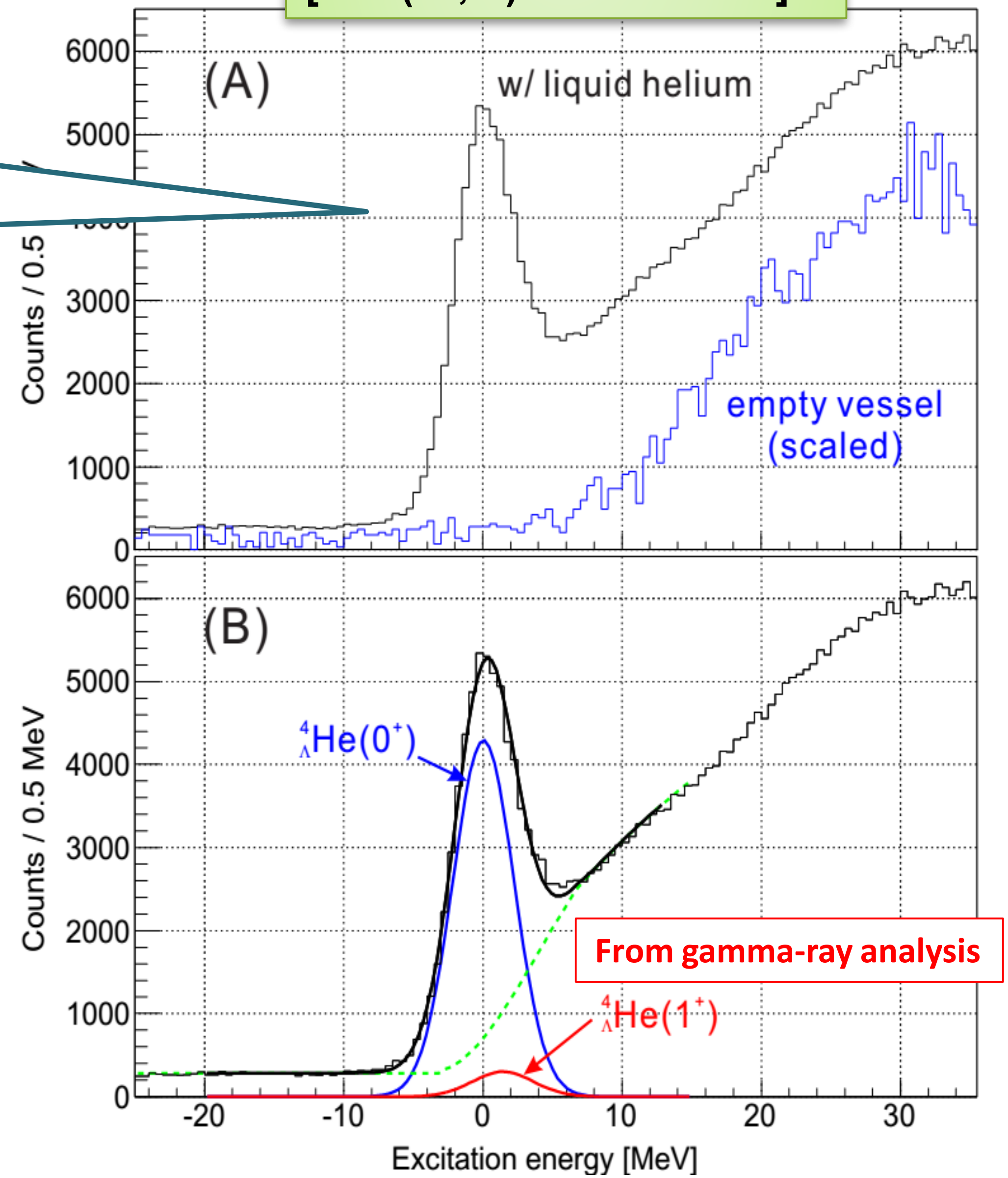
**Missing mass analysis**

- **Peak structure : $^{4}_{\Lambda}$He bound events**
- **Low level background due to background veto counters**

**$^{4}_{\Lambda}$He bound events can be clearly selected**

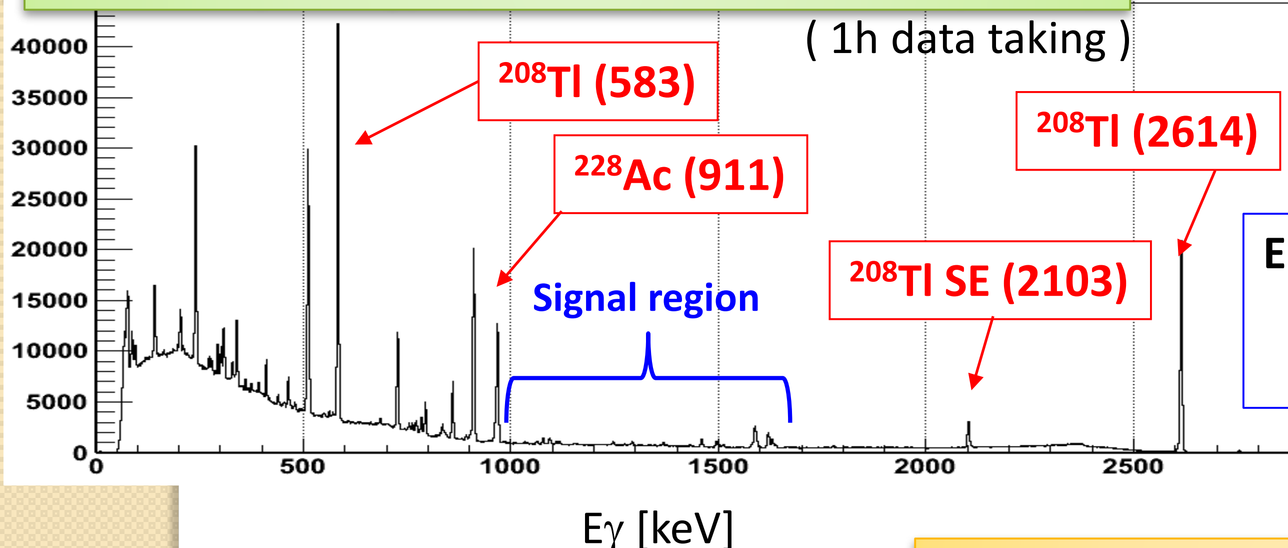
- **Missing mass resolution : 5 MeV (FWHM)**
- **$^{4}_{\Lambda}$He($1^+$) yield < $^{4}_{\Lambda}$He($0^+$) yield (considering Ge detector efficiency) → same as theoretical prediction**

**Missing mass distribution [ $^{4}$He(K-,π-)X kinematics]**



# Gamma-ray measurement

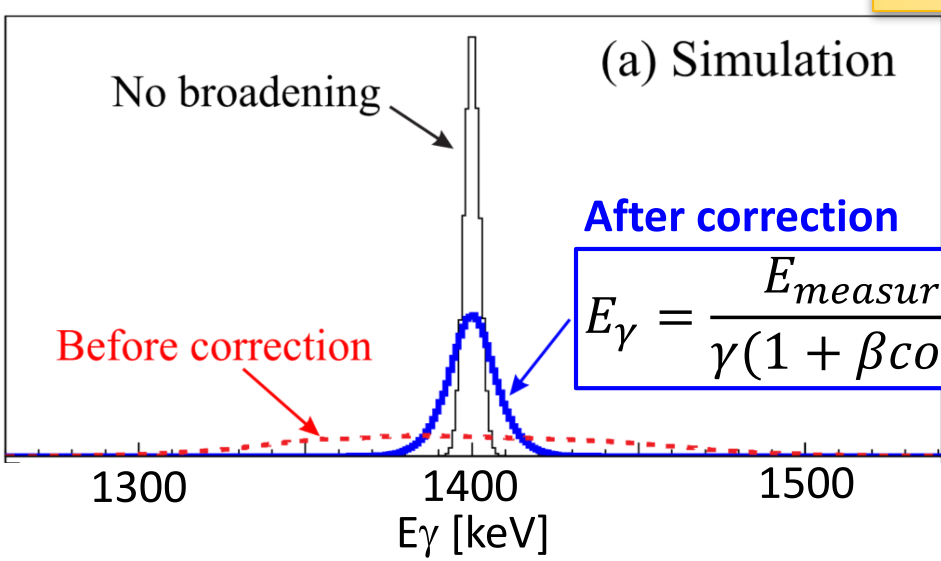
**Gamma-ray energy spectrum (Spill-off beam period)**



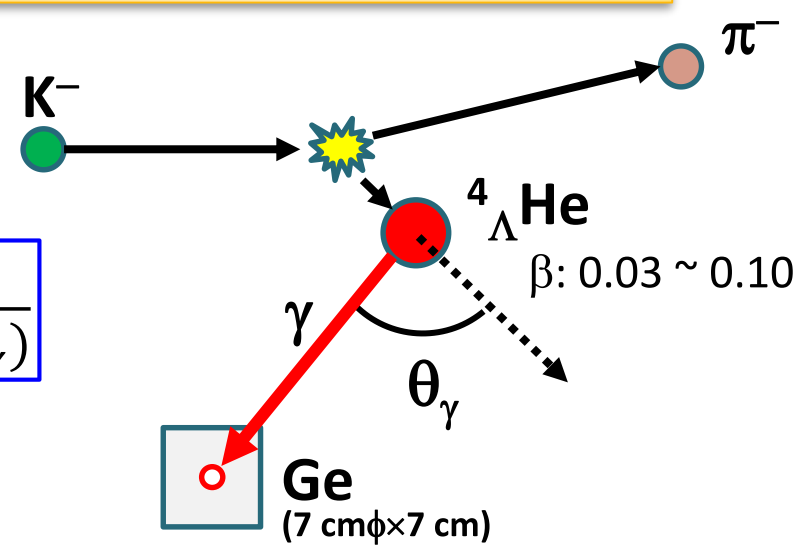

**Run-by-run Energy calibration ( w/ Th-series source )**

**Energy resolution :**
**~5 keV (FWHM) @ 1.4 MeV**
**( summing all detectors )**

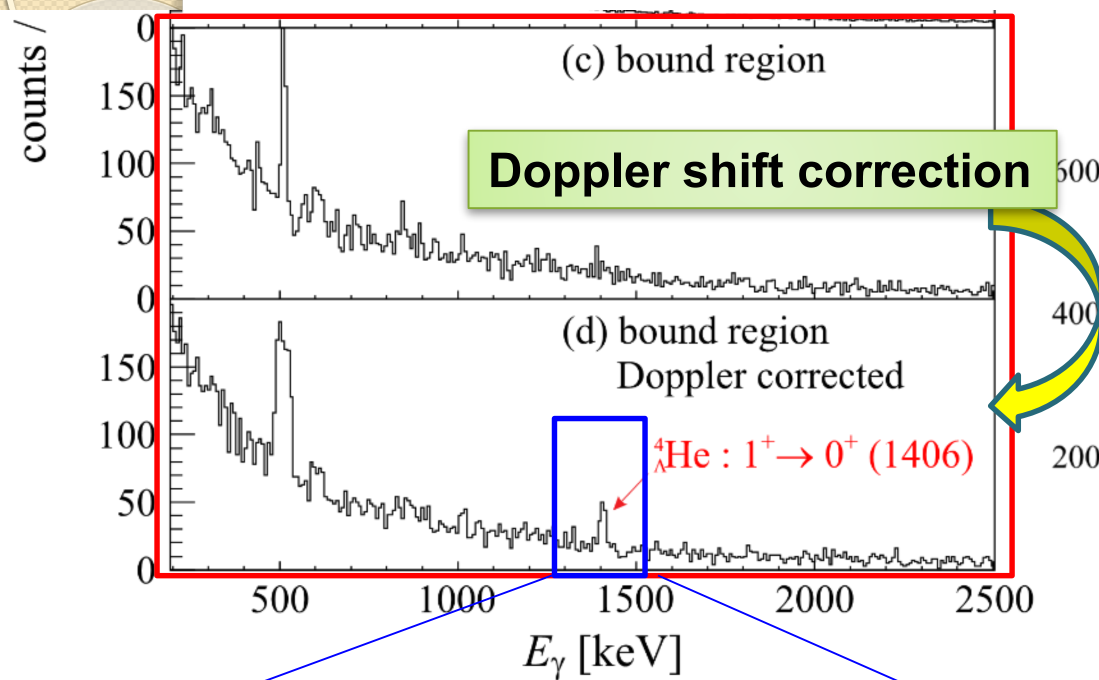
**Event-by-event Doppler correction**

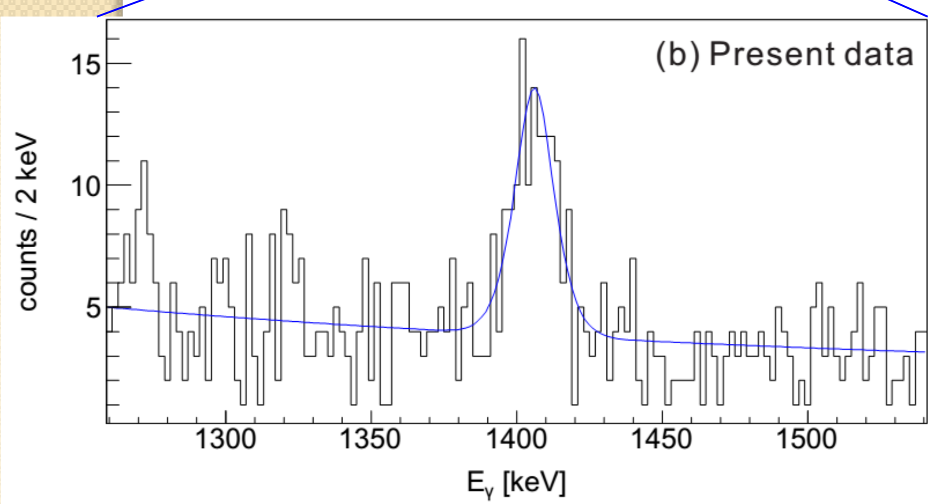



$$E_\gamma = \frac{E_{measured}}{\gamma(1 + \beta\cos\theta_\gamma)}$$

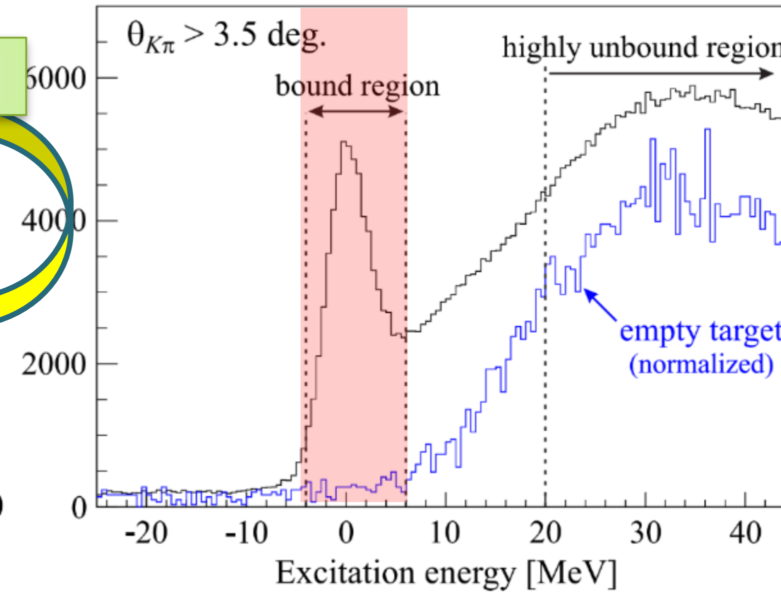


# Result of J-PARC E13



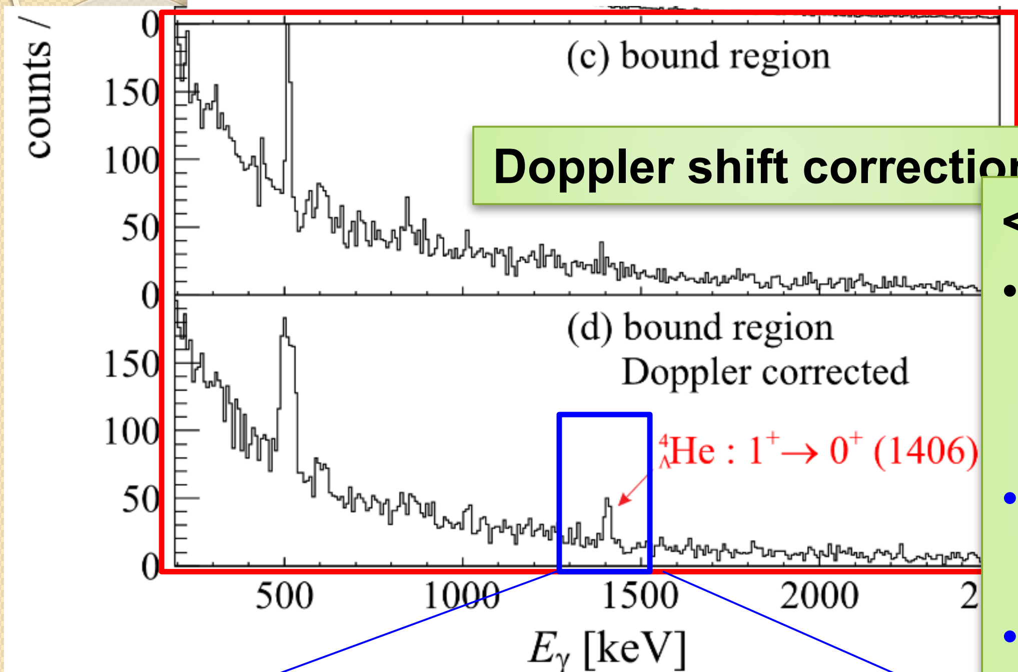

**Tag hypernuclear production w/ missing mass analysis**



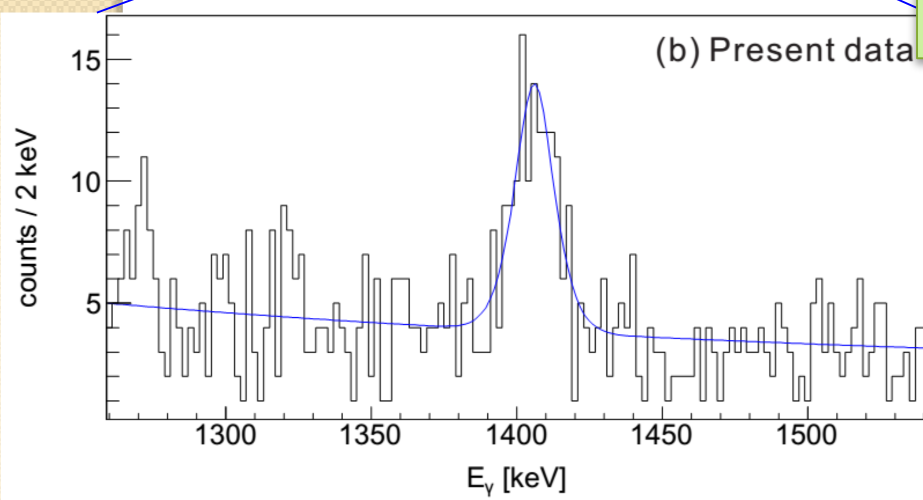

**Single peak was observed**

# Result of J-PARC E13

Tag hypernuclear production w/ missing mass analysis


Doppler shift correction




<Evidence for peak assignment>

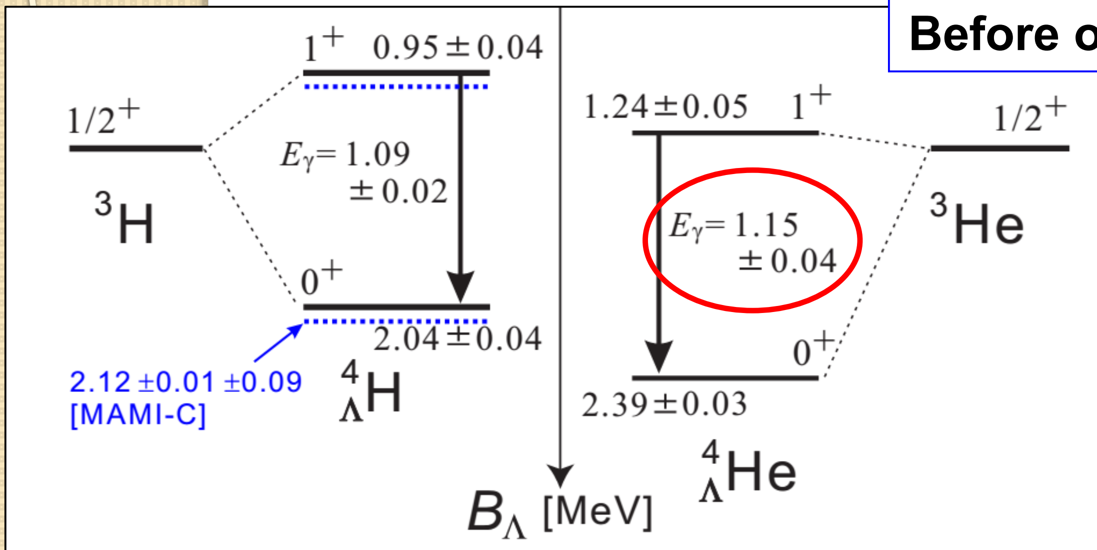
- Only one peak structure after…
  - Bound event selection
  - Doppler correction
- Obtained peak shape was consistent with simulated one
- Gamma-ray yield is reasonable (assuming theoretical prediction)

We successfully measured $^{4}_{\Lambda}He$ ($1^+ \rightarrow 0^+$) M1 transition

Peak energy :
**1406 ± 2(stat.) ± 2(syst.) keV**

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

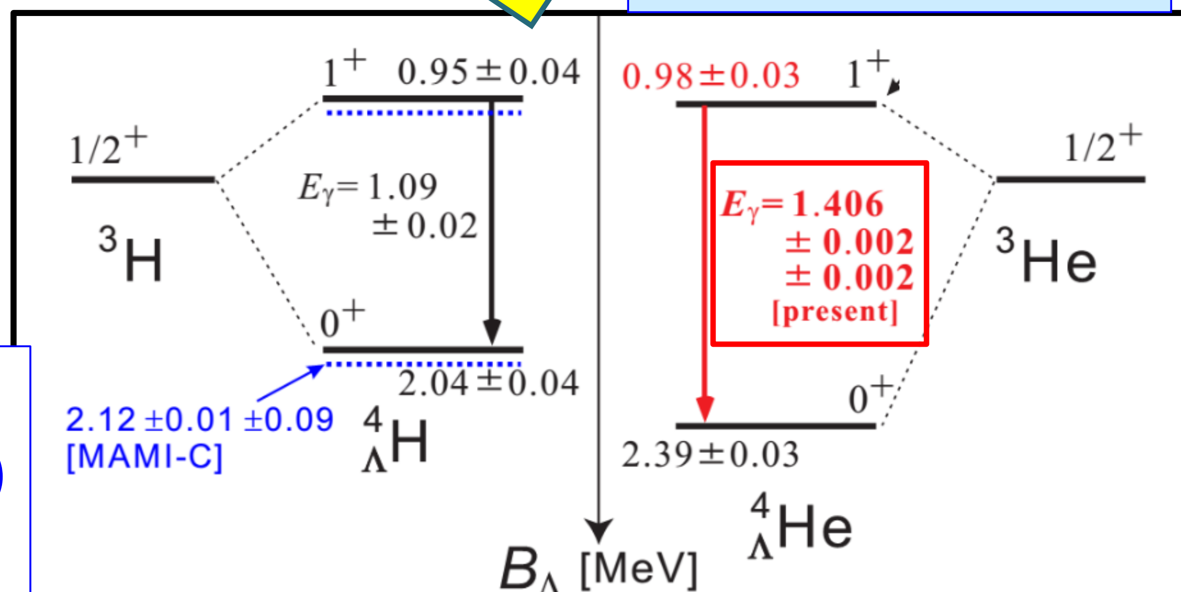
# Updated level scheme




**Before our experiment**

- **Clear hypernuclear identification method**
- **Good energy resolution w/ Doppler correction**

**With our new result**




$$\Delta E_\gamma = E_\gamma({}^4_\Lambda\mathrm{He}) - E_\gamma({}^4_\Lambda\mathrm{H}) = 0.32 \pm 0.02\ \mathrm{MeV}$$

Combined with $B_\Lambda(0^+)$ data

$$\Delta B_\Lambda(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}(1^+)) - B_\Lambda({}^4_\Lambda\mathrm{H}(1^+)) = 0.03 \pm 0.05\ \mathrm{MeV}$$

# Our finding

$\Delta E_\gamma = E_\gamma(^4_\Lambda He) - E_\gamma(^4_\Lambda H)$

$= 0.32 \pm 0.02$ MeV

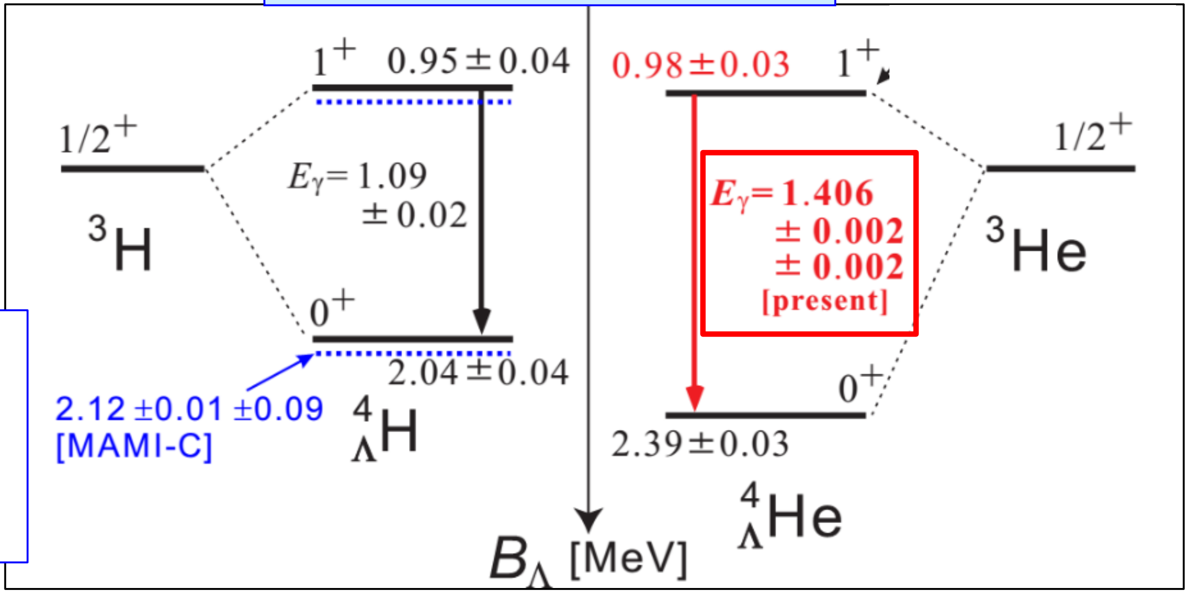
Combined with $B_\Lambda(0^+)$ data

$\Delta B_\Lambda(1^+)$

$= B_\Lambda(^4_\Lambda He(1^+)) - B_\Lambda(^4_\Lambda H(1^+))$

$= 0.03 \pm 0.05$ MeV

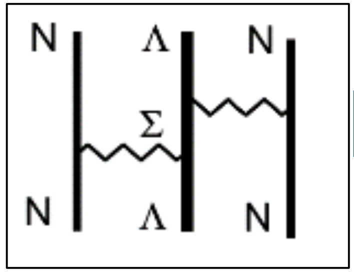
**Updated level schema**



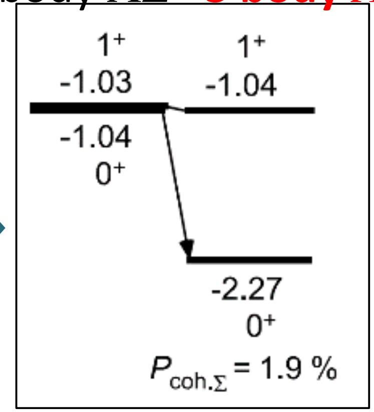

- Sizable Ex difference between mirror hypernuclei
  → **Confirm existence of CSB effect uniquely by γ-ray data**
- $B_\Lambda$ difference in $0^+$ and $1^+$ : $\Delta B_\Lambda(1^+) = 0.03 \pm 0.05$ MeV
  $\Delta B_\Lambda(0^+) = 0.35 \pm 0.05$ MeV
  → **CSB effect has strong spin dependence**

# Theoretical studies

**ΛΣ mixing is key of CSB effect?**




w/o 3 body ΛΣ | **w/ 3 body ΛΣ**




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

**Larger effect In $0^+$ state?**

## CSB effect calc. w/ ΛΣ 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**

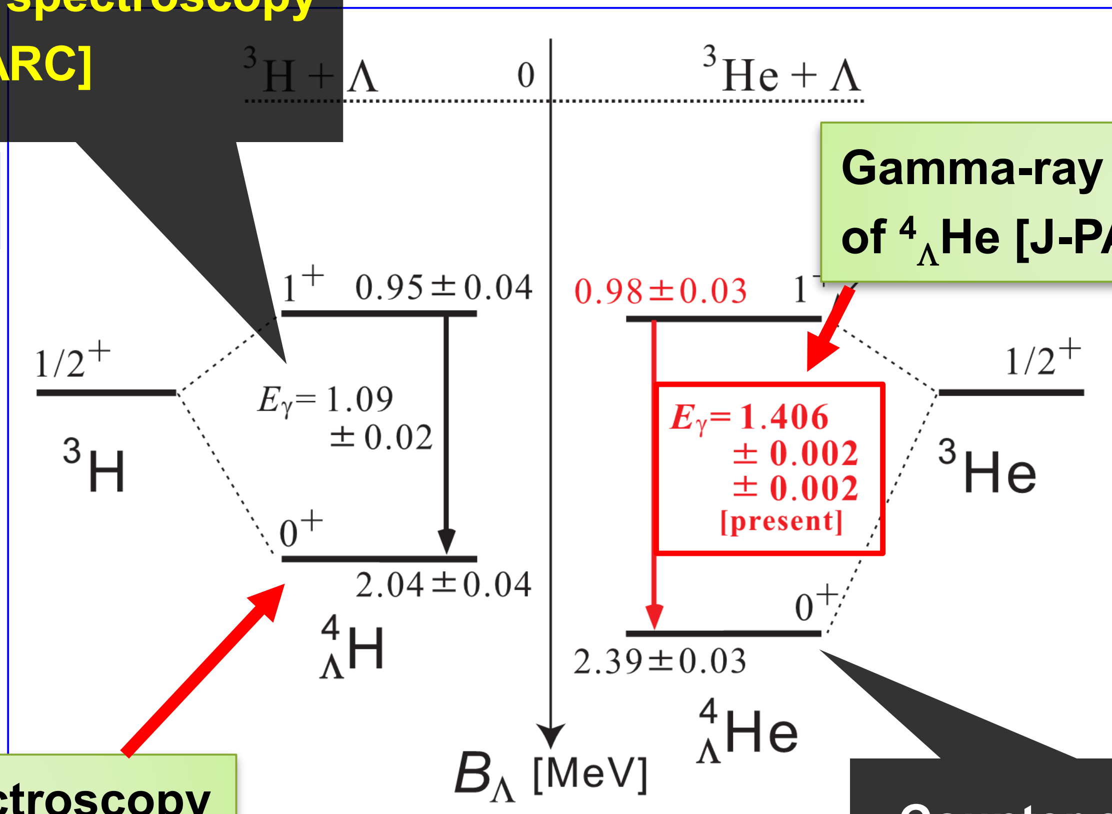
**ΛN-ΣN can be source of CSB effect?**

**High accuracy data of CSB effect may provide new information to investigate origin of CSB and underlying ΛN interaction**

J-PARC E63

# Gamma-ray spectroscopy of ${}^{4}_{\Lambda}\mathrm{H}$
# (future experiment at J-PARC)

# Toward the exp. completeness




Gamma-ray spectroscopy of $^4_\Lambda$H [J-PARC]

***Next step***

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

***Done***

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

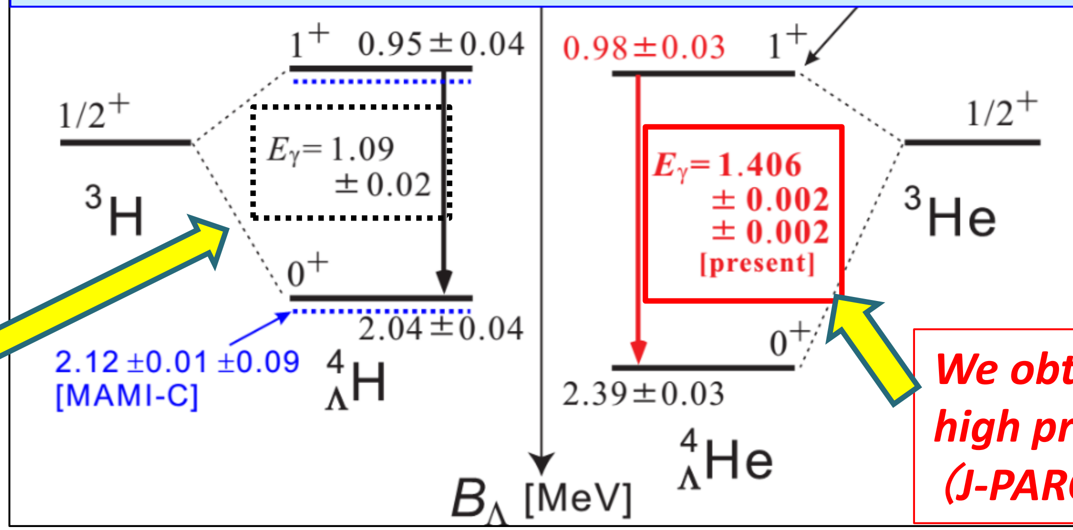
***Done***

Counter experiment ( $^4_\Lambda$He ) [ ? ]

***Not yet elaborated***

# For experimental completeness

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




**We are aiming for J-PARC E63**

***Need high precision data !***

***We obtained high precision data (J-PARC E13)***

| | $^{4}_{\Lambda}H(1^+ \rightarrow 0^+)$ |
|---|---|
| M. Bedjidian *et al.* (1976) [12] | 1.09 ±0.03 |
| M. Bedjidian *et al.* (1979) [13] | 1.04 ±0.04 |
| A. Kawachi (1997) [14] | 1.114 ±0.030 |
| Weighted average | 1.09 ±0.02 |

***rather large deviation***

All of three used

- Stopped K⁻ reaction
- NaI detector

**<10 keV accuracy data can help theoretical studies of ΛN interaction**

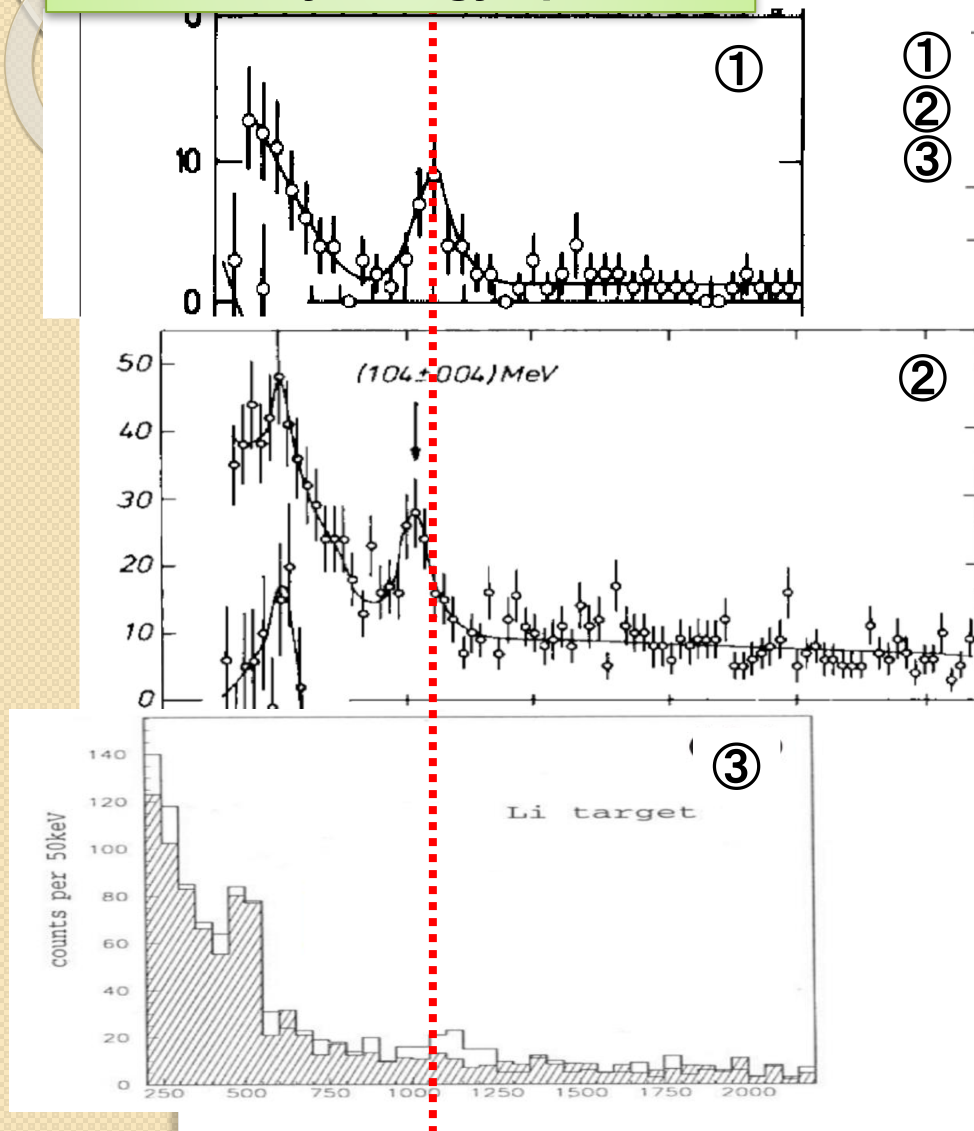
**For higher precision**

- **Stopped K- → in-flight $(K^-,\pi^-)$**
- **NaI detector → Ge detector**

**Experimental method used in $^{4}_{\Lambda}He$ can be used!**

# Old experiment for $E_\gamma(^4_\Lambda H)$

**Gamma-ray energy spectrum**

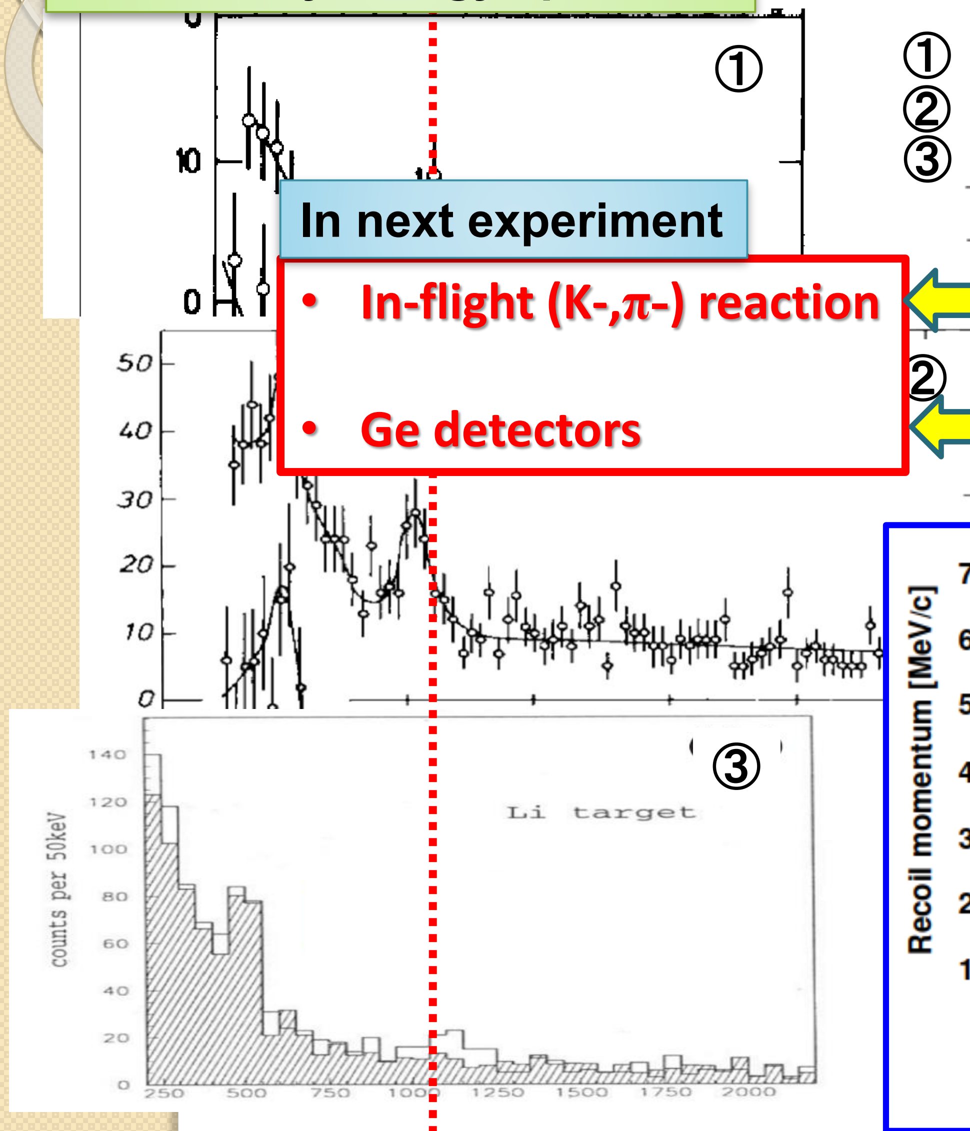



| | $^4_\Lambda H(1^+ \to 0^+)$ |
|---|---|
| ① M. Bedjidian *et al.* (1976) [12] | 1.09 ±0.03 |
| ② M. Bedjidian *et al.* (1979) [13] | 1.04 ±0.04 |
| ③ A. Kawachi (1997) [14] | 1.114 ±0.030 |
| Weighted average | 1.09 ±0.02 |

- Stopped K- reaction (Li target)
  → Doppler broaden γ peak
- NaI detectors

# Old experiment for $E_\gamma(^4_\Lambda H)$

**Gamma-ray energy spectrum**




| | $^4_\Lambda H(1^+ \to 0^+)$ |
|---|---|
| ① M. Bedjidian *et al.* (1976) [12] | 1.09 ±0.03 |
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| ③ A. Kawachi (1997) [14] | 1.114 ±0.030 |
| Weighted average | 1.09 ±0.02 |

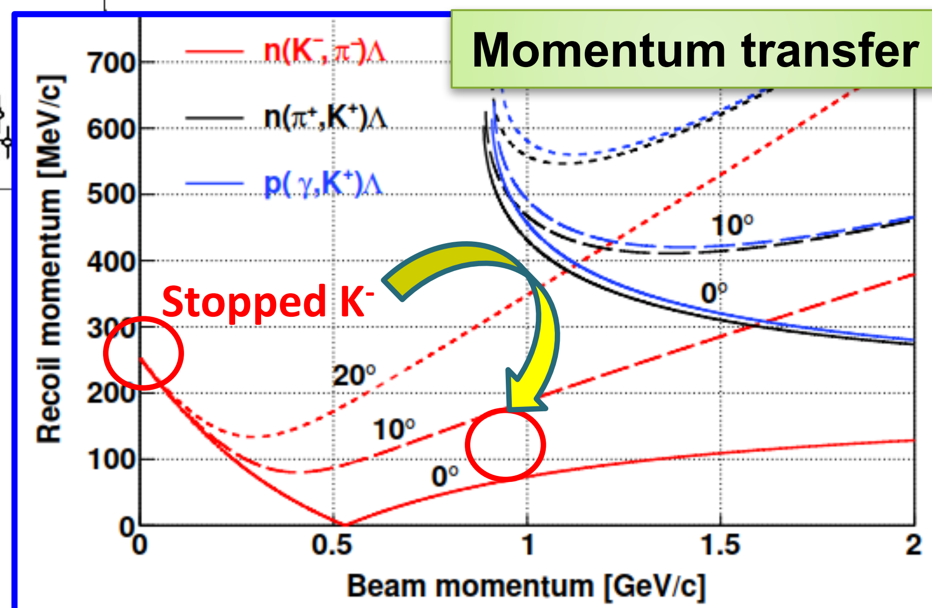
**In next experiment**

- In-flight (K-,π-) reaction
- Ge detectors

- Stopped K- reaction (Li target)

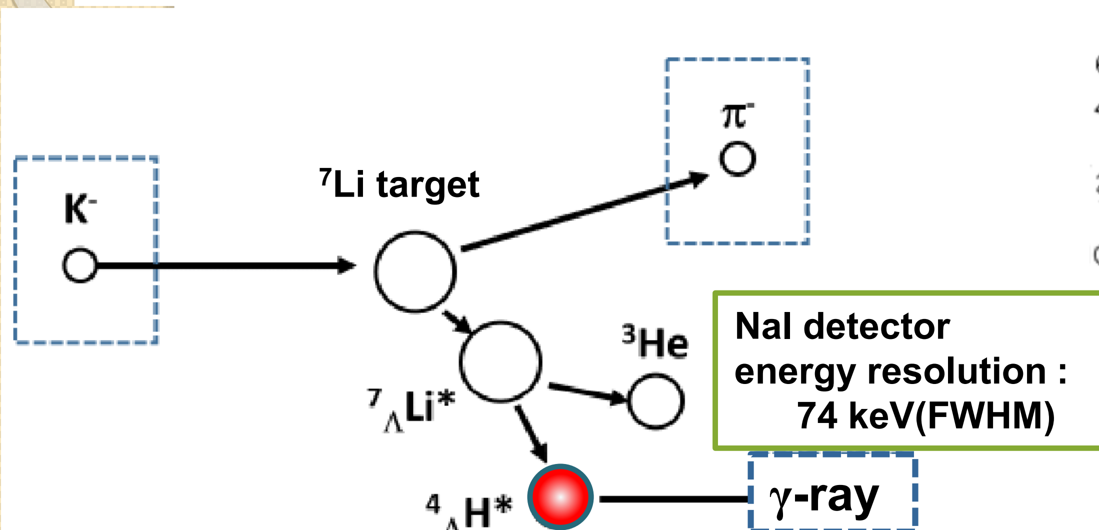
  → Doppler broaden γ peak
- NaI detectors

**Momentum transfer**

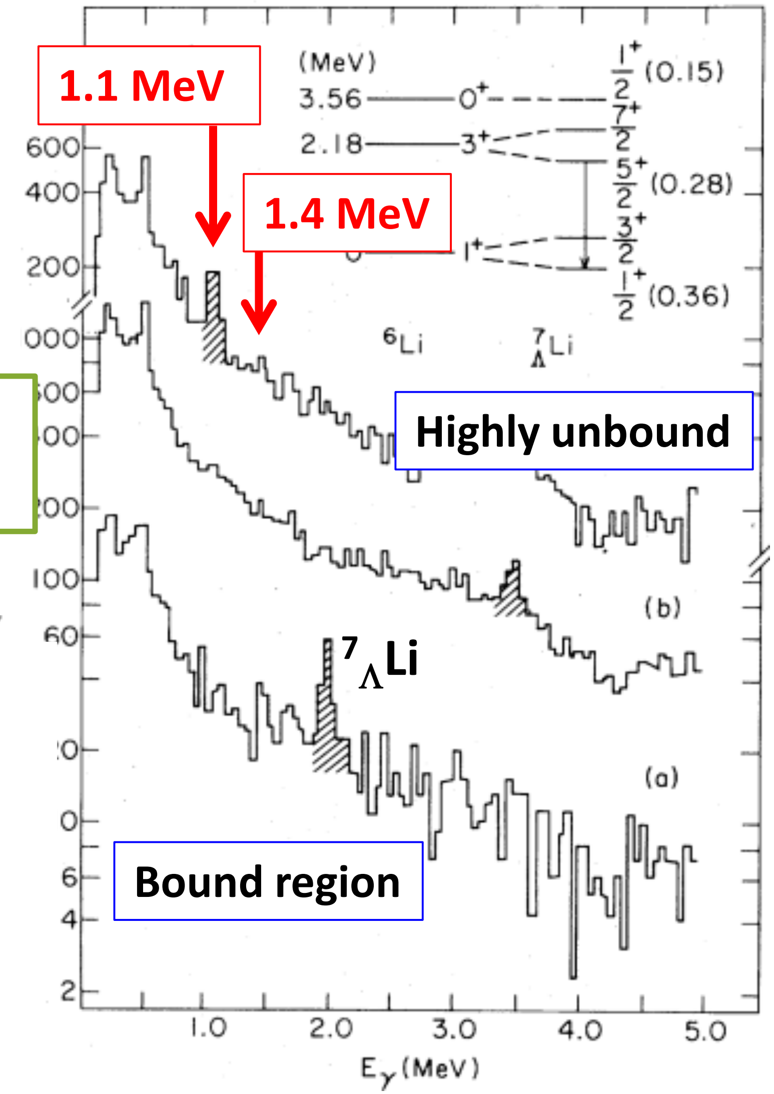


# Hint of $^{4}_{\Lambda}H$? via in-flight $^{7}Li(K^{-},\pi^{-})$ @0.9 GeV/c

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



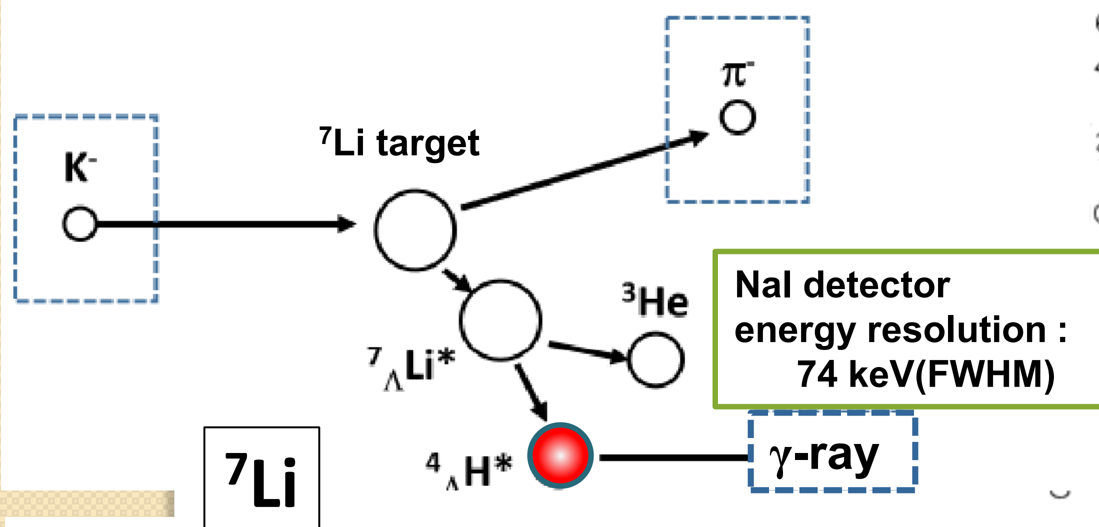

M.May, PRL 51(1983)2085



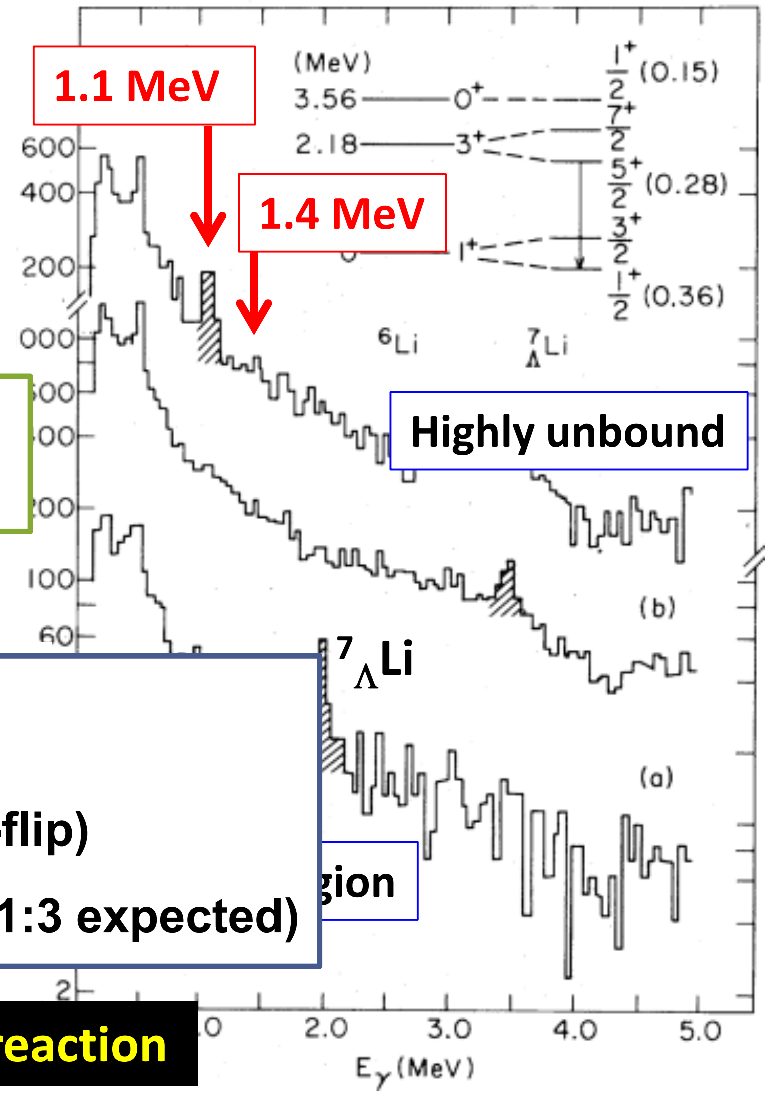

**They considered 1.1 MeV peak as $^{4}_{\Lambda}H + ^{4}_{\Lambda}He$ mixture (now we know this is not the case → only $^{4}_{\Lambda}H$)**

# Hint of $^{4}_{\Lambda}H$? via in-flight $^{7}Li(K^{-},\pi^{-})$ @0.9 GeV/c

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




M.May, PRL 51(1983)2085




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

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

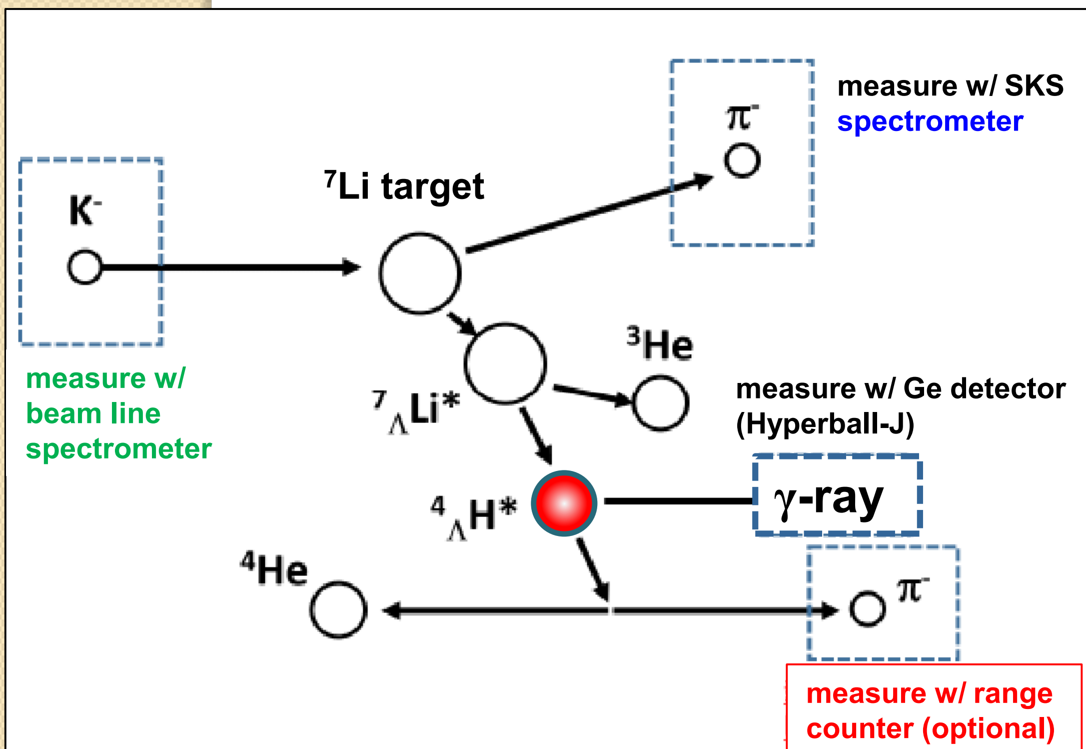
[two step] $\Lambda + {}^{3}H \rightarrow {}^{4}_{\Lambda}H$ (Both $0^{+}$,$1^{+}$, ratio =1:3 expected)

**We can measure $^{4}_{\Lambda}H$ gamma-ray with this reaction**

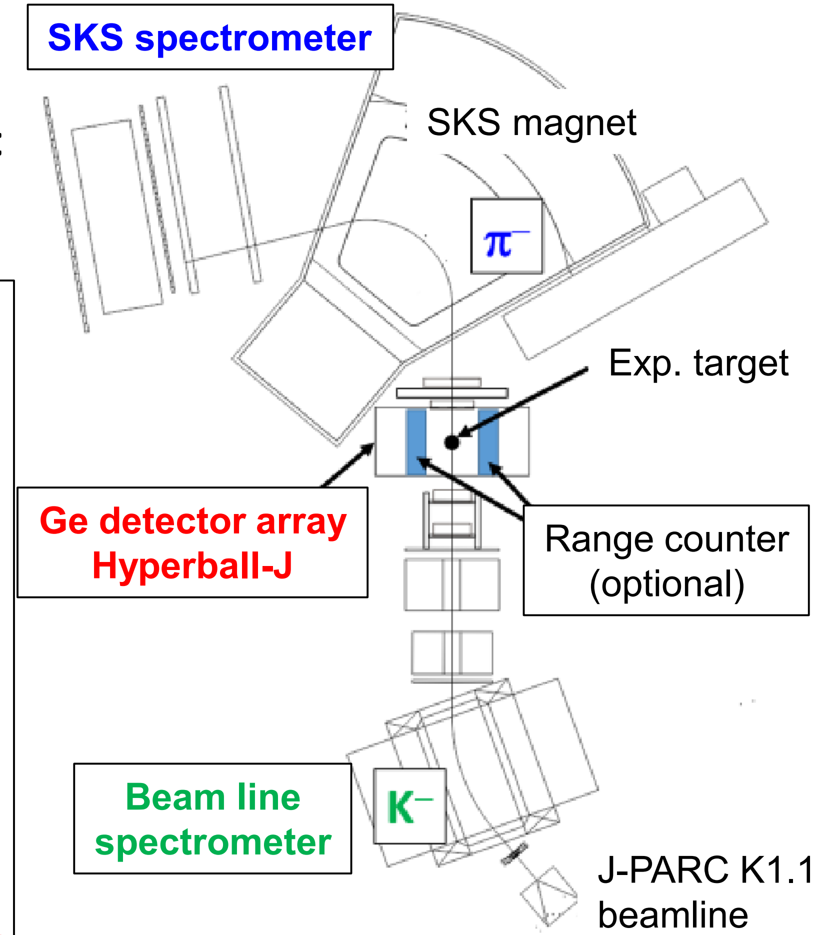
# γ-ray spectroscopy of ${}^{4}_{\Lambda}$H (J-PARC E63)

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

**Low momentum $K^-$ beam for small Doppler effect**
**→ move to J-PARC K1.1 beam line**



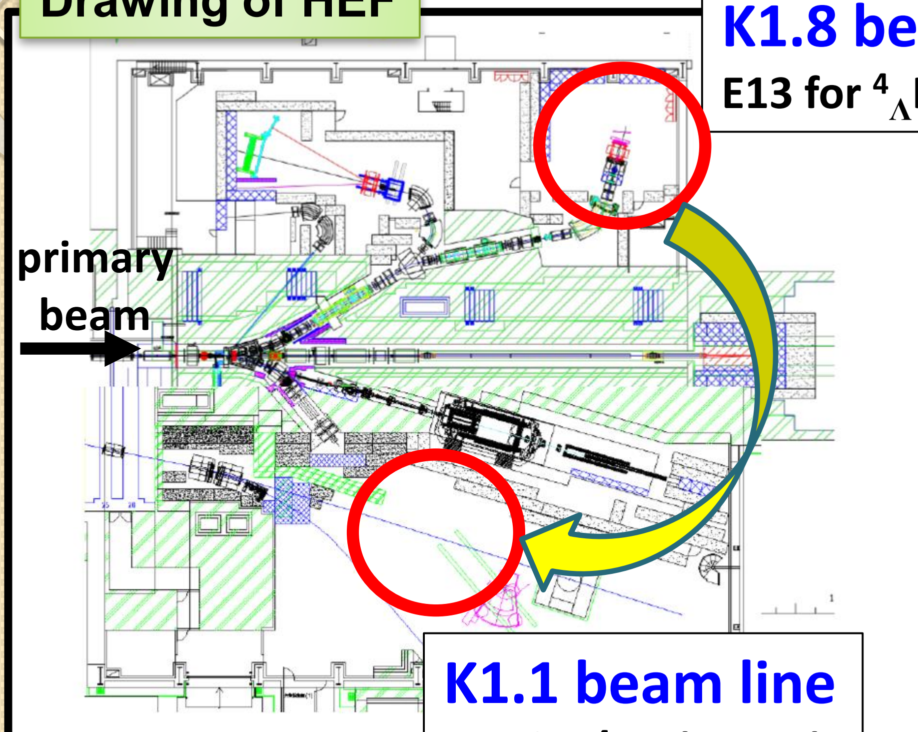

**Experimental setup** (J-PARC E63)




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

# γ-ray spectroscopy of $^{4}_{\Lambda}H$ (J-PARC E63, 2018?)

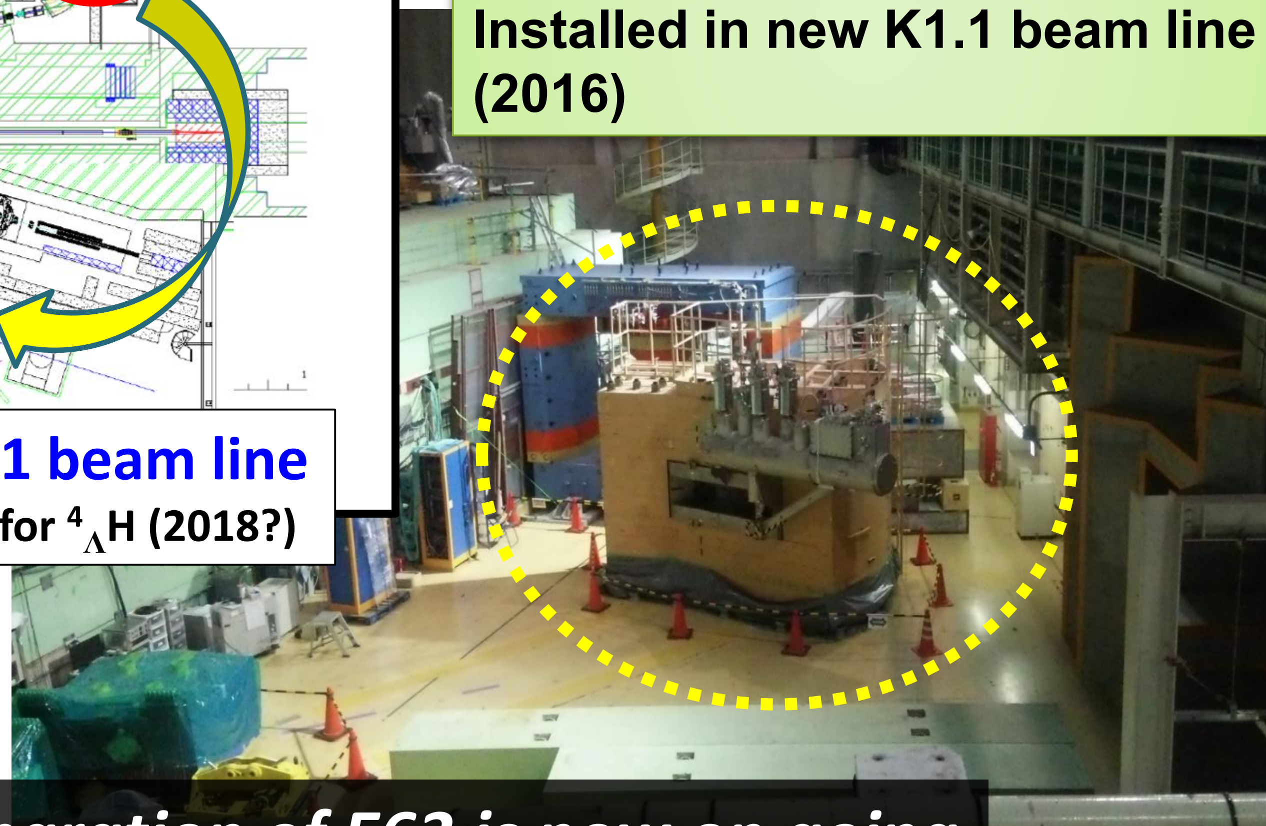
Drawing of HEF




**K1.8 beam line**
E13 for $^{4}_{\Lambda}He$ (2015.4)

**K1.1 beam line**
E63 for $^{4}_{\Lambda}H$ (2018?)

SKS magnet
Installed in new K1.1 beam line
(2016)



*Preparation of E63 is now on going*

# Far future experiment for CSB in *p*-shell hypernuclei

HYPER BALL TOHOKU

**Theoretical prediction: ~100 keV CSB effect**

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

**Existing data**

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

**Difficulty in reaction spectroscopy**

**“ Need charge exchange reaction for mirror hypernuclei “**

**Experiment with (e,e’K$^+$) reaction (JLAB)**

**-> A=7, 10 hypernuclei (~100 keV accuracy)**

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

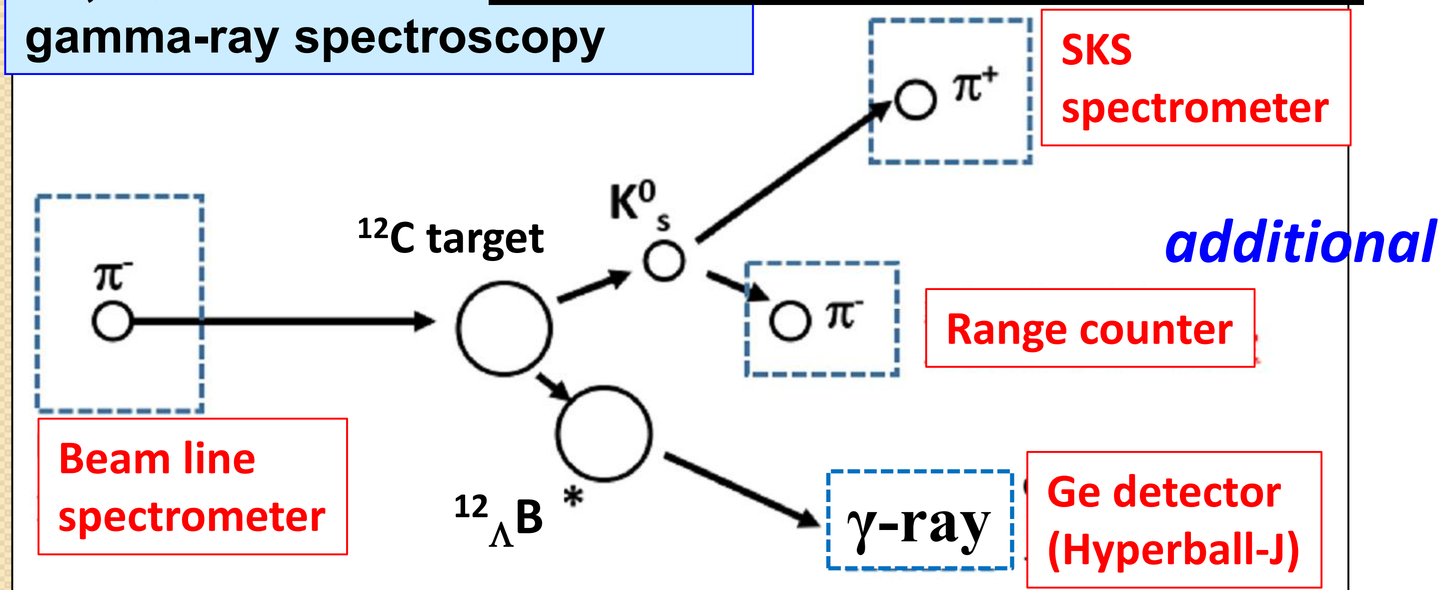
**T. Gogami et al.: Phys. Rev. C 93 (2016) 034314.**

# Far future experiment for CSB in *p*-shell hypernuclei

**Next step : Gamma-ray spectroscopy of *p*-shell mirror hypernuclei**

($\pi^-$,$K^0$) reaction + gamma-ray spectroscopy

**Need charge exchange reaction**




**Challenges**

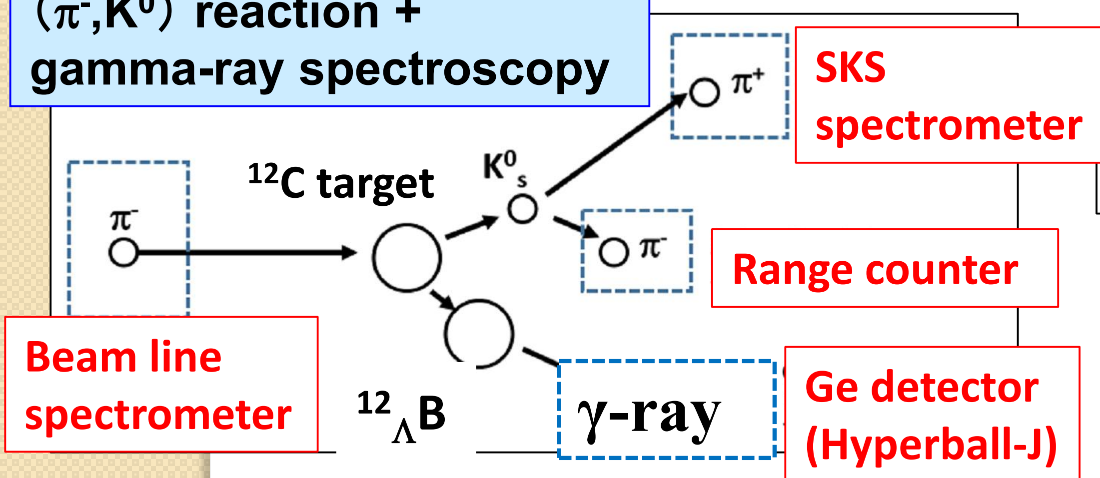
- Smaller cross section
- Limited acceptance (for additional counter)
  -> Need to handle high intensity beam

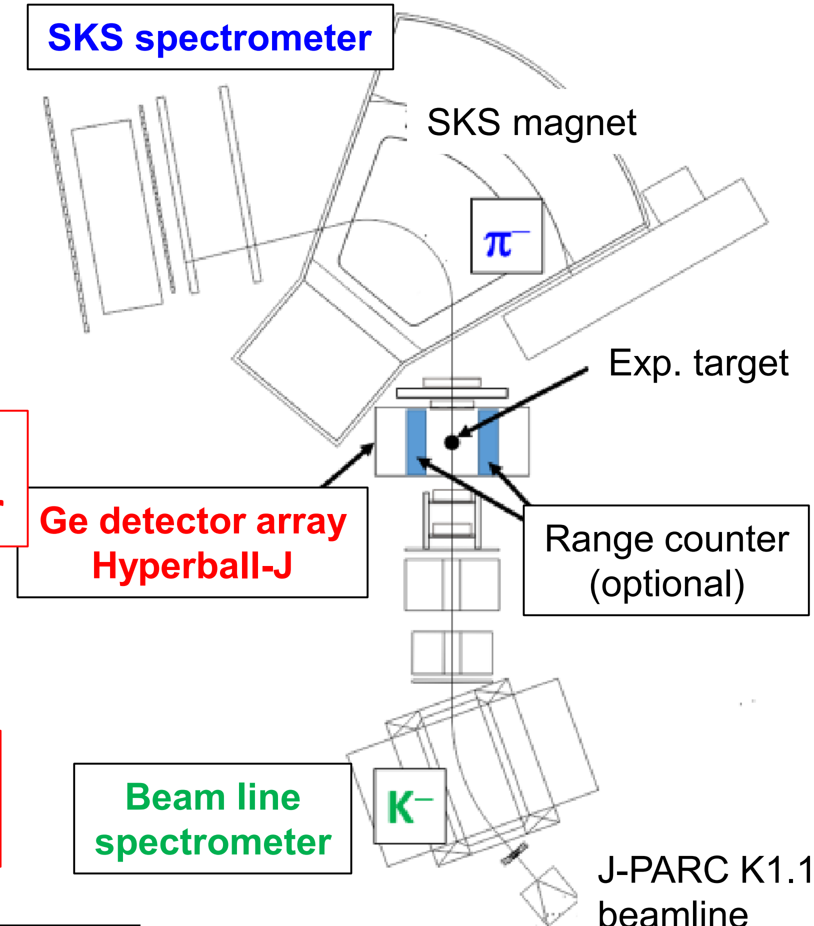
# Far future experiment for **CSB in *p*-shell hypernuclei**

**Almost same setup with $^{4}_{\Lambda}H$ gamma-ray spectroscopy**

**+ additional range counter inside Ge array**

**($\pi^-$,$K^0$) reaction + gamma-ray spectroscopy**




**Need detector development ( range counter, Readout system, etc )**

# Summary

➢ **Charge symmetry breaking (CSB) in $\Lambda$N interaction studied via A=4 hypernuclei**

Large CSB effect in $B_\Lambda$ ?

Need to check old experimental data

- **Gamma-ray spectroscopy of $^4_\Lambda$He** (J-PARC E13, 2015)

  - new result: $^4_\Lambda$He($1^+$) excitation energy

    $E_x(^4_\Lambda\text{He}) = 1.406 \pm 0.004$ MeV $\leftrightarrow$ ~1.1 MeV ($^4_\Lambda$H)

    $\rightarrow$ existence and spin dependence of CSB effect

- **Gamma-ray spectroscopy of $^4_\Lambda$H** (J-PARC E63)

  - near future plan: $^4_\Lambda$H($1^+$) excitation energy

    New J-PARC K1.1 beam line, preparation on going

*Far future : gamma-ray spectroscopy of p-shell mirror hypernuclei*