奇妙な強い力、それによる結合系

# S-2S による シングル Λ ハイパー核の 高精度分光 : A = 7, 10, 12

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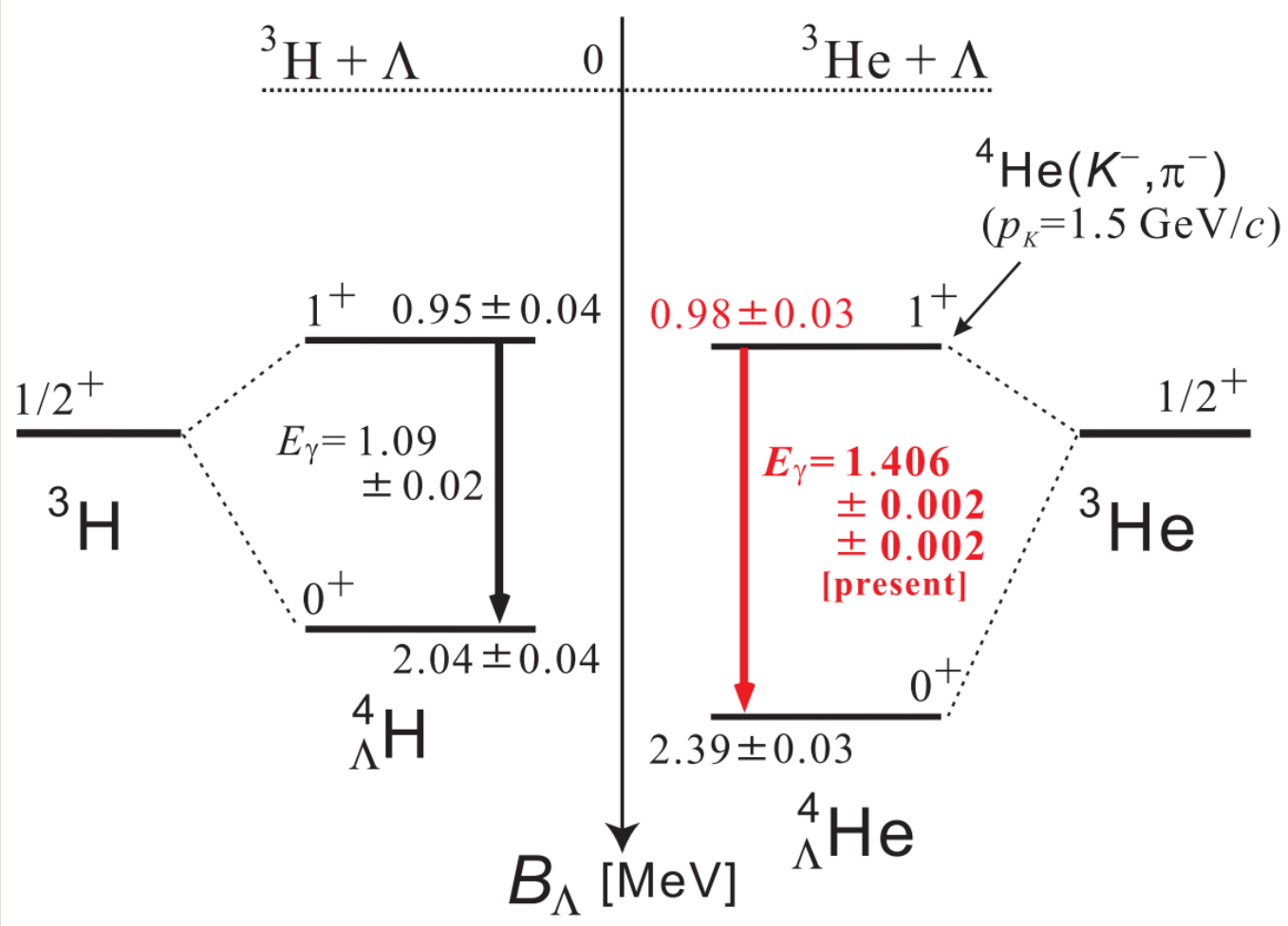
# J-PARC E94 Experiment

- $(\pi^+, K^+)$ reaction spectroscopy of single $\Lambda$ hypernuclei
- Measure $\Lambda$ binding energies of ${}^{7}_{\Lambda}\mathrm{Li}$ , ${}^{10}_{\Lambda}\mathrm{B}$ , ${}^{12}_{\Lambda}\mathrm{C}$
  - Energy resolution : **1 MeV**
  - Accuracy : **100 keV**
  - Calibration source : ${}^{7}_{\Lambda}\mathrm{Li}$
- Physics motivation
  - Investigation of charge symmetry breaking (CSB) in $A = 10$
  - Confirm $\Lambda$ binding energy of ${}^{12}_{\Lambda}\mathrm{C}^{\mathrm{g.s.}}$ in $(\pi^+, K^+)$ reaction

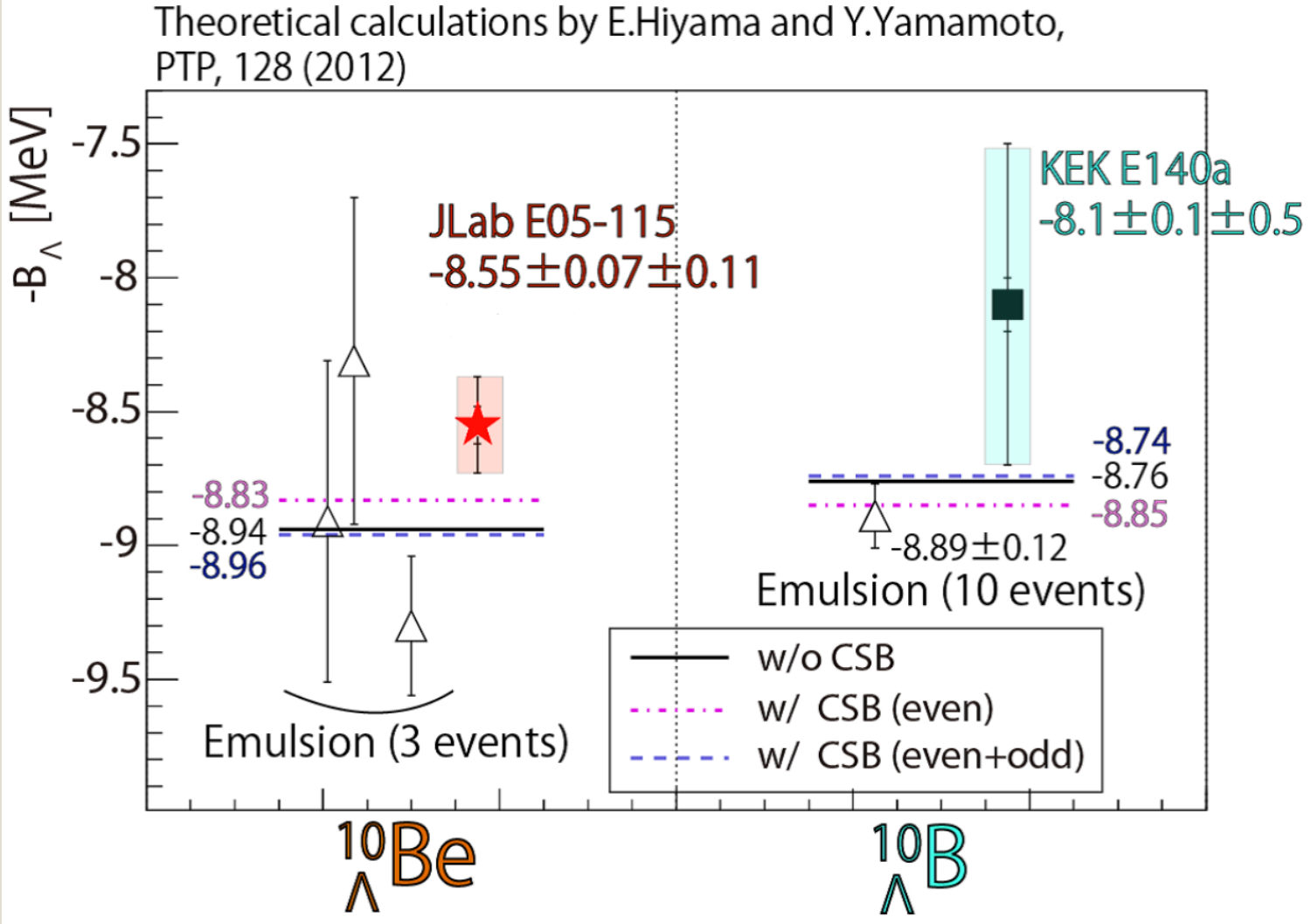
# CSB in $\Lambda N$ interaction

- CSB in A = 4 is observed




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

# Comparison of $B_\Lambda$ of ${}^{10}_{\Lambda}\mathrm{B}$ and ${}^{10}_{\Lambda}\mathrm{Be}$



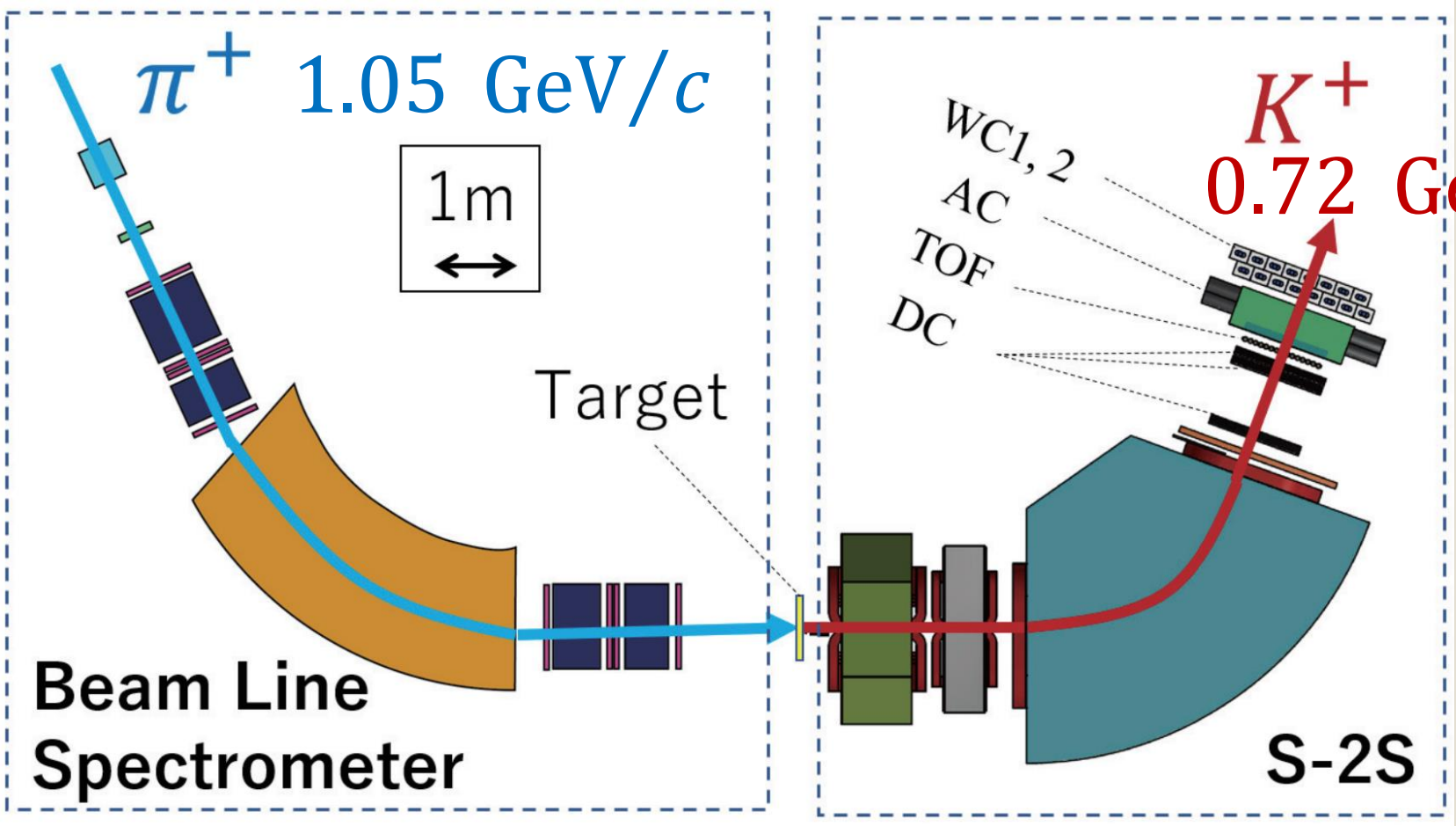

We aim to provide $B_\Lambda$ of ${}^{10}_{\Lambda}\mathrm{B}$ with 100 keV accuracy in counter experiment

# Accuracy of $\Lambda$ binding energy in E94

- To provide new information of CSB in A = 10 and $B_\Lambda$ of ${}^{12}_{\Lambda}\mathrm{C}^{\mathrm{g.s.}}$ , we need higher accuracy than past $(\pi^+, K^+)$ reaction experiment

→ ${}^{7}_{\Lambda}\mathrm{Li}$ calibration source enable us to determine $B_\Lambda$ with 100 keV accuracy

# Experimental Setup



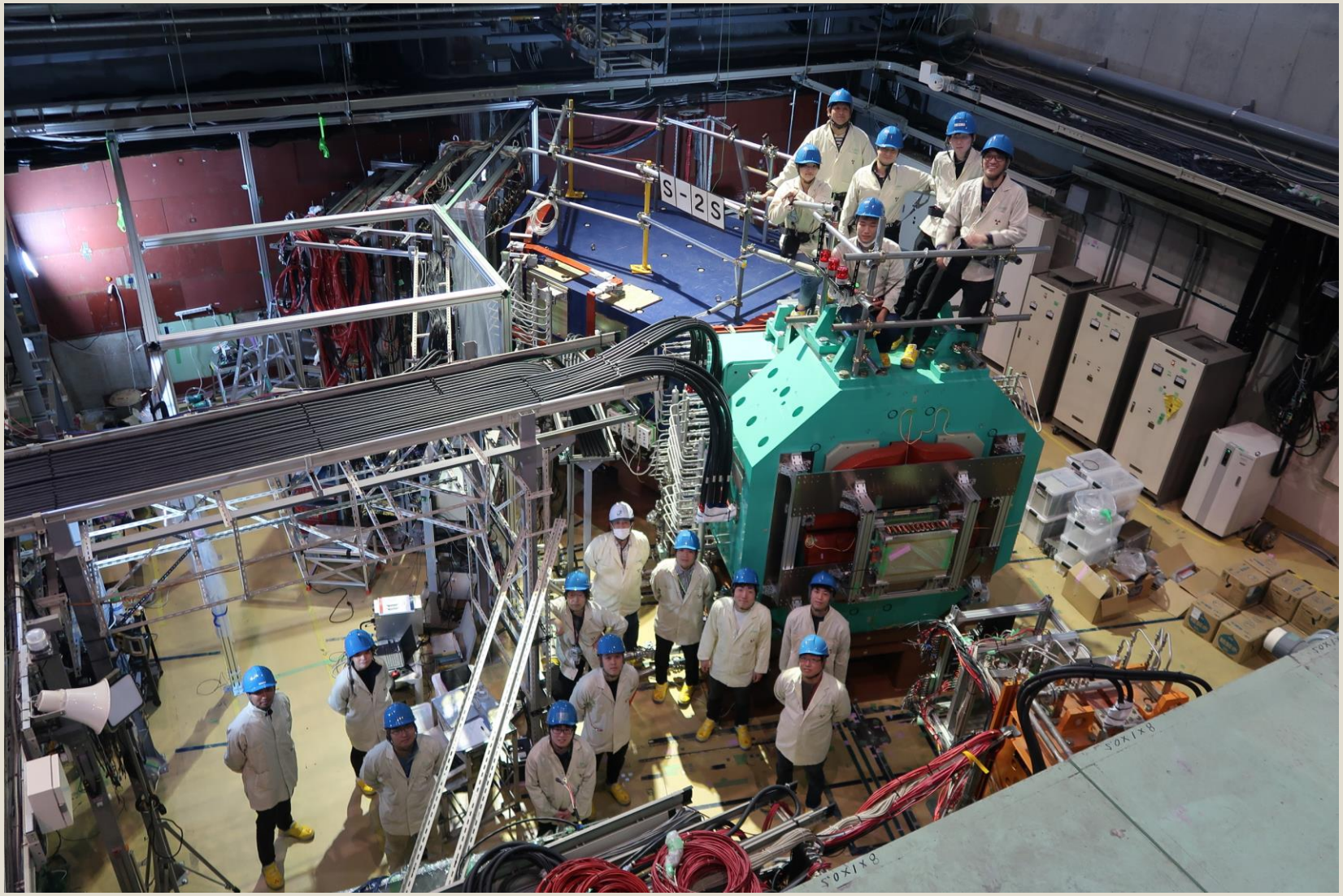

Kinematics

$$M_{\mathrm{H}} = \sqrt{{E_{\mathrm{H}}}^2 - (\vec{p}_{\mathrm{H}})^2} = \sqrt{(E_\pi + M_{\mathrm{T}} - E_{\mathrm{K}})^2 - (\vec{p}_\pi - \vec{p}_{\mathrm{K}})^2}$$

$$B_\Lambda = M_{\mathrm{core}} + M_\Lambda - M_{\mathrm{H}}$$

- Almost same experimental apparatus as E70 experiment

# S-2S and collaborators




2022/8
Proposal
→1st stage

2022/12
FIFC
→2nd stage

2023 – 2024
Run experiment

# Yield estimation of ${}^{10}_{\Lambda}\mathrm{B}^{\mathrm{g.s.}}$

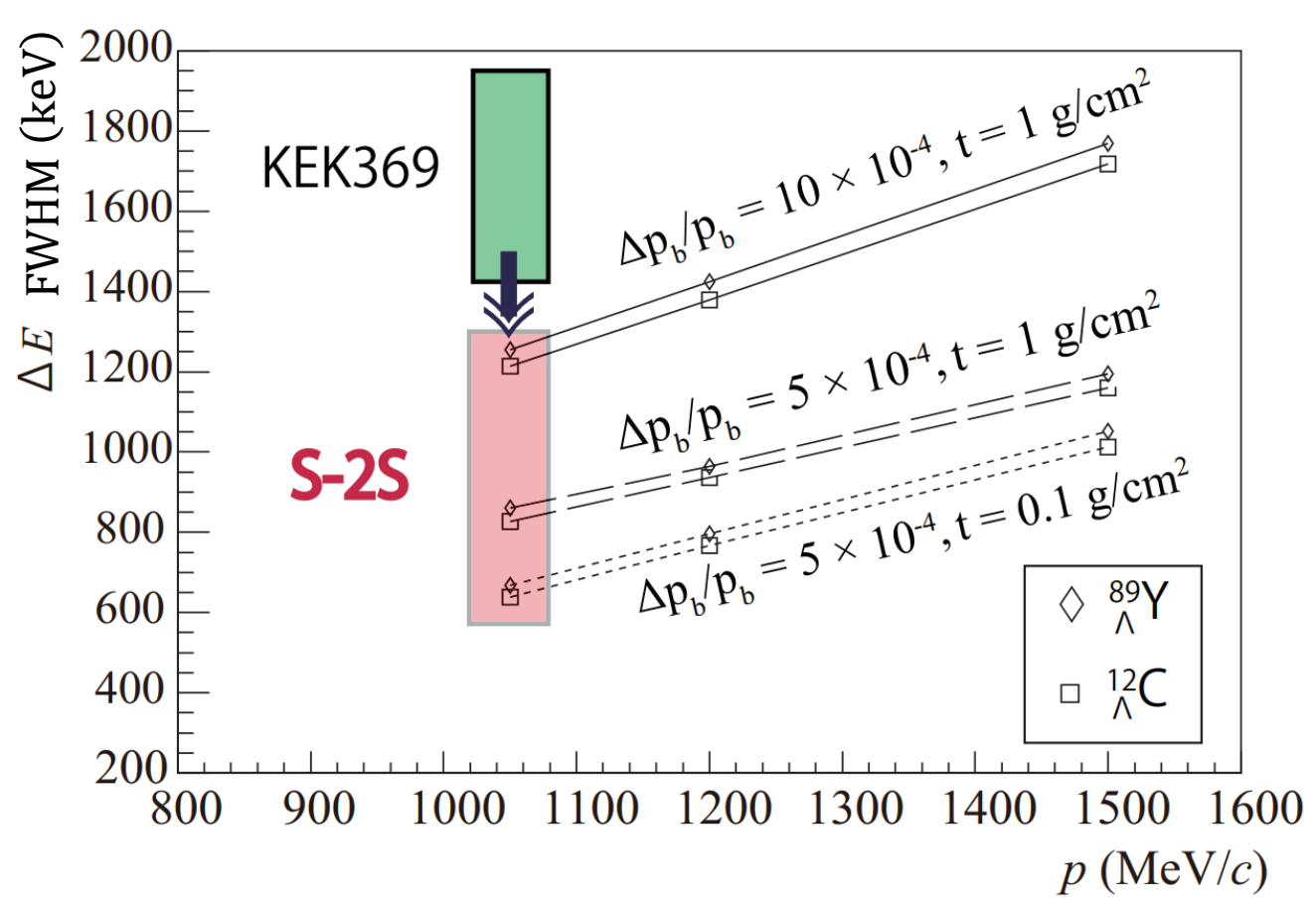
- Yield $N_{\mathrm{H}}$

$$N_{\mathrm{H}} = \frac{d\sigma}{d\Omega} \times \Delta\Omega \times \epsilon \times N_{\mathrm{target}} \times N_{\mathrm{beam}}$$

  - Differential cross section $\frac{d\sigma}{d\Omega}$ : $1.2\ \mu\mathrm{b/sr}$
  - The number of target nuclei $N_{\mathrm{target}}$ : $6.02 \times 10^{22}\ \mathrm{cm}^{-2}$
  - Solid angle acceptance $\Delta\Omega$ : $55\ \mathrm{msr}$
  - Total efficiency $\epsilon$ : $0.1$ (Kaon survival ratio $(0.2)$ and analysis efficiency $(0.5)$)
  - Beam intensity : $\frac{5\times10^{6}\mathrm{pions}}{\mathrm{spill}(4.2\ \mathrm{s})}$
  - Beam time : $112\ \mathrm{hours}$

$$N_{\mathrm{H}} \cong 190$$

# Momentum resolution

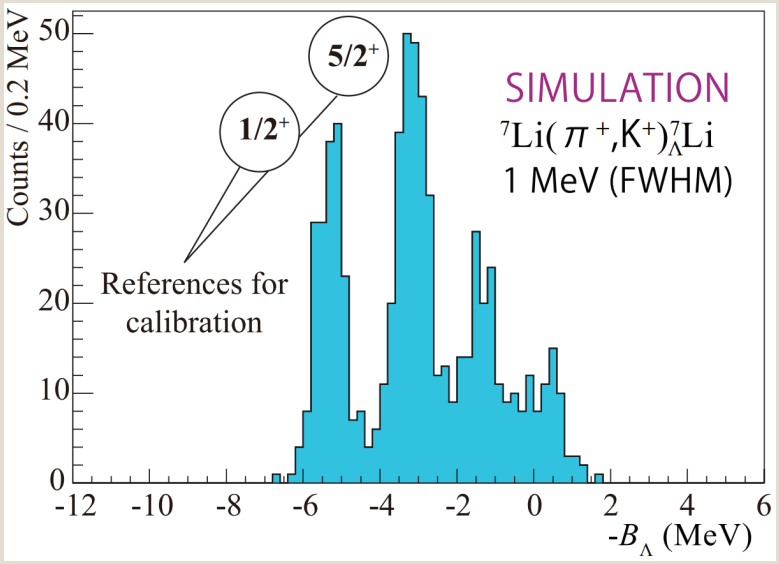


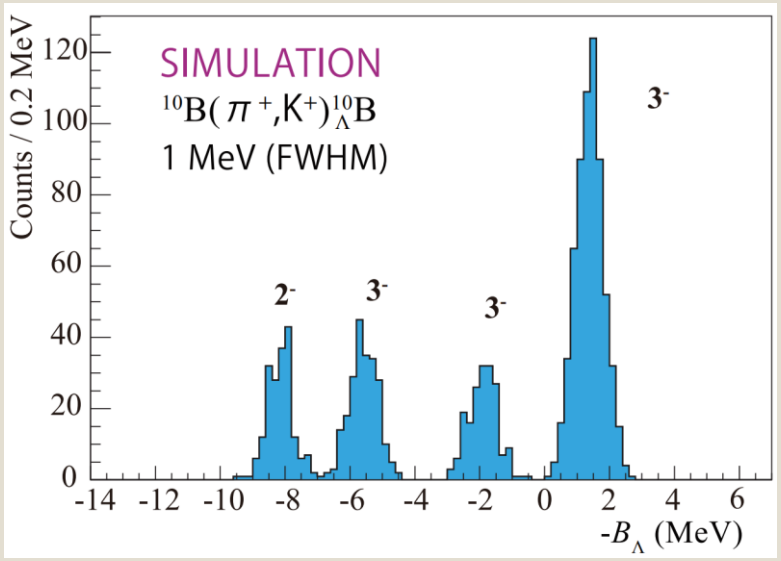

- Assumed resolution of S-2S
  - $\frac{\Delta p}{p} = 6 \times 10^{-4}$ (FWHM)

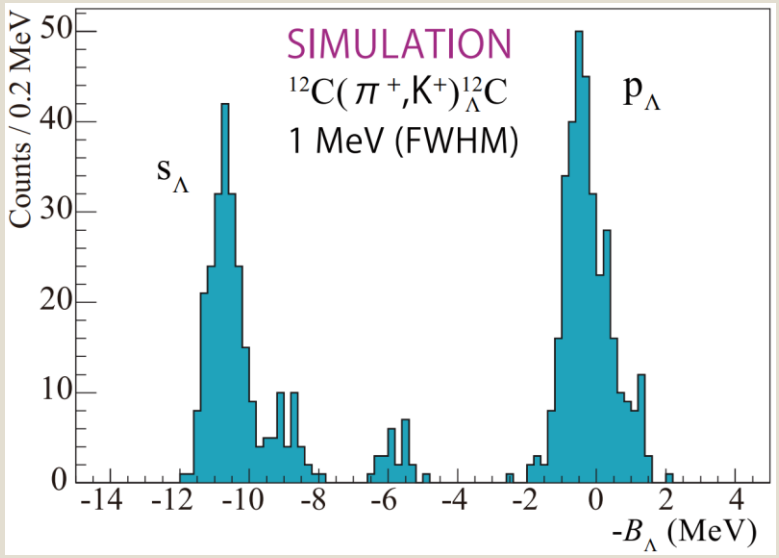
$\Delta E \cong 1$ MeV (FWHM) is achieved !

# Expected spectrum

$^{7}_{\Lambda}\mathrm{Li}$ $^{10}_{\Lambda}\mathrm{B}$ $^{12}_{\Lambda}\mathrm{C}$



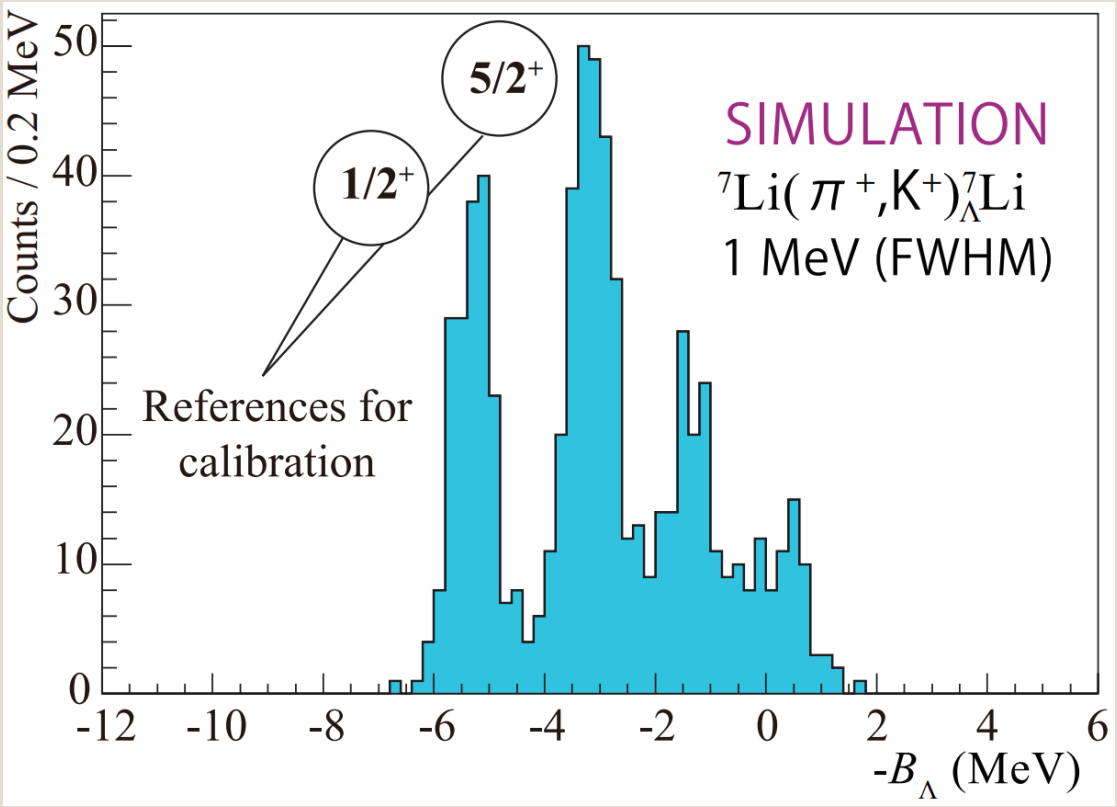

Calibration source to achieve high accuracy

**First attempt !**

Determine $B_\Lambda$ with high accuracy

$|B_\Lambda| \cong 100$ keV

# Calibration source ${}^{7}_{\Lambda}\mathrm{Li}$




- ${}^{7}_{\Lambda}\mathrm{Li}\ \frac{1}{2}^{+}$ and $\frac{5}{2}^{+}$ states are used for calibration source
- $B_\Lambda$ of ${}^{7}_{\Lambda}\mathrm{Li}\ \frac{1}{2}^{+}$ state :

  $5.58 \pm 0.03^{\mathrm{stat.}}\ \mathrm{MeV}$
- $B_\Lambda$ of ${}^{7}_{\Lambda}\mathrm{Li}\ \frac{5}{2}^{+}$ state :

  $3.53 \pm 0.03^{\mathrm{stat.}}\ \mathrm{MeV}$

(Systematic error : $0.04 - 0.05\ \mathrm{MeV}$)

- Emulsion and gamma ray experiment data are referenced


D.H. Davis, Nucl. Phys. A 754 3c–13c (2005).

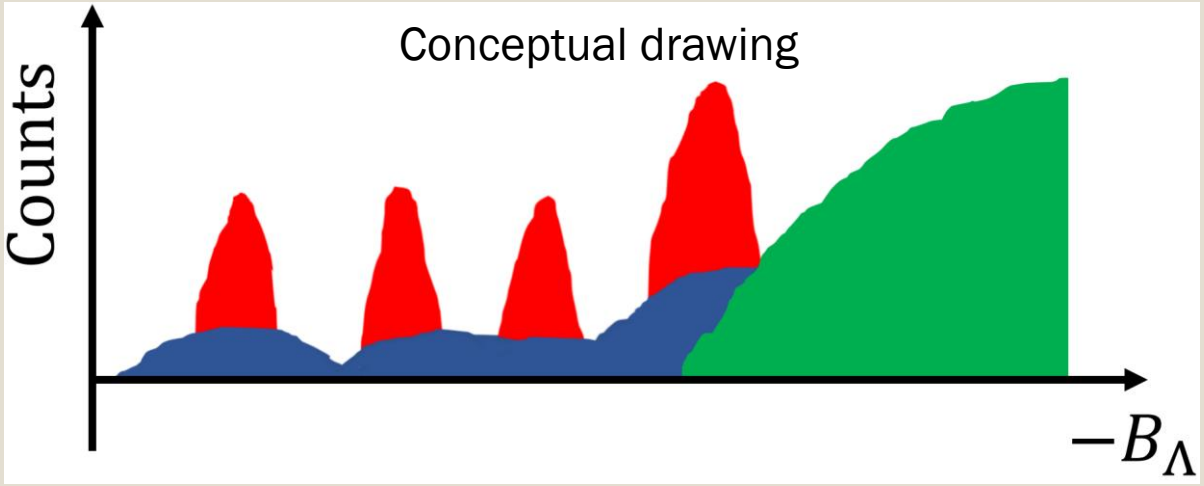
K. Tanida et al., Phys. Rev. Lett. 86, 10 (2001).

M. Ukai et al., Phys. Rev. C 73, 012501(R) (2006).

# $^{10}B_4C$ target

$B_4C$

- $^{10}B_4C$ target may be used to produce $^{10}_{\Lambda}B$
- Merit of $^{10}B_4C$ target
  - Easy to use
- Demerit of $^{10}B_4C$ target
  - Contamination of $^{12}_{\Lambda}C$ spectrum as a background

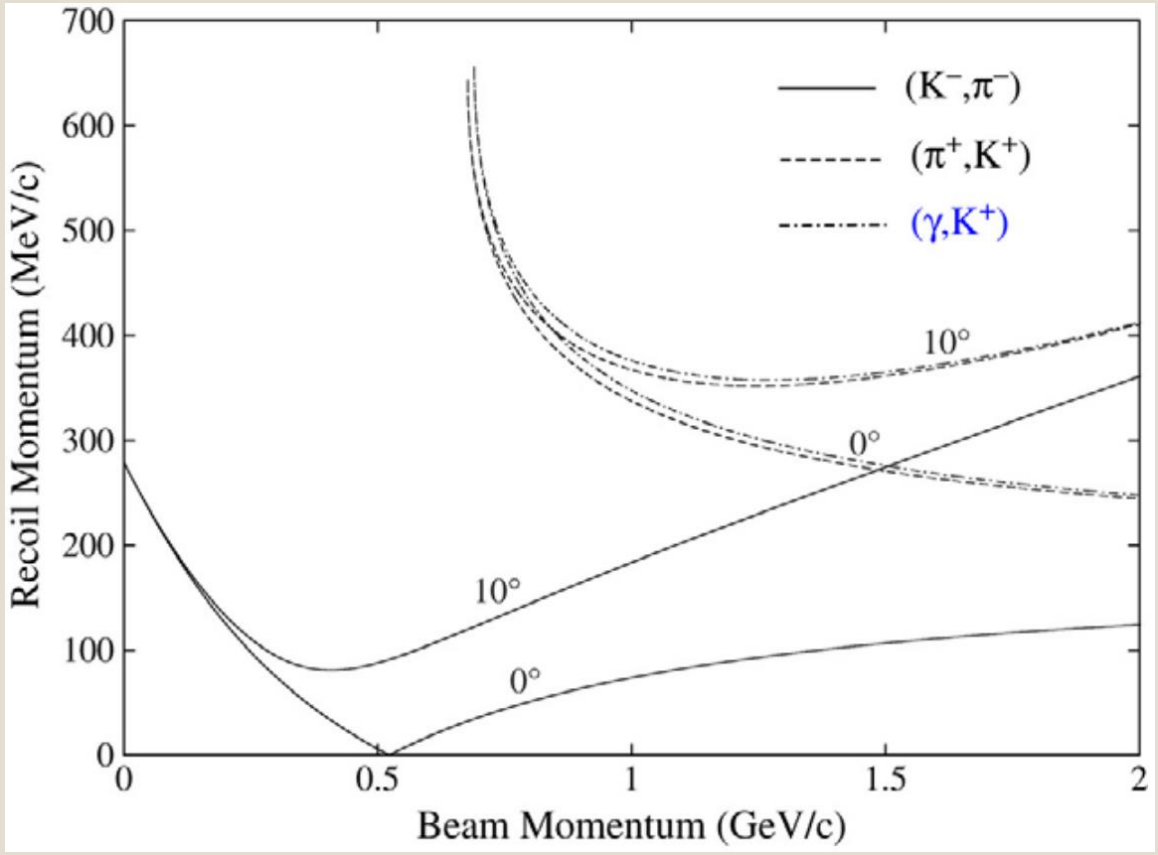


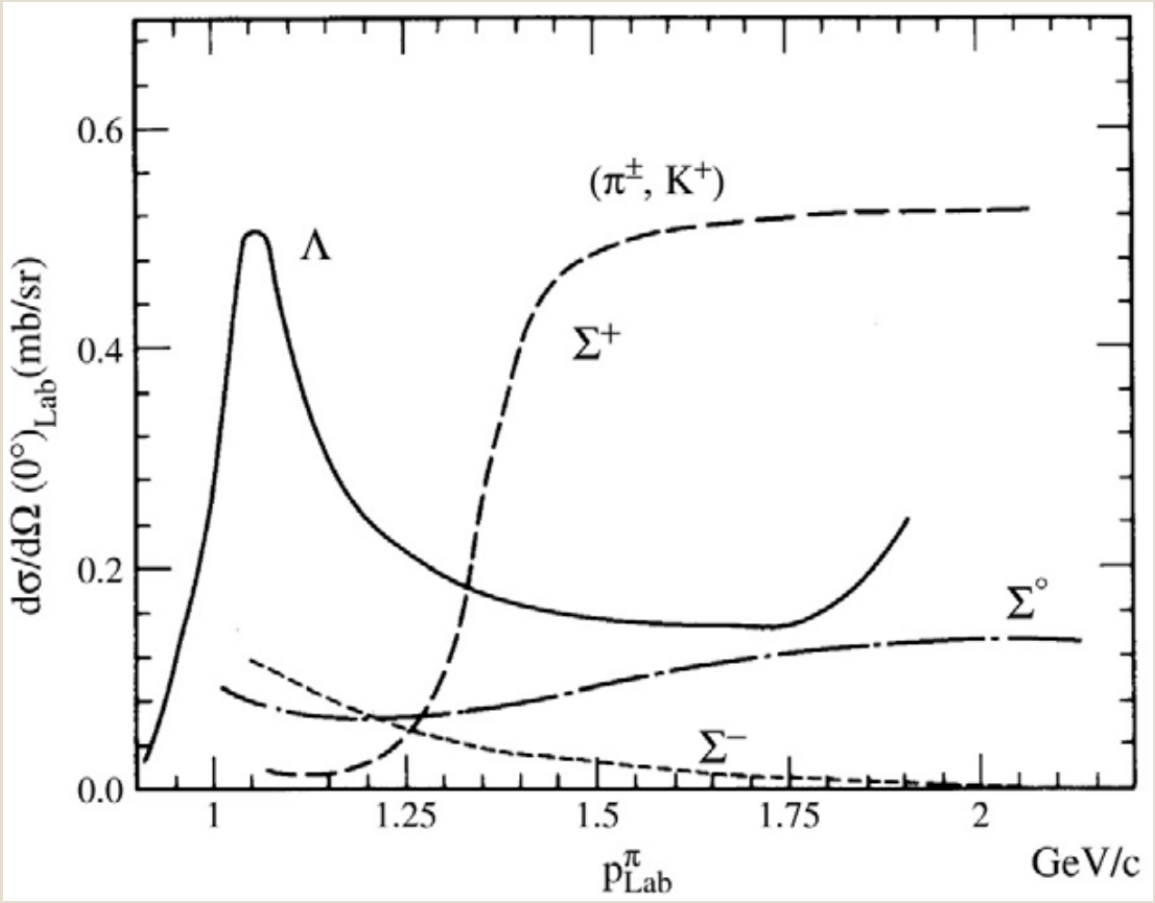
# Summary

- New generation $(\pi^+, K^+)$ reaction spectroscopy in E94
  - Measure $\Lambda$ binding energies of ${}^{7}_{\Lambda}\mathrm{Li}$ , ${}^{10}_{\Lambda}\mathrm{B}$ , ${}^{12}_{\Lambda}\mathrm{C}$
  - Energy resolution : 1 MeV (FWHM)
  - Accuracy : 100 keV

- Investigation of CSB in A = 10
- Confirm $\Lambda$ binding energy of ${}^{12}_{\Lambda}\mathrm{C}^{\mathrm{g.s.}}$ in $(\pi^+, K^+)$ reaction
- Physics run : 2023 - 2024

# Backup


Recoil Momentum (MeV/c)
Beam Momentum (GeV/c)
(K⁻,π⁻)
(π⁺,K⁺)
(γ,K⁺)
10°
0°
10°
0°
0
100
200
300
400
500
600
700
0
0.5
1
1.5
2


dσ/dΩ (0°)Lab(mb/sr)
(π±, K+)
Λ
Σ+
Σ°
Σ−
0.0
0.2
0.4
0.6
1
1.25
1.5
1.75
2
pπLab
GeV/c

# Yield estimation

| Hypernucleus | ${}^{7}_{\Lambda}$Li (g.s.) | ${}^{10}_{\Lambda}$B (g.s.) | ${}^{12}_{\Lambda}$C (g.s.) |
|---|---|---|---|
| Differential Cross Section $\frac{d\sigma}{d\Omega}$ [/($\mu$b/sr)] | 1.2 | 1.2 | 5 |
| Target (thickness) | ${}^{7}$Li (1 g/cm$^2$) | ${}^{10}$B (1 g/cm$^2$) | ${}^{12}$C (1 g/cm$^2$) |
| The Number of Target Nuclei $N_{\mathrm{target}}$ (/cm$^{-2}$) | $8.60 \times 10^{22}$ | $6.02 \times 10^{22}$ | $5.02 \times 10^{22}$ |
| Solid Angle Acceptance $\Delta\Omega$ (/msr) | 55 | | |
| Total Efficiency $\epsilon$ | 0.1<br>[$K^+$ survival ratio ($= 0.2$) and others ($= 0.5$)] | | |
| Beam Intensity | 5M pions / spill (4.2 sec) | | |
| Beam time (/hours) | 80 | 112 | 36 |
| Yield | 194 | 190 | 212 |