Study of Λ hypernuclei close to neutron drip-line

Atsushi Sakaguchi (Osaka University)

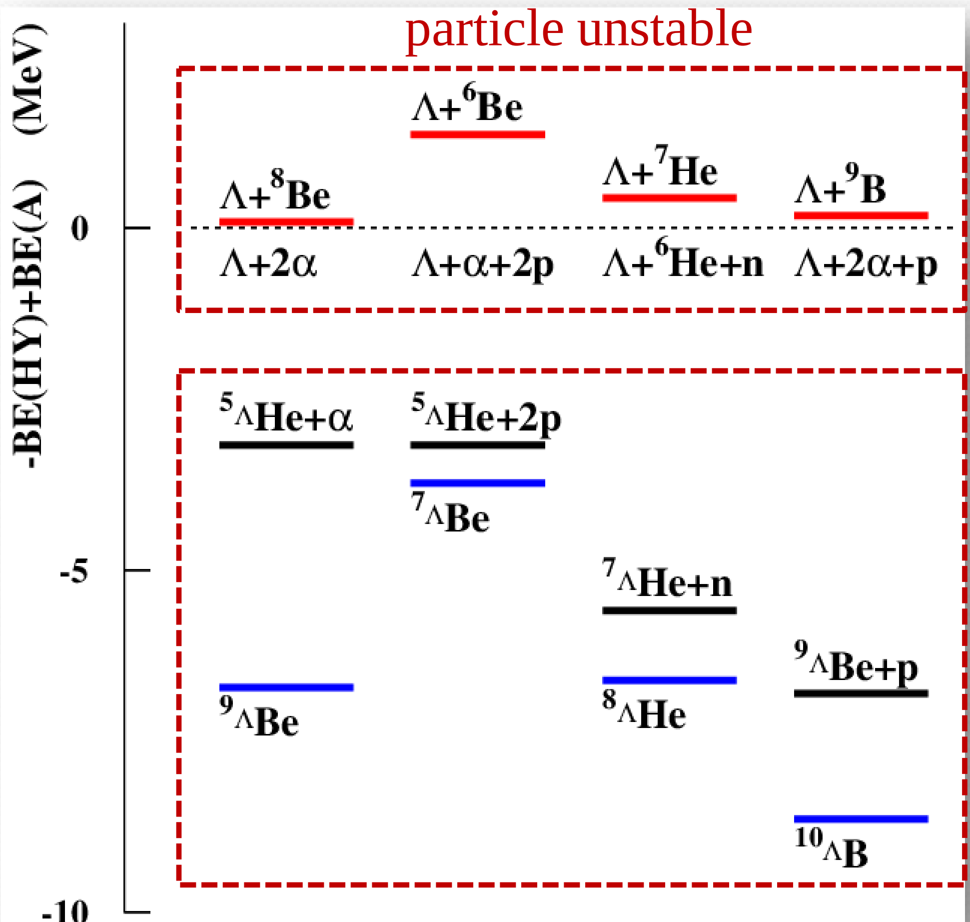
Physics OSAKA UNIVERSITY
Department of Physics, Graduate School of Science

for the **J-PARC E10** Collaboration

J-PARC

Some properties of Λ hypernuclei

- Property 1: "**glue-like role**" **of Λ hyperon**
  - Some examples of the "glue" effect



Λ hyperon plays "glue-like role"

attractive ΛN interaction

Λ is free from Pauli blocking

these diagrams show the "glue" effect is a general phenomenon in Λ hypernuclei

boundary of stability of nuclei may be extended by the "glue" effect

- Property 2: **effect of "ΛN-ΣN mixing"**
  - Discussed by Gibson, Goldberg and Weiss in 1972
    - mixing could be large due to relatively small energy gaps

in normal nuclei

$$m(\Delta N) - m(NN) \approx 293\ \mathrm{MeV/c^2}$$

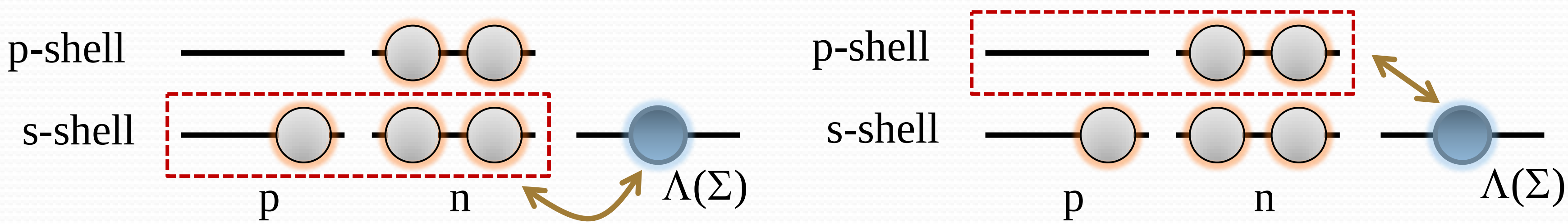
in hypernuclei

$$m(\Sigma^- p) - m(\Lambda n) \approx 80.5\ \mathrm{MeV/c^2}$$
$$m(\Sigma^0 N) - m(\Lambda N) \approx 77.0\ \mathrm{MeV/c^2}$$
$$m(\Sigma^+ n) - m(\Lambda p) \approx 75.0\ \mathrm{MeV/c^2}$$

  - Quantitative discussions made only for several hypernuclei
    - A=3-5 (${}^4_\Lambda$H, ${}^4_\Lambda$He and ${}^5_\Lambda$He), Z=5 (${}^{10}_\Lambda$B and ${}^{11}_\Lambda$B)
  - "ΛN-ΣN mixing" is also general phenomenon
  - Non-zero isospin of core nucleus is essential in mixing
  - Studies of mixing effect in neutron-rich hypernuclei are inevitable to understand properties of the mixing effect

ΛN-ΣN mixing effect in detail

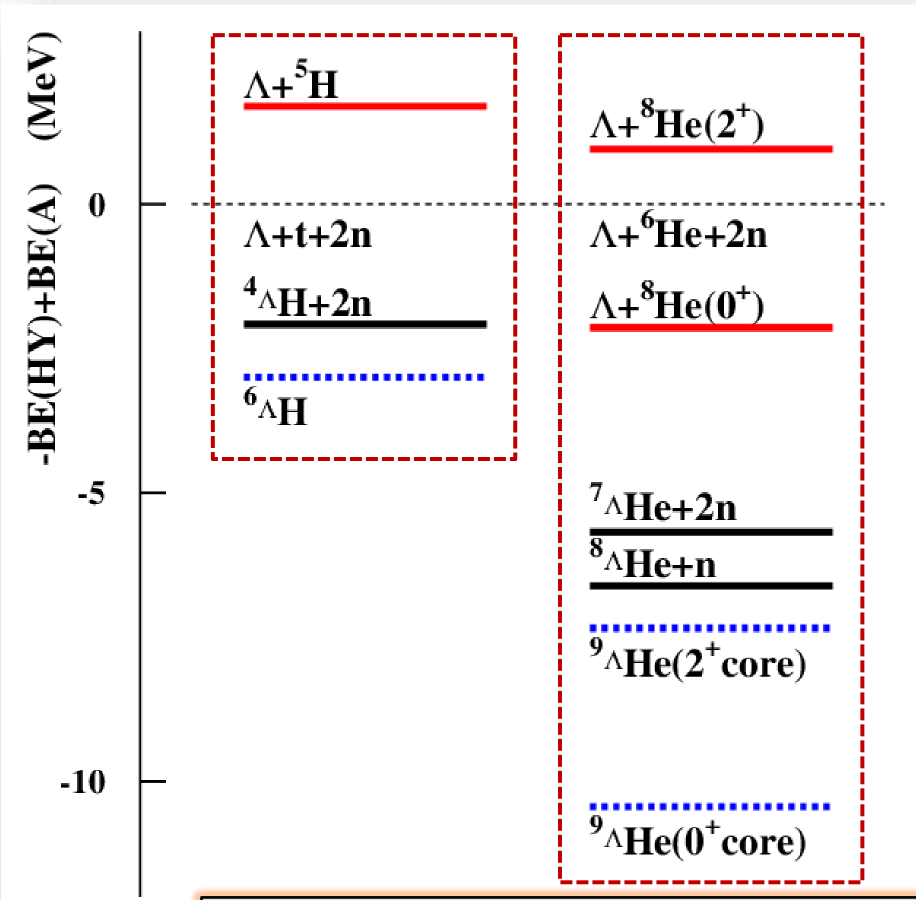
- Different shells contribute differently to the mixing
  - Λ(Σ) is in s-shell for low-lying states
  - Nucleons are in s-shell and higher-shells



  - s-shell and higher-shell contributions may be different, and we wish to separate these contributions if possible
- Separation may be possible by neutron-rich hypernuclei
  - Pure s-shell: s-shell hypernuclei (e.g., ${}^4_\Lambda$H and ${}^4_\Lambda$He)
  - Pure p-shell: p-shell neutron-rich hypernuclei (e.g., ${}^9_\Lambda$He)
  - Interplay: s-shell neutron-rich hypernuclei (e.g., ${}^6_\Lambda$H)

Aims of J-PARC E10 experiment

- Aim 1: **extend boundary of stability of nuclei**
  - Planning to produce ${}^{6}_{\Lambda}H$ and ${}^{9}_{\Lambda}He$



core ${}^{5}H$ is a resonant state
superheavy hydrogen

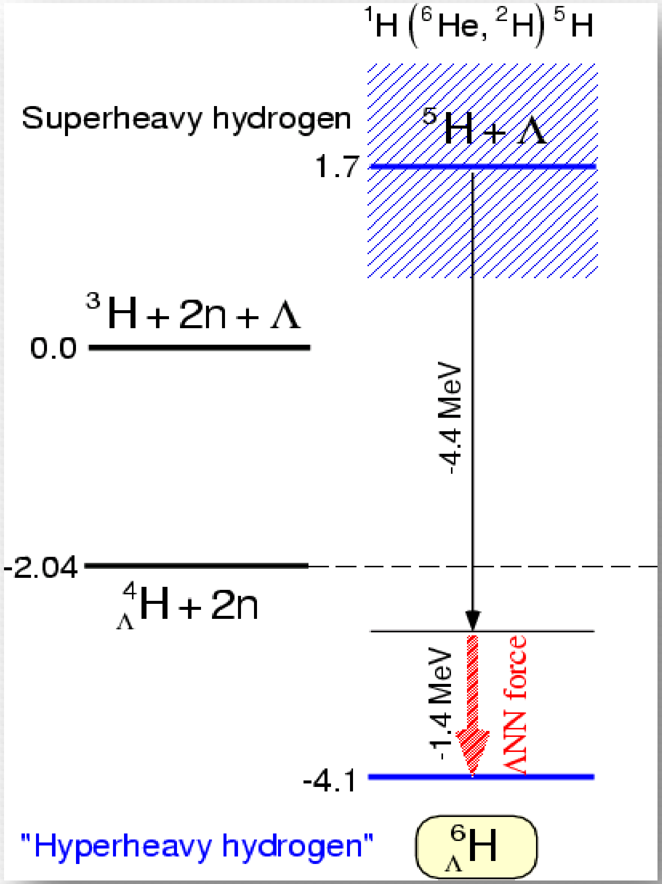
Λ may stabilize ${}^{5}H$ nucleus
by the "glue" effect
${}^{6}_{\Lambda}H$ may be particle stable
hyperheavy hydrogen

${}^{8}He$ is a typical halo nucleus
excited 2^+ state is unbound

Λ may change structure of core
$\Lambda + {}^{8}He(2^+)$ may be particle stable

We wish to produce these hypernuclei close to neutron drip-line

- Aim 2: **investigation of ΛN-ΣN mixing**
  - Precise measurement of binding energy of $^{6}_{\Lambda}H$



Suggestion of the calculation

Normal ΛN interaction
$B_{\Lambda} \sim 4.4$ MeV

Coherent ΛN-ΣN mixing
$B_{\Lambda} \sim 4.4$ **+ 1.4 MeV**

Difference is considerably large
experimentally accessible

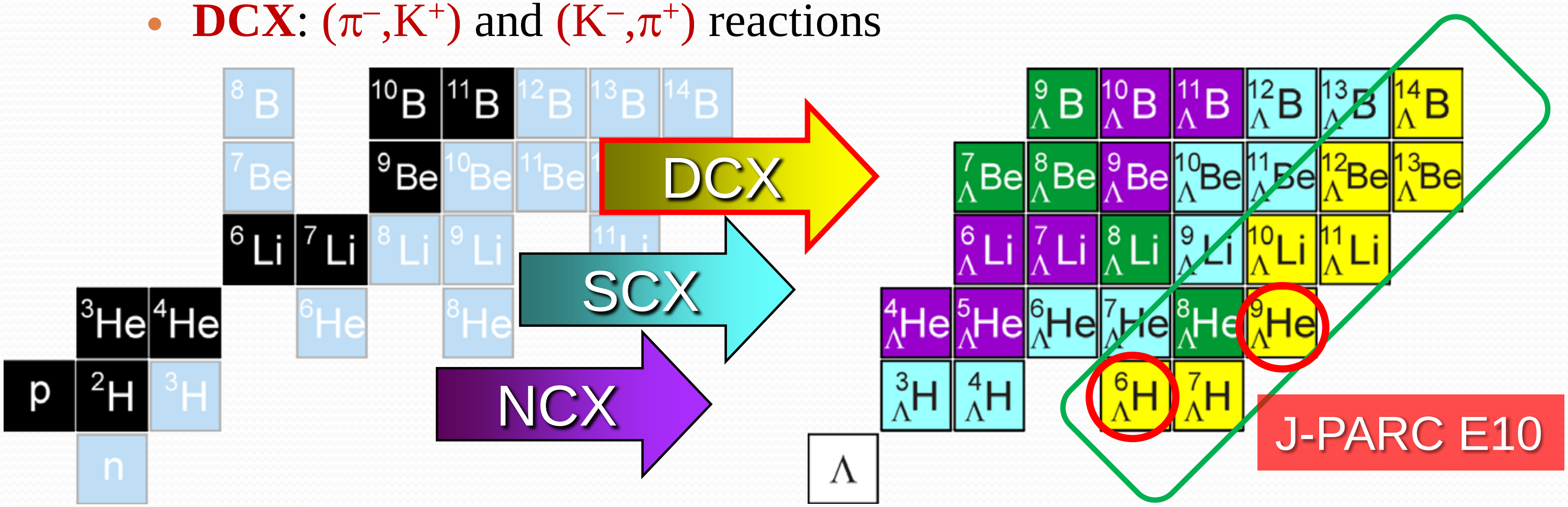
Our basic idea

Precise measurement of B.E.
→ estimate mixing effect

Y. Akaishi et al. Frascati Phys. Ser. XVI (1999) 59

How to produce n-rich hypernuclei?

- Use double charge-exchange (DCX) reactions
  - Category of reactions to produce Λ hypernuclei
    - **NCX**: (π^+,K^+) and (K^-,π^-) reactions
    - **SCX**: $(e,e'K^+)$, (π^-,K_S), (K^-,π^0) reactions, etc.
    - **DCX**: (π^-,K^+) and (K^-,π^+) reactions



DCX reaction

$$\pi^- + p + p \rightarrow K^+ + \Lambda + n$$

the reaction has two-step nature
tiny cross section, ~1/1000 of NCX

Previous experiments with DCX

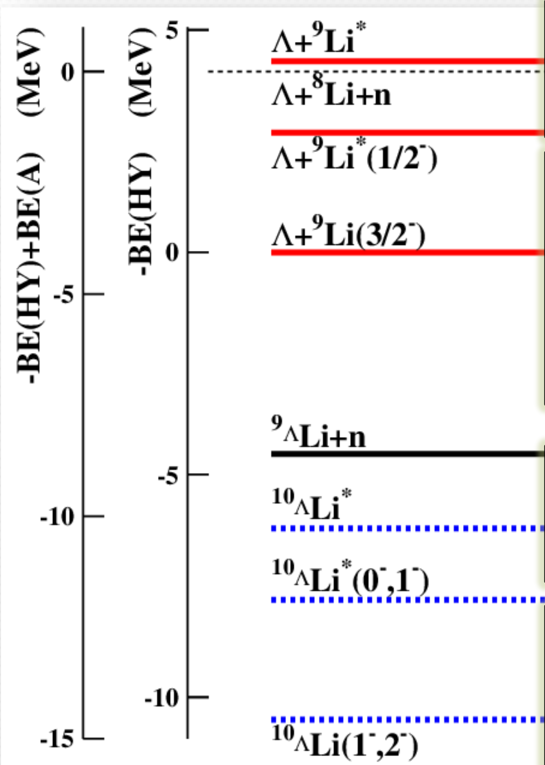
- Experiments by the (stopped-K^-,π^+) reaction
  - **KEK-PS**: K. Kubota et al. NP A602 (1996) 327
    - Upper-limits of BR(DCX) for ${}^{9}_{\Lambda}$He, ${}^{12}_{\Lambda}$Be and ${}^{16}_{\Lambda}$C
  - **FINUDA**: M. Agnello et al. PL B640 (2006) 145
    - Upper-limits of BR(DCX) for ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H
  - **FINUDA**: M. Agnello et al. PRL 108 (2012) 042501
    - observation of 3 candidate events of ${}^{6}_{\Lambda}$H bound state
    - BR(DCX) / BR(NCX, ${}^{12}_{\Lambda}$C) ~ 3×10^{-3}

Confirmation and precise determination of mass (or binding energy) are necessary in E10 experiment

- Experiments by the (π^-,K^+) reaction
  - **KEK E521**: S. Pranab et al. PRL 94 (2005) 052501
    - Pilot experiment for J-PARC E10 experiment

KEK E521 experiment

- Demonstrated production of n-rich hypernuclei by DCX
  - Measured the $^{10}B(\pi^-,K^+)^{10}{}_{\Lambda}Li$ reaction
    - core nucleus ^{9}Li is bound, we are sure $^{10}{}_{\Lambda}Li$ is well bound
    - good hypernucleus to evaluate DCX reaction

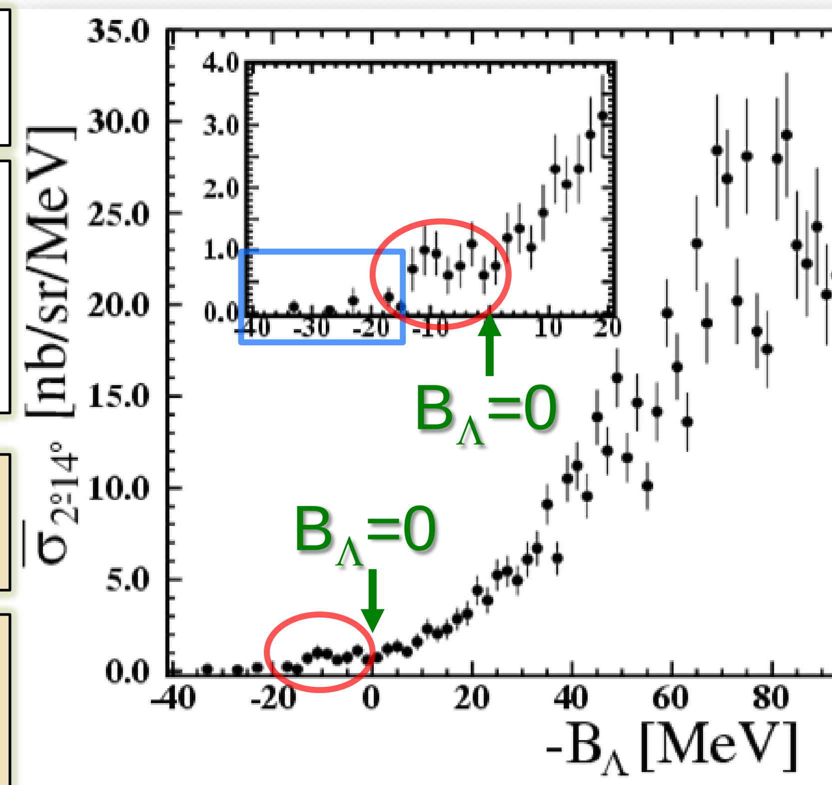


clear population in the Λ bound region

almost no event in B_{Λ}>15MeV region
the (π^-,K^+) reaction is very clean

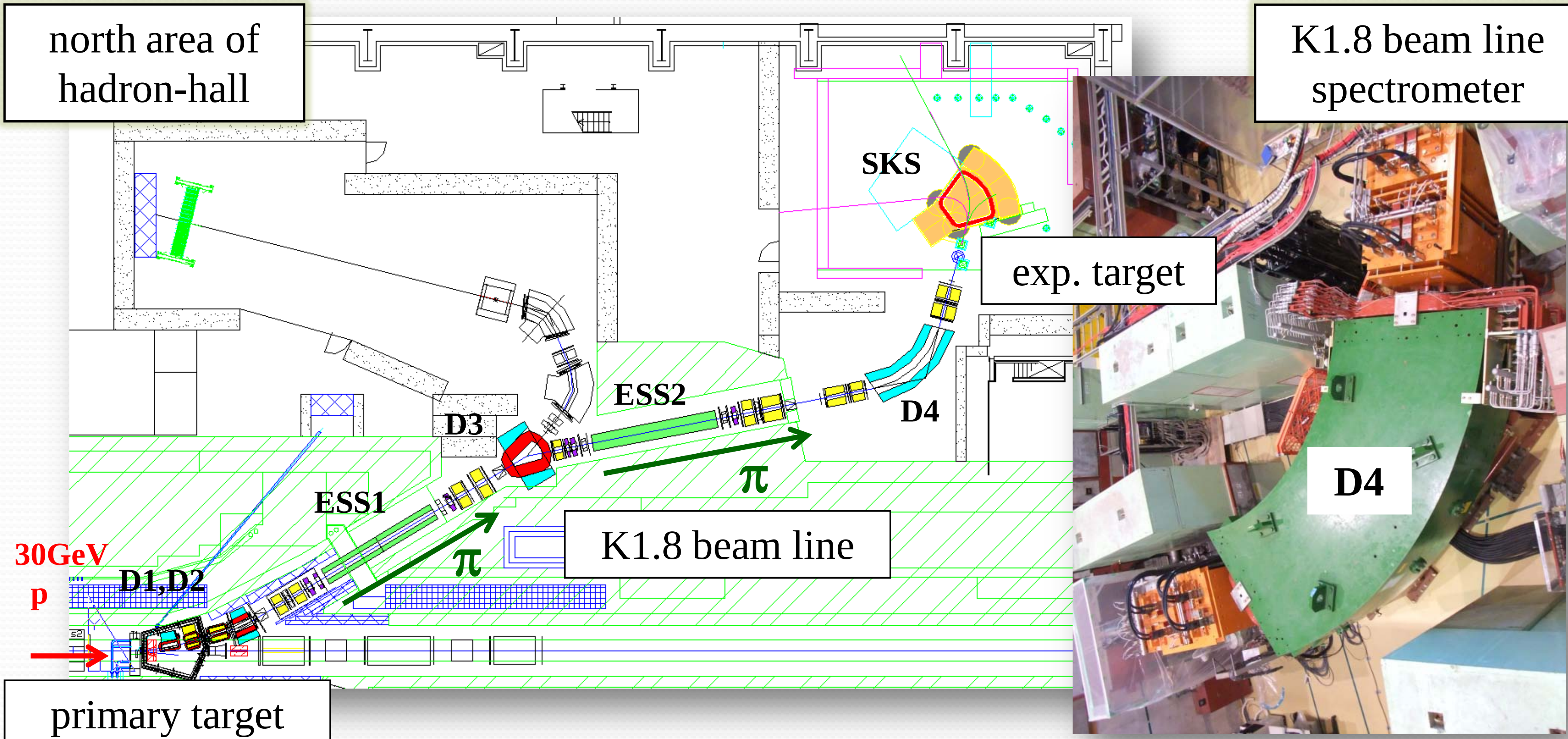
We wish to extend study at J-PARC

high intensity pion beams to override tiny cross section



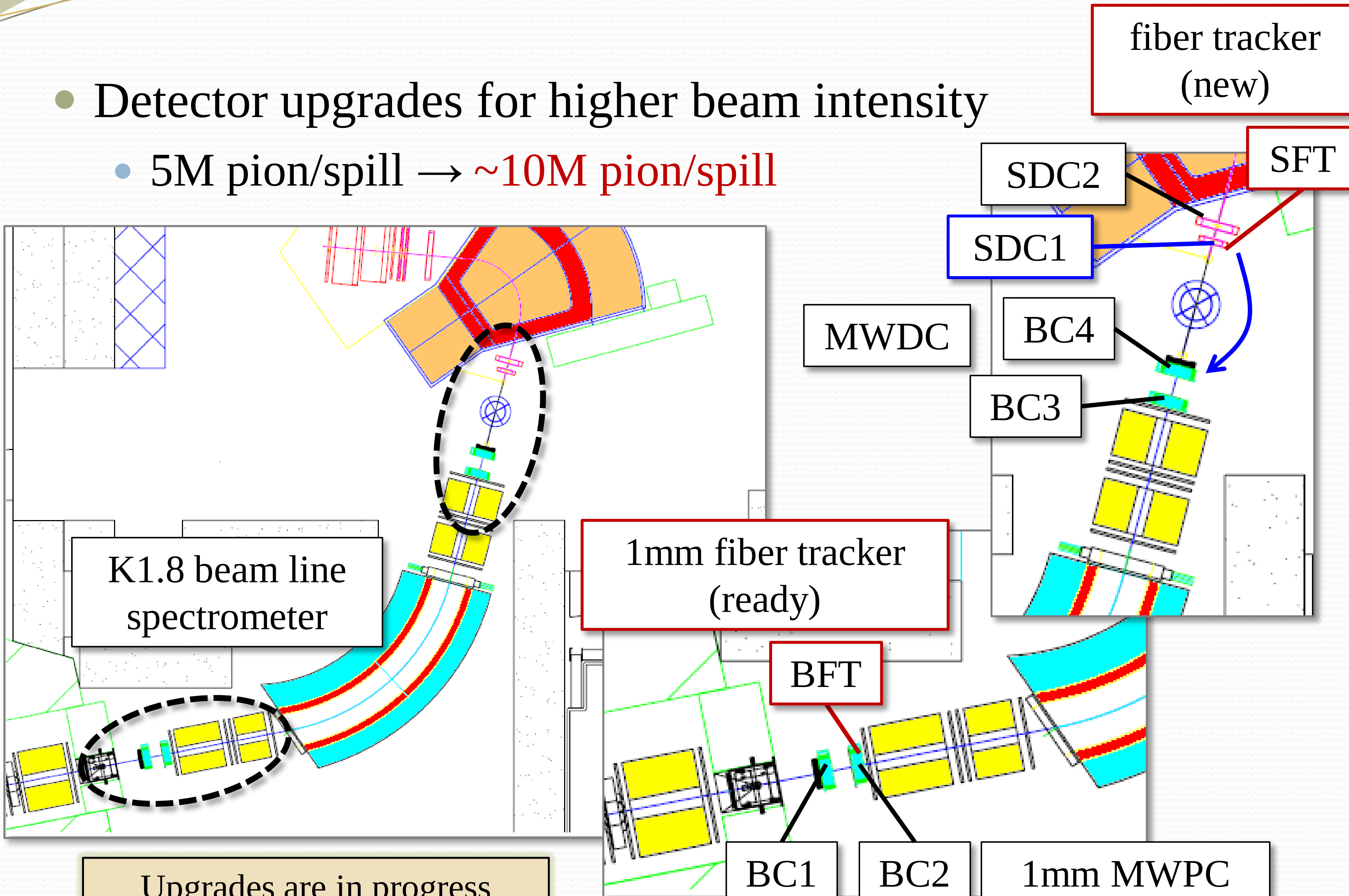
Experimental Setup of E10

- K1.8 beam line in hadron-hall of J-PARC 50GeV PS



- $1.2 GeV/c$ pion beams, typical intensity ~10M/spill
- Momentum resolution of beam line $dp/p \sim 3\times10^{-4}$

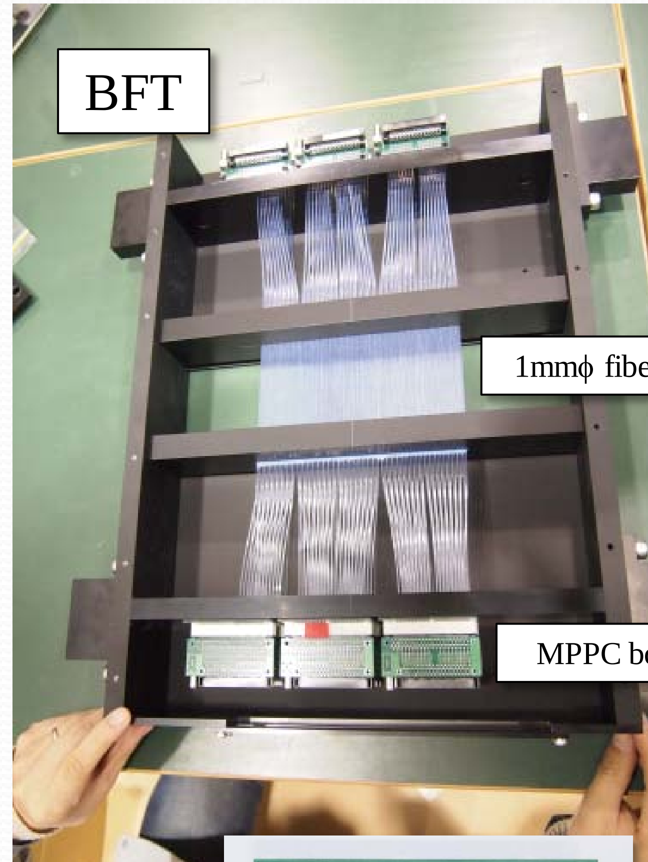
- Detector upgrades for higher beam intensity
  - 5M pion/spill → ~10M pion/spill

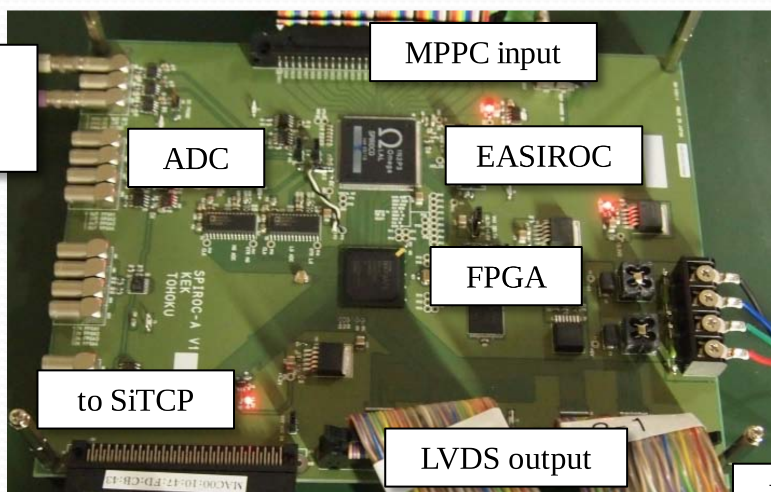


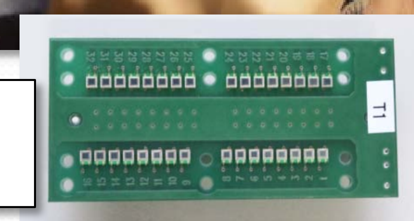
Upgrades are in progress

BFT (beam fiber tracker) design

- 1mm ϕ scintillating fibers
  - 2 layers staggered by 0.5mm
  - $160 \times 2 = 320$ fibers
- Read out
  - MPPC+EASIROC
  - Flexible and easy to handle

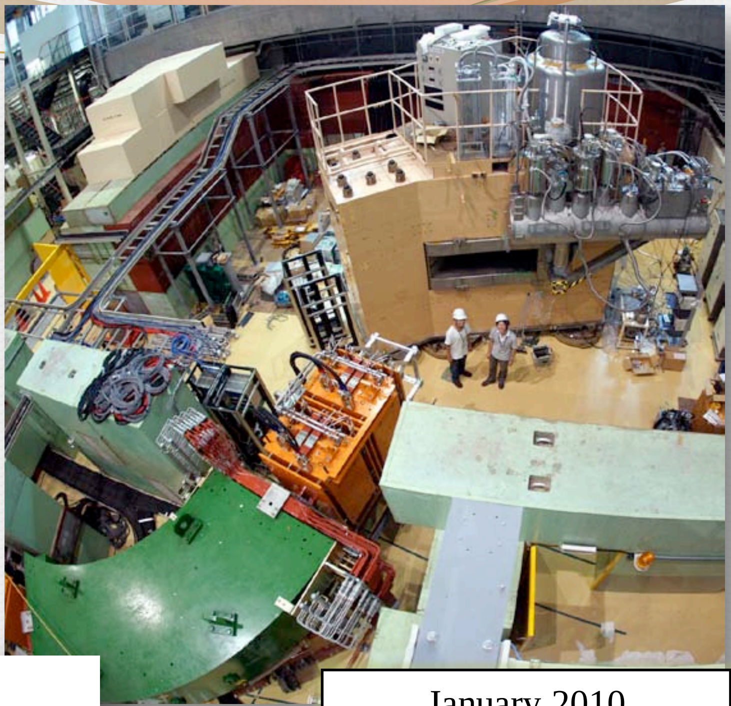






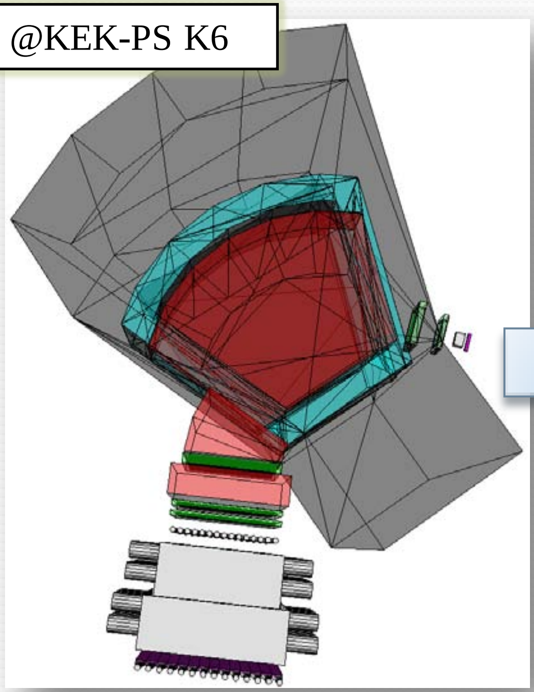
Developed by K. Miwa, S. Hasegawa and R. Honda
(Tohoku Univ. and JAEA)

- SKS for kaon measurement
  - Mom. resolution $dp/p \sim 10^{-3}$
  - Large acceptance ~100msr
  - Moved KEK → J-PARC
- Detector upgrades done

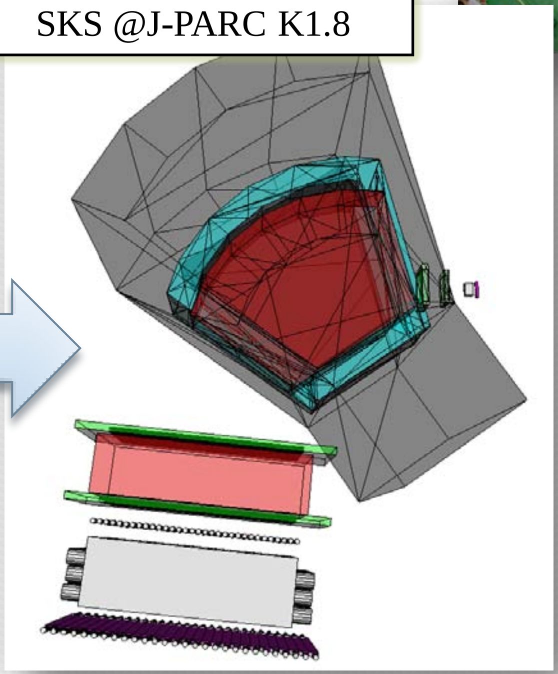


January 2010
before earthquake
(photo by K. Tanaka)

SKS @KEK-PS K6



SKS @J-PARC K1.8



tracking and trigger detectors were enlarged to make momentum acceptance wider

Prospects of E10 experiment

- ${}^{6}_{\Lambda}H$ production run in Dec. and Jan. (E10 1st phase)
  - E10 run conditions and expected yields

Parameters	Values
Pion beam momentum	1.2 GeV/c
Pion beam intensity	10 M/spill
Total number of pions (run for 3 weeks)	3T pions
Target thickness (^{6}Li)	3.5 g/cm^2
DCX cross section (assumed)	10 nb/sr
SKS acceptance	100 msr
Spectrometer efficiency	0.5
Analysis efficiency	0.5
Estimated ${}^{6}_{\Lambda}H$ yield	265

← high intensity beams

← optimized for yield and resolution

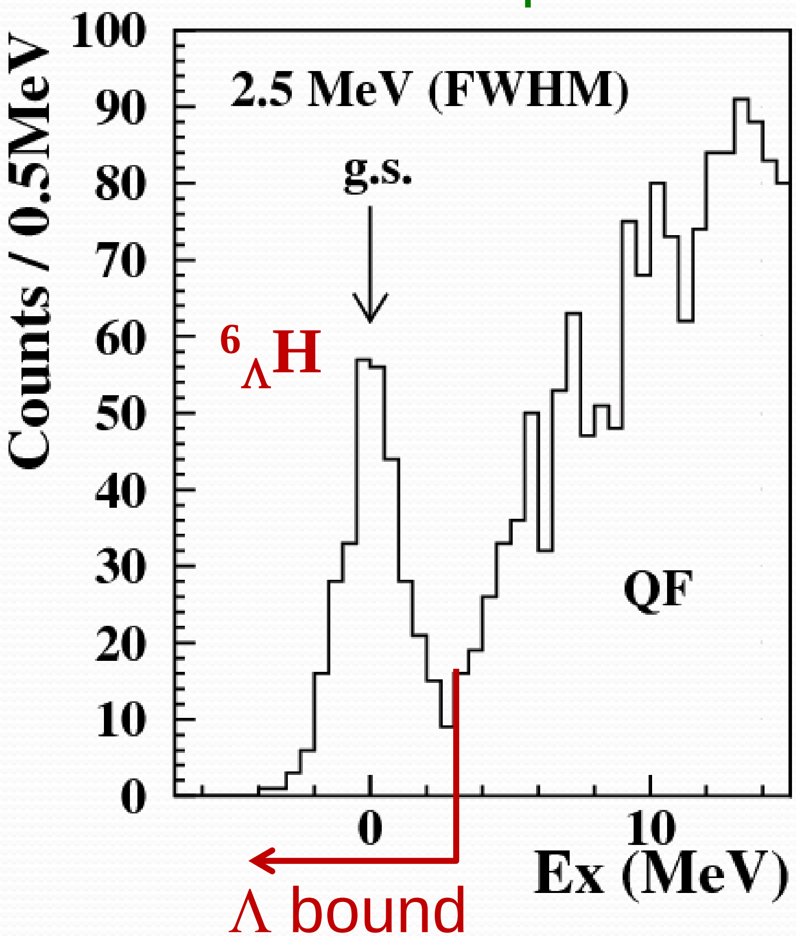
← large acceptance

  - About 6 times larger yields than KEK E521

Binding energy measurement

- Prospect of B.E. measurement of ${}^{6}_{\Lambda}$H

simulated spectrum



Assumptions

missing-mass resolution

≈ 2.5 MeV(FWHM)

${}^{6}_{\Lambda}$H yield

≈ 300 events

${}^{6}_{\Lambda}$H/QF ratio (Ex<23MeV)

≈ 1/10

estimated from ${}^{4}_{\Lambda}$He and ${}^{10}_{\Lambda}$Li

Peak is well separated from QF

Statistical error of B.E. < 0.1MeV

Summary

- Properties of Λ hypernuclei
  - "glue-like role" of Λ hyperon in hypernuclei
  - effect of "ΛN-ΣN mixing"
- Aims of J-PARC E10 experiment
  - Extend the boundary of stability of nuclei by the "glue" effect
  - Estimate ΛN-ΣN mixing from B.E. of neutron-rich hypernuclei
  - Produce neutron-rich hypernuclei: ${}^{6}_{\Lambda}H$ and ${}^{9}_{\Lambda}He$
- E10 prospects (E10 phase-1 in December and January)
  - 6 times larger yield than previous E521 experiment
  - precise measurement of B.E. of ${}^{6}_{\Lambda}H$ is possible