Production of Λ hypernuclei close to neutron drip-line

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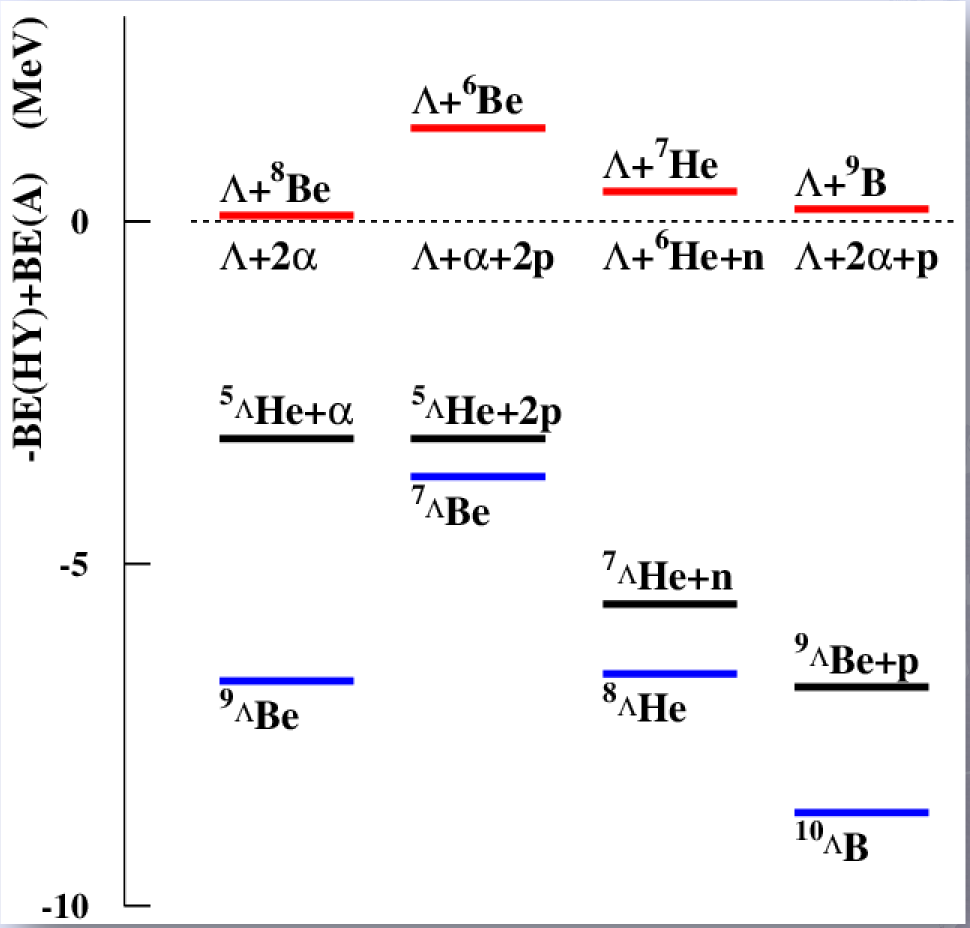
Some properties of Λ hypernuclei

- Property 1: "**glue-like role**" of **Λ hyperon**
  - We already know many examples

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

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

  - 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
    - studies of mixing effect in neutron-rich hypernuclei are inevitable to understand properties of the mixing effect

J-PARC E10 experiment

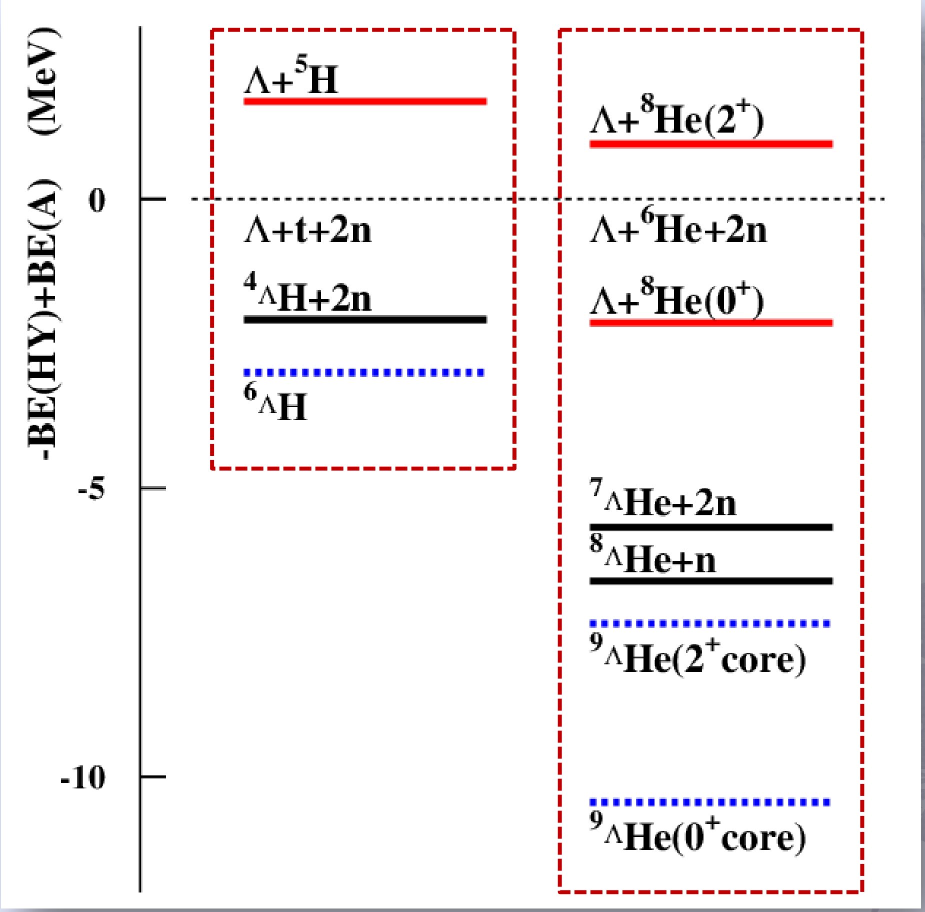
- Aim 1: **extend boundary of stability**
  - Planning to produce $^{6}_{\Lambda}H$ and $^{9}_{\Lambda}He$

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

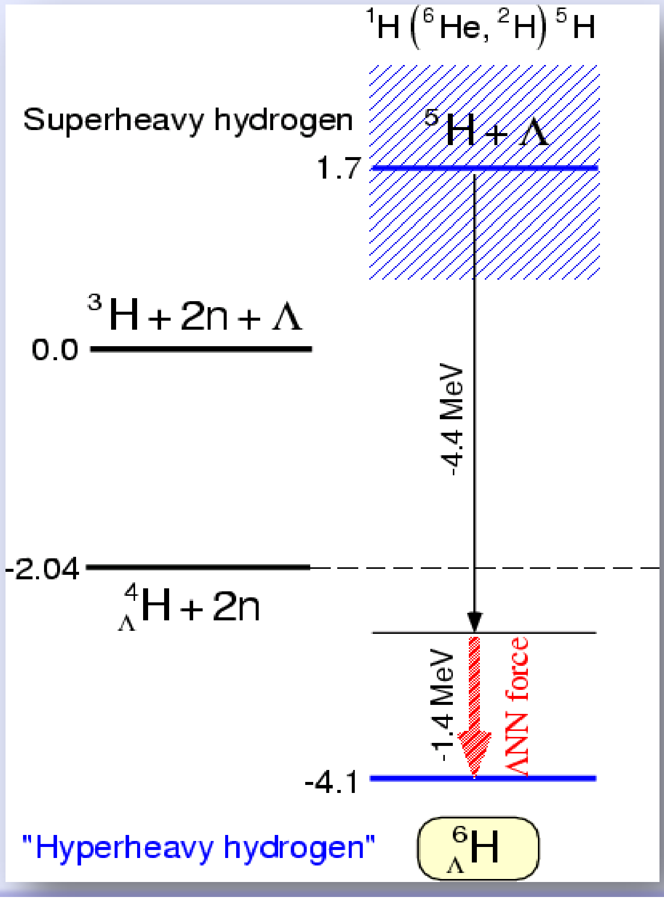
^{8}He is a typical halo nucleus
excited 2^{+} state is unbound

Λ may change structure
$\Lambda + ^{8}He(2^{+})$ may be 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 $^{6}_{\Lambda}H$



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

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

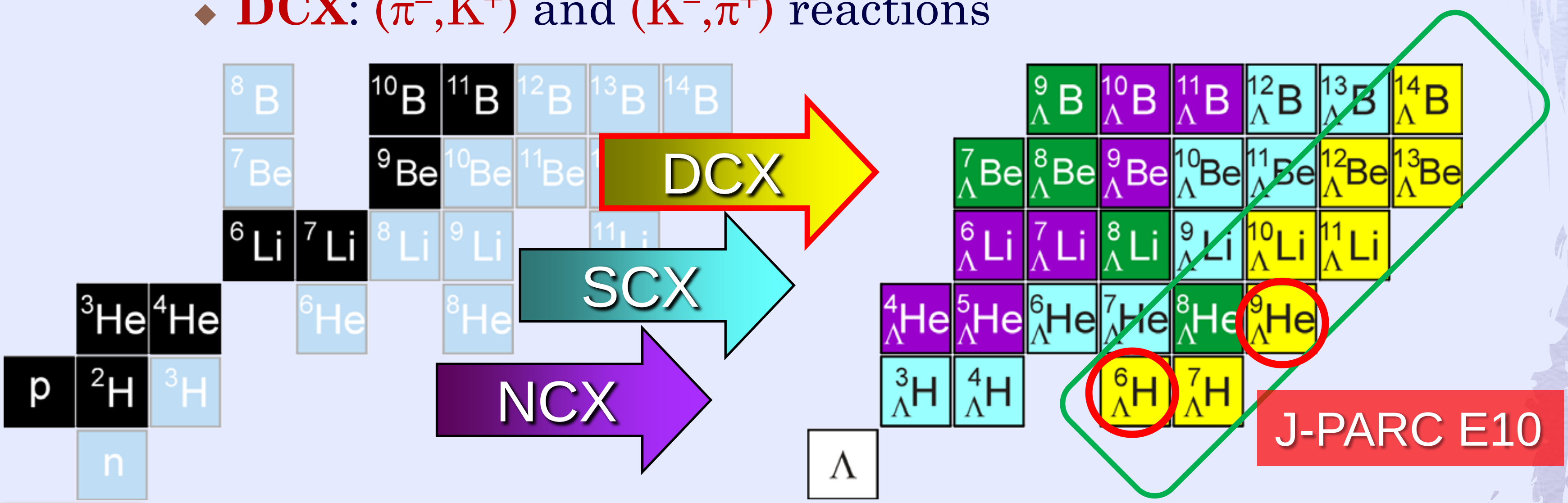
Difference is considerably large
experimentally accessible

Our basic idea

Precise measurement of B.E.
→ estimate mixing effect

How to produce n-rich HY?

- 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

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

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

Previous experiments with DCX

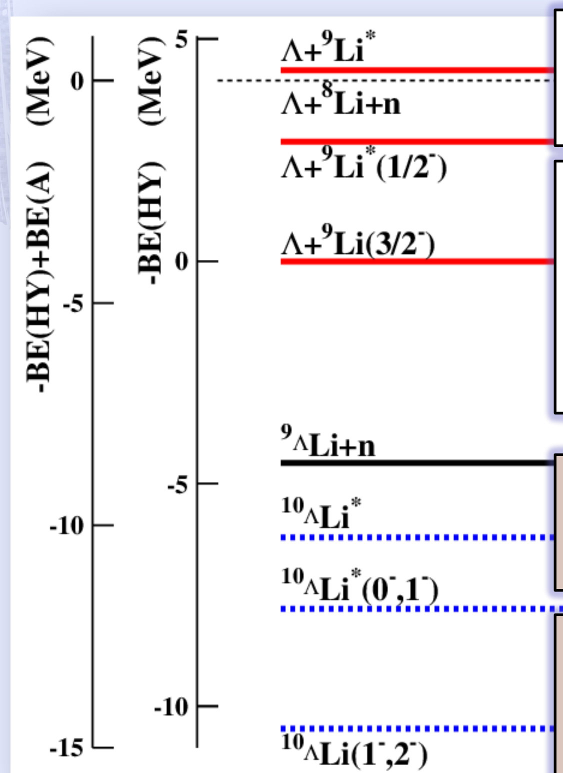
- Experiments by the (stopped-K^-,π^+) reaction
  - **KEK-PS**: K. Kubota et al. NP A602 (1996) 327
    - Upper-limits of BR(DCX) for $^{9}_{\Lambda}$He, $^{12}_{\Lambda}$Be and $^{16}_{\Lambda}$C
  - **FINUDA**: M. Agnello et al. PL B640 (2006) 145
    - Upper-limits of BR(DCX) for $^{6}_{\Lambda}$H 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}

impact of FINUDA result to E10 experiment will be discussed later

- 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 HY 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

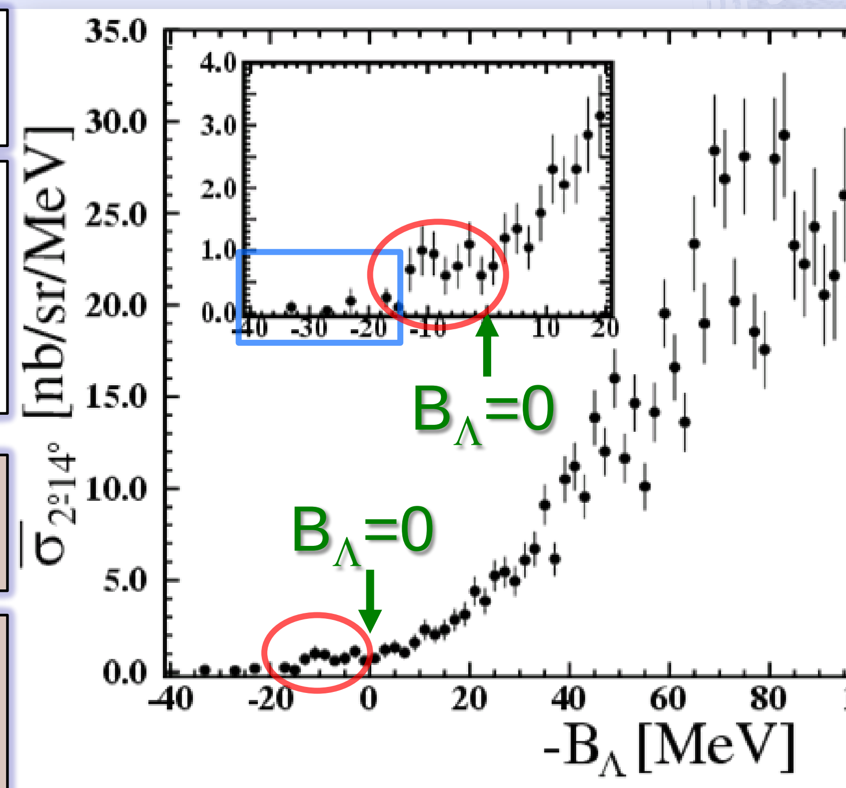


clear population in the Λ bound region

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



(π^-,K^+) reaction and mixing effect

- Beam momentum dependence of cross section
  - Obtained in KEK E521 experiment

pion beam momentum	1.05 GeV/c	1.2 GeV/c
$^{10}B(\pi^-,K^+)^{10}{}_{\Lambda}Li$ cross sections	5.8±2.2 nb/sr	11.3±1.9 nb/sr

- Favors "one-step" reaction mechanism
  - Naïve processes of DCX: Two-step reactions

$$\pi^- + p \to K^0 + \Lambda, \quad K^0 + p \to K^+ + n$$

$$\pi^- + p \to \pi^0 + n, \quad \pi^0 + p \to K^+ + \Lambda$$

$\sigma(1.05\ \mathrm{GeV/c}) > \sigma(1.2\ \mathrm{GeV/c})$

  - "One-step" reaction mechanism

$$\pi^- + p \to K^+ + \Sigma^-, \quad (\Sigma^- p) \to (\Lambda n)$$

ΛN-ΣN mixing

$\sigma(1.05\ \mathrm{GeV/c}) < \sigma(1.2\ \mathrm{GeV/c})$

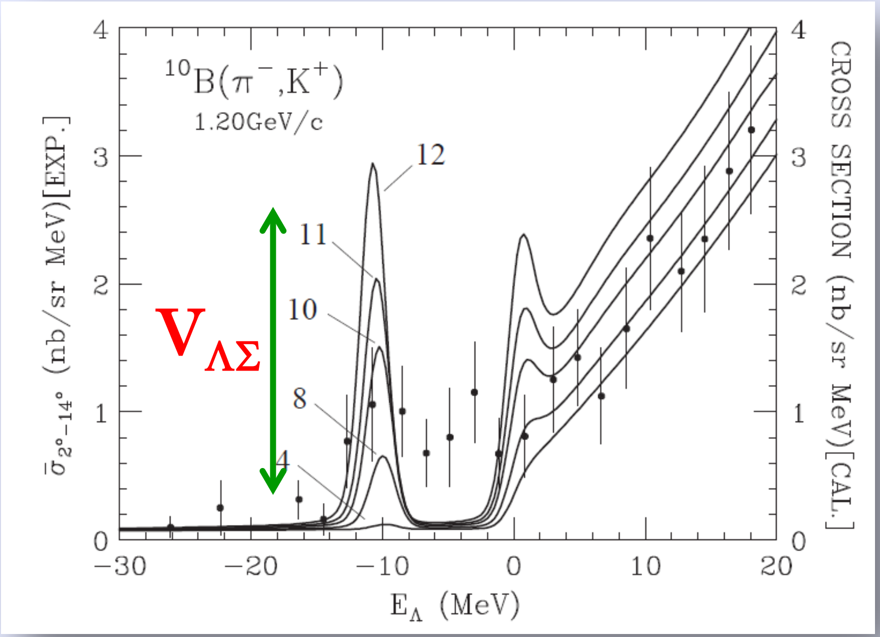
beam momenta are close to Σ threshold

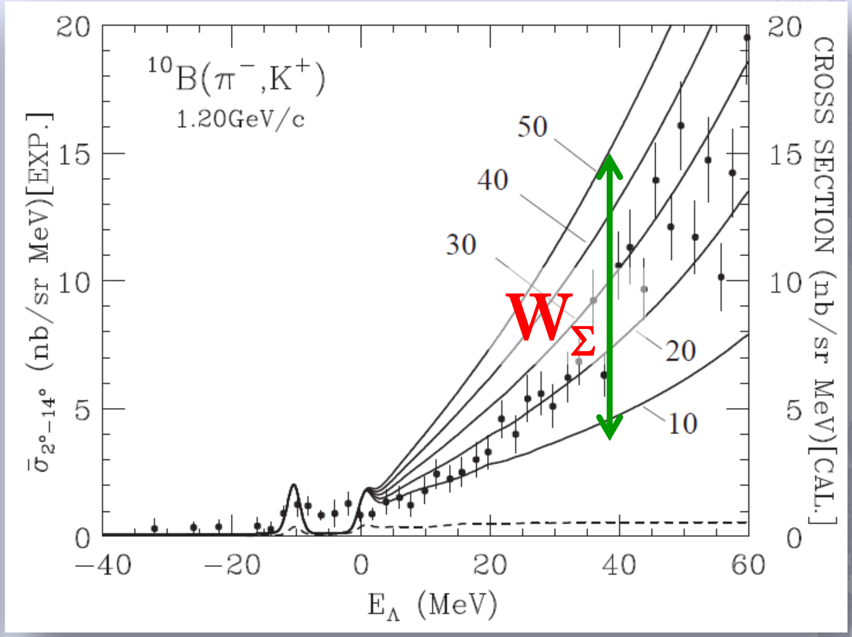
"One-step" mechanism and mixing

- Estimate mixing parameters from spectrum

production cross section → $V_{\Lambda\Sigma}$

shape of QF region → W_{Σ}





T. Harada et al., Phys Rev C79 (2009) 014603

based on "one-step" mechanism

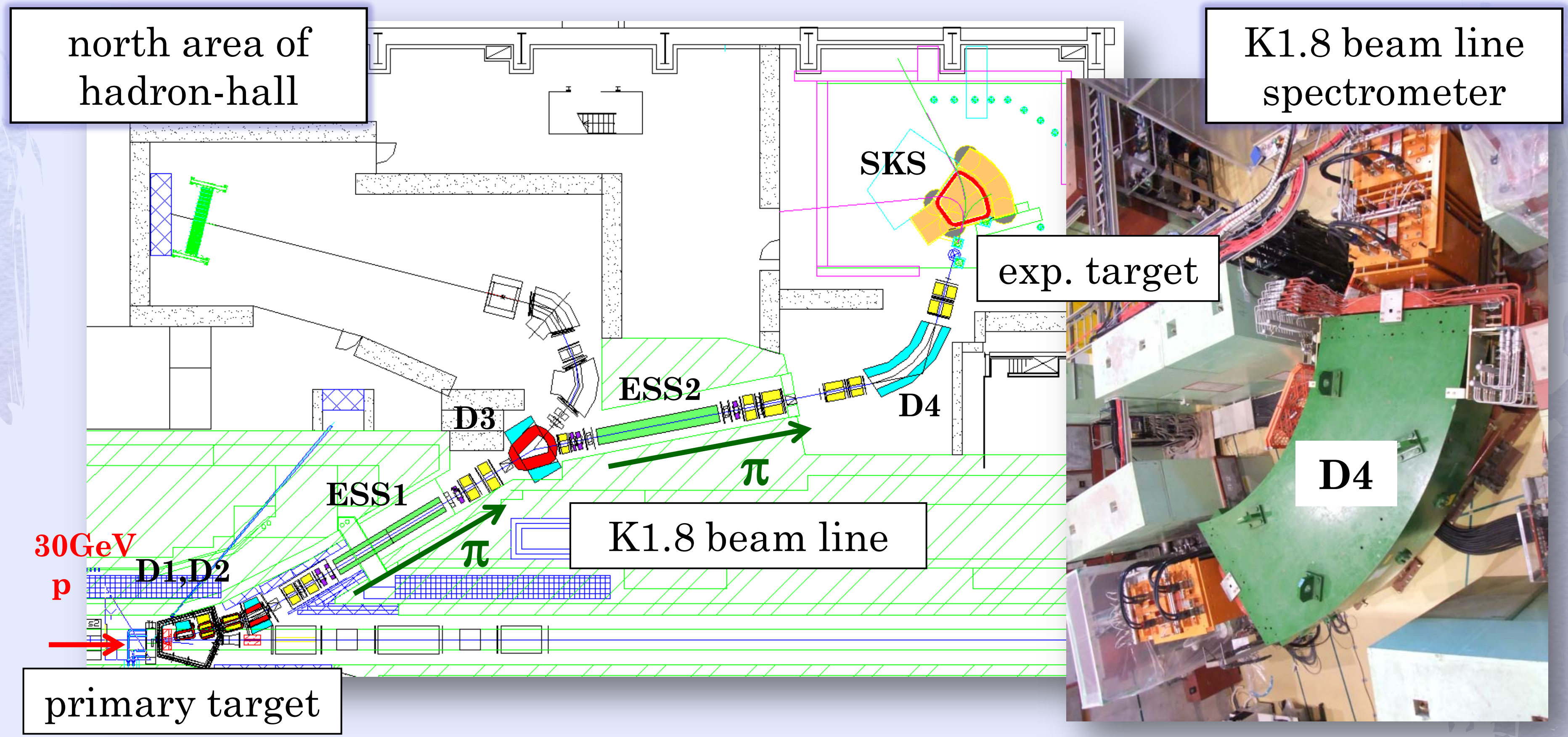
- We are planning to measure a wide range of messing-mass spectrum in J-PARC E10 experiment

Impact of FINUDA results

- Candidate events of bound ${}^{6}_{\Lambda}H$
  - Bound candidates are quite encouraging for E10
    - Although E10 can observe unbound states, bound states may be observed more clearly in missing-mass spectrum.
- BR(DCX) was about 3/1000 of BR(NCX)
  - Ratio was close to ratio we assume for DCX
    - we assume DCX/NCX ratio for (π,K) reaction is 1/1000
    - this fact was also encouraging for E10 experiment
- Indication of g.s. doublet splitting ~1MeV
  - Population of excited state by DCX reaction?
  - We have to make carful analyses for the g.s. region
    - we have to carefully look at peak shape in missing-mass spectrum and its angular dependence

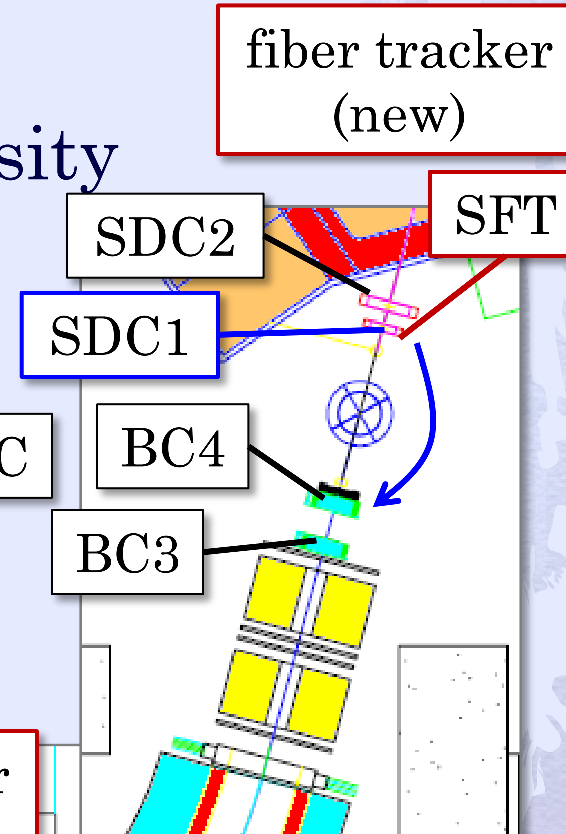
Experimental Setup of E10

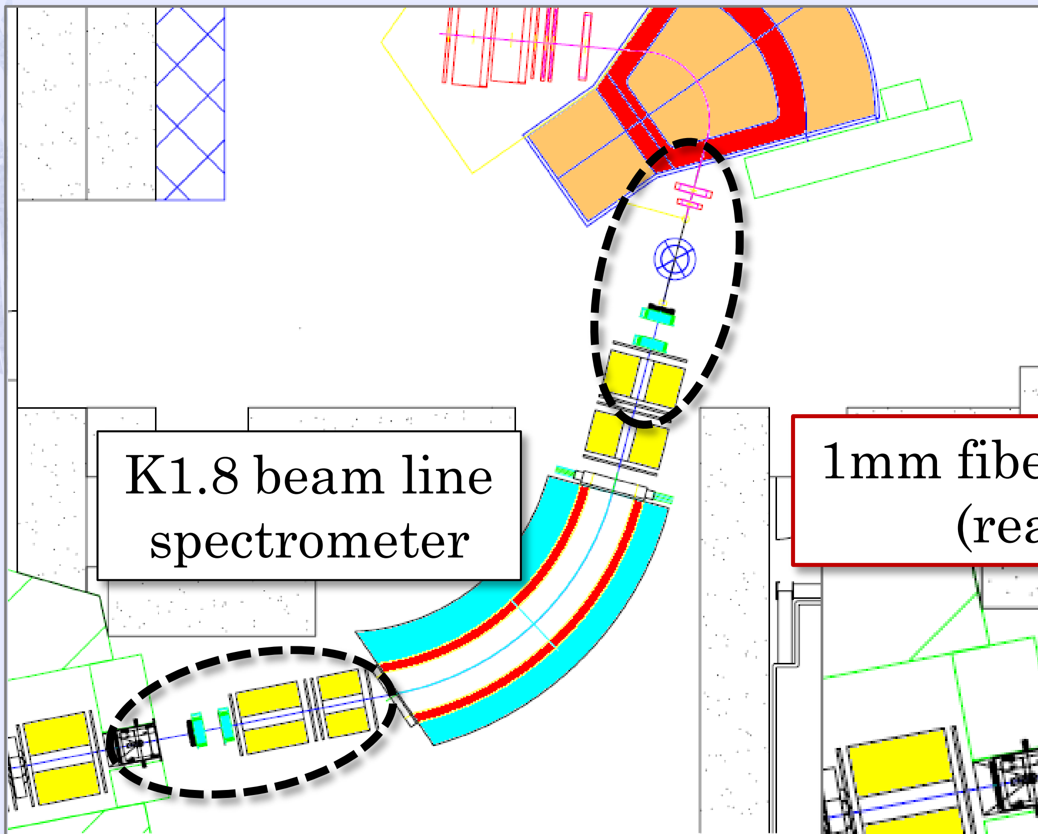
- K1.8 beam line in hadron-hall of 50GeV PS

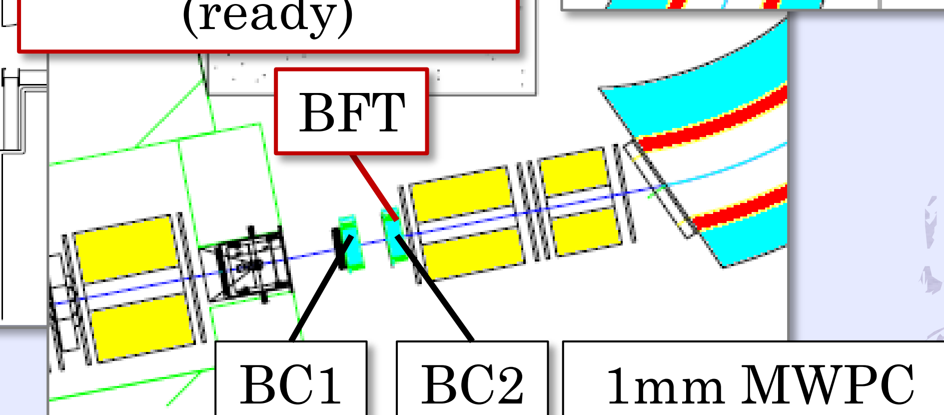


- 1.2GeV/c pion beams, typical intensity ~10M/spill
- Momentum resolution of beam line dp/p~3×10^{-4}

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

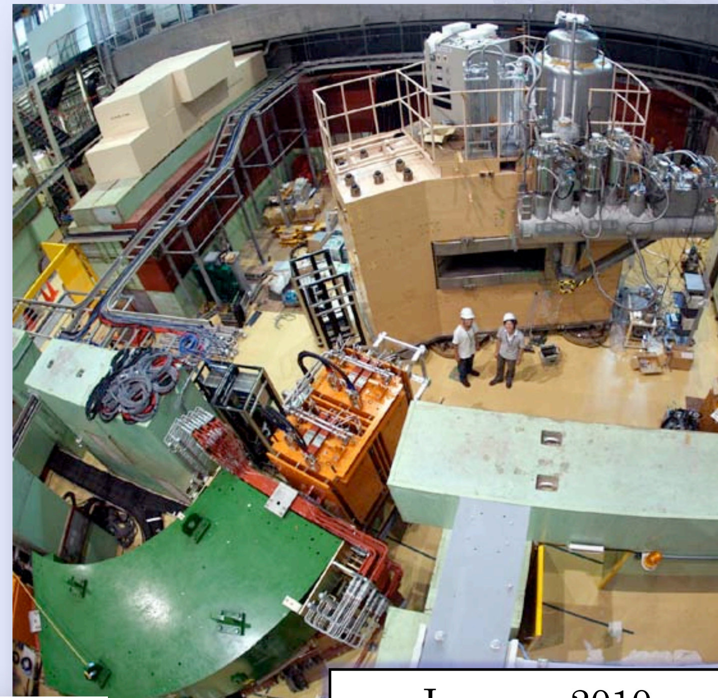






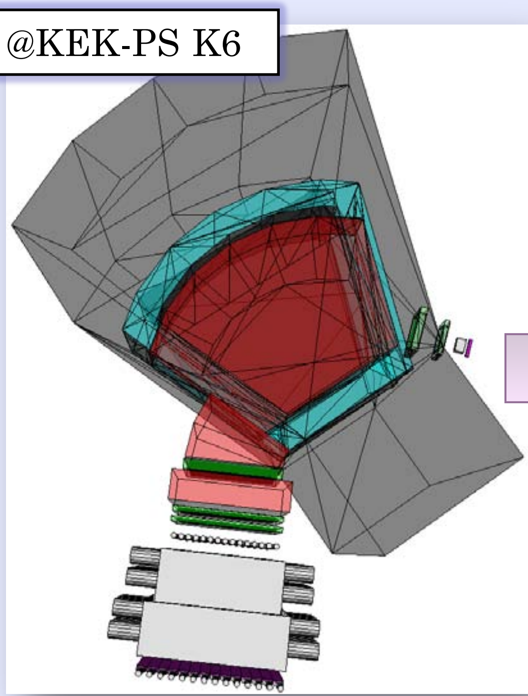
Upgrades are in progress

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

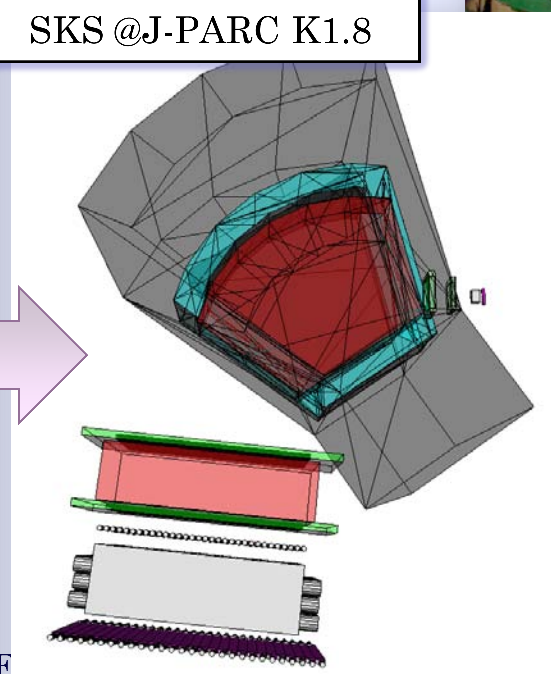


January 2010
before earthquake
(photo by K. Tanaka)

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 winter (E10 phase-1)
  - 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**

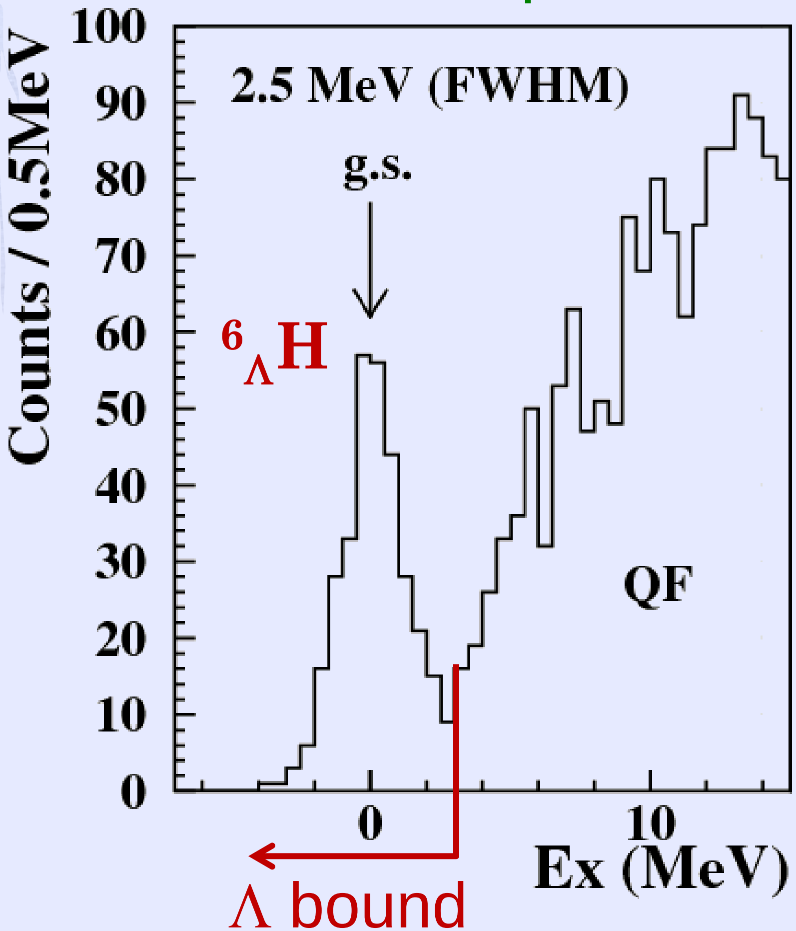
← **large acceptance**

  - 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 this winter)
  - 6 times larger yield than previous E521 experiment
  - precise measurement of B.E. of ${}^{6}_{\Lambda}H$ is possible