Neutron-rich Λ Hypernuclei

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for the **J-PARC E10 Collaboration**

J-PARC E10 collaboration

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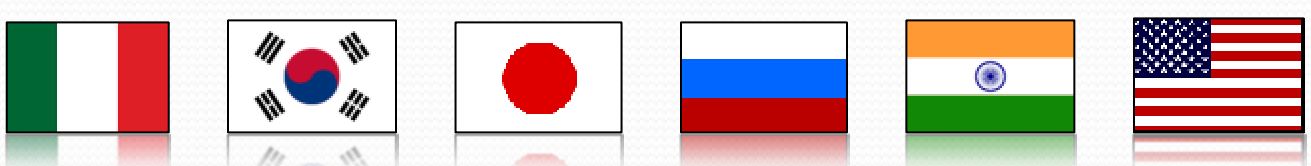
Politecnico di Torino, Koria University, RCNP, Tohoku University, Kyoto University, KEK, Seoul National University, Osaka University, JINR, INFN, Osaka Electro-Communication University, JAEA, Pusan National University, BARC, Virginia Military Institute (15 institutes)

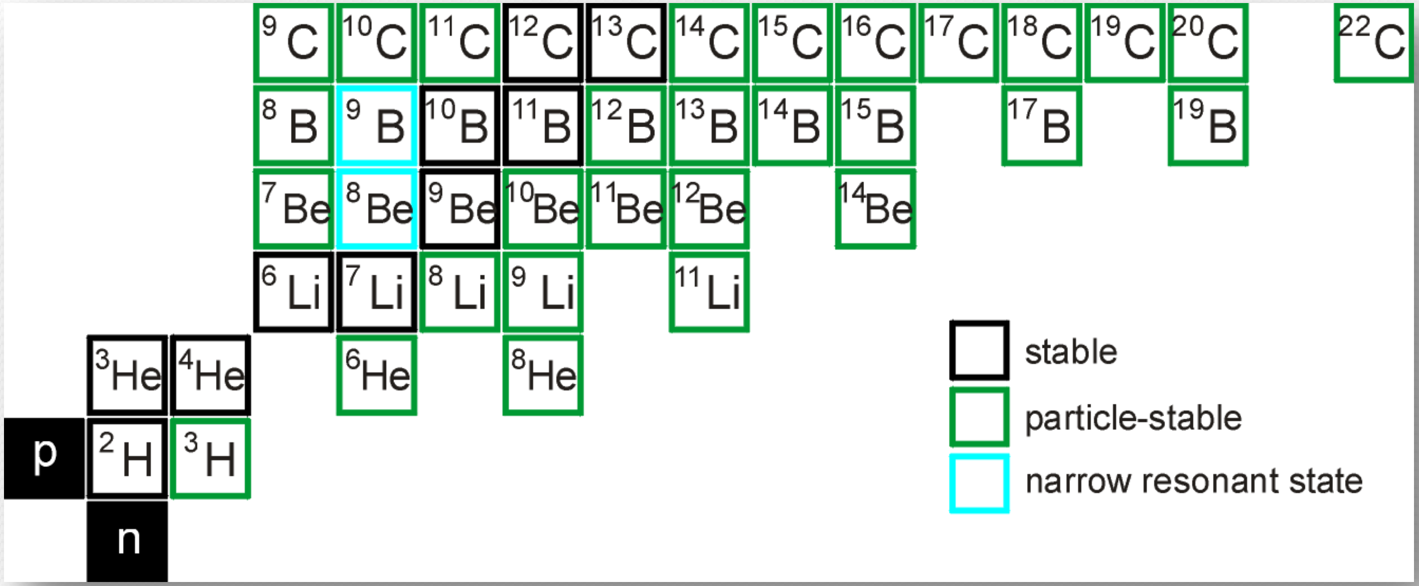


- Contents
  - Neutron-rich Λ hypernuclei close to neutron drip-line
    - Why neutron-rich Λ hypernuclei?
    - Spectroscopic tool is the charge-exchange reaction
  - Recent status of studies by charge-exchange reactions
  - E10 experiment at J-PARC
    - Recent results of search for ${}^{6}_{\Lambda}$H hypernucleus
      - Design of experiment, data analyses and results
    - Recent activity of study of unbound Λ production
      - Understanding of Λ/Σ-nucleus interaction
  - Summary

Study of neutron-rich Λ hypernuclei

- Why neutron-rich hypernuclei?
  - Extensive studies done on neutron-rich nuclei
  - Nuclear chart has wide spreading in neutron-rich side

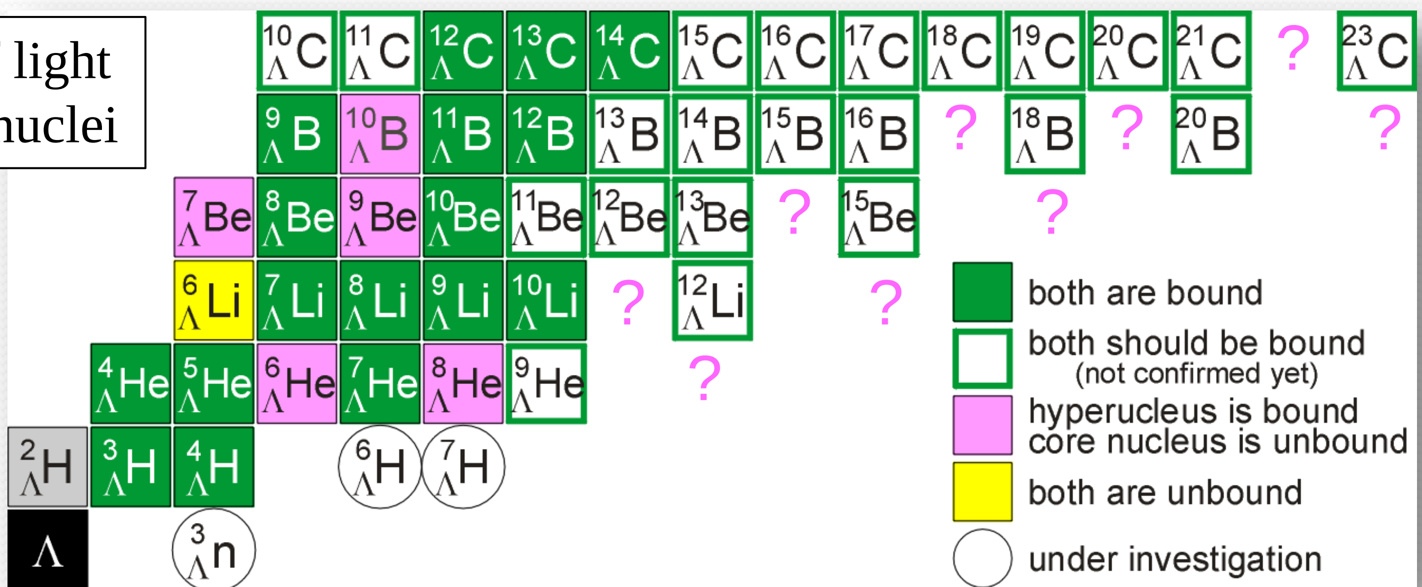
Chart of particle-stable light nuclei



Study of neutron-rich Λ hypernuclei

- What's happen for Λ hypernuclei?
  - Particle-stable Λ hypernuclei ←Particle-stable nuclei
    - Still there are many unobserved Λ hypernuclei
  - Particle-stable Λ hypernuclei ←Particle-unstable nuclei
    - Glue-like role of Λ hyperon may extend the boundary

Chart of light
Λ hypernuclei

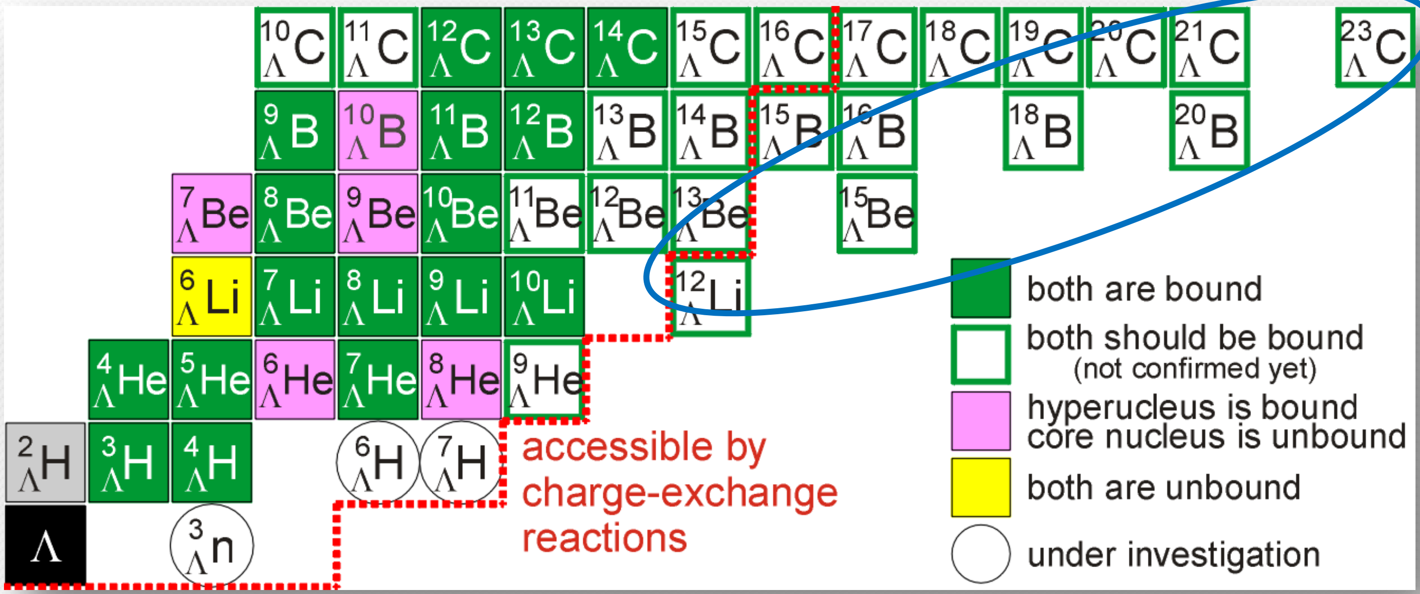


SCX: Single Charge-eXchange
DCX: Double Charge-eXchange

Tools to access neutron-rich hypernuclei

- Old emulsion experiments with stopped-K^- beams
  - Hypernuclear species were limited and yield was low
- Charge-exchange reactions
  - SCX: $(e,e'K^+)$, (K^-,π^0) and DCX: (π^-,K^+), (K^-,π^+)
- Relativistic heavy-ion collisions

L. Majling, Nucl. Phys. A585 (1995) 211c



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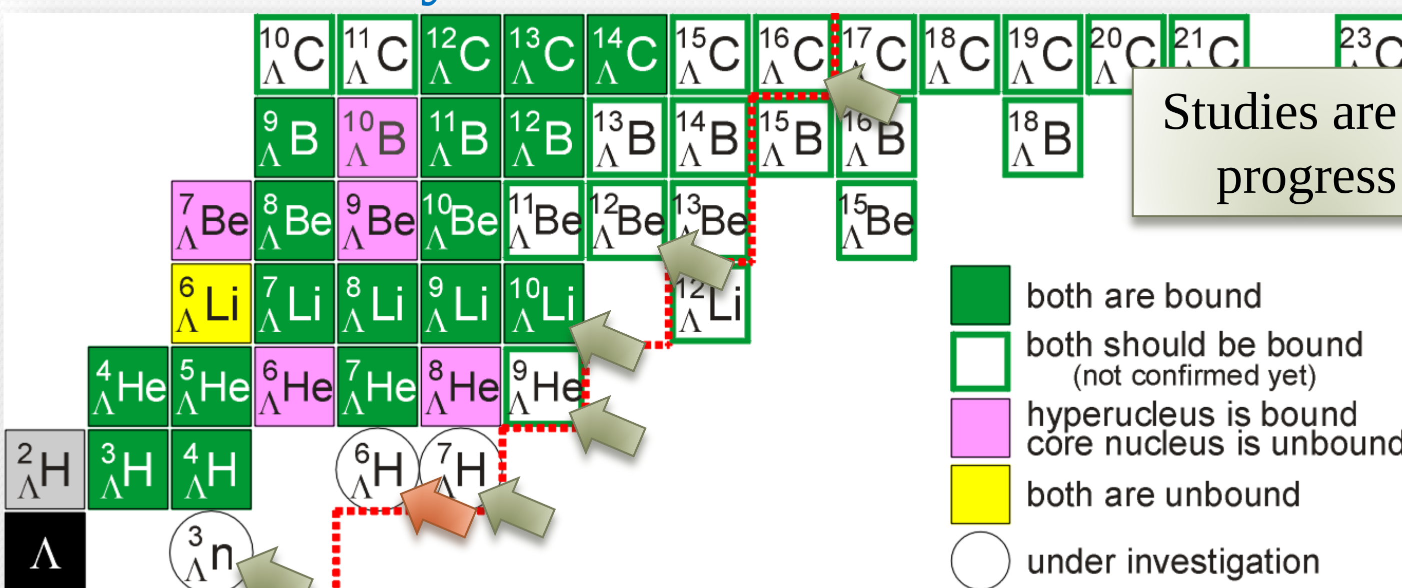
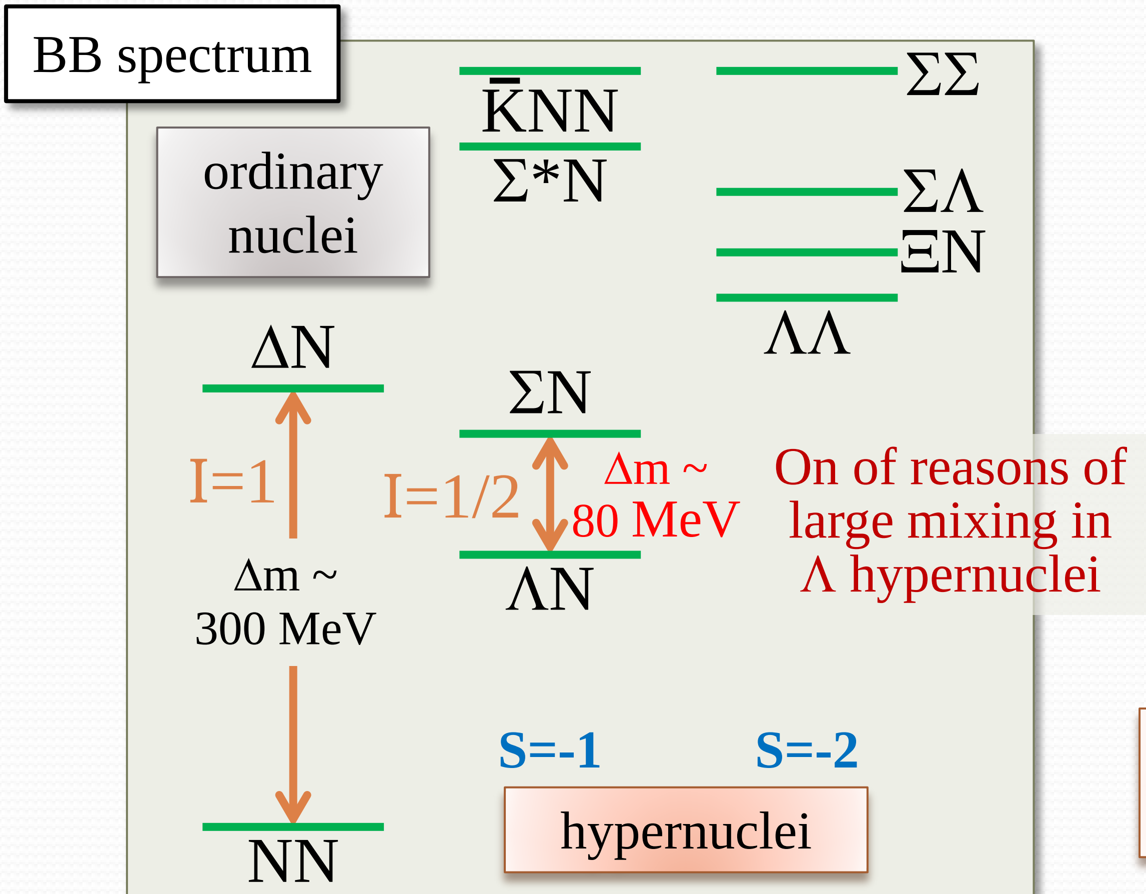
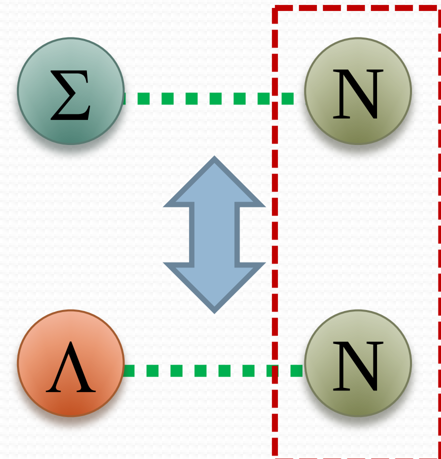


Studies are in progress

ΛN interaction in n-rich Λ hypernuclei

- Large contribution of ΛN-ΣN mixing is expected
  - B.F. Gibson et al. PR C6 (1972) 741





Large overlap in nucleon part if N≠Z ($I_{core} \neq 0$)
Pauli blocking may be small

How large ΛN-ΣN mixing in neutron-rich Λ hypernuclei?

DCX: (π^-,K^+)
NCX: (π^+,K^+) for $^{12}{}_{\Lambda}C$

Recent status of studies by DCX (1)

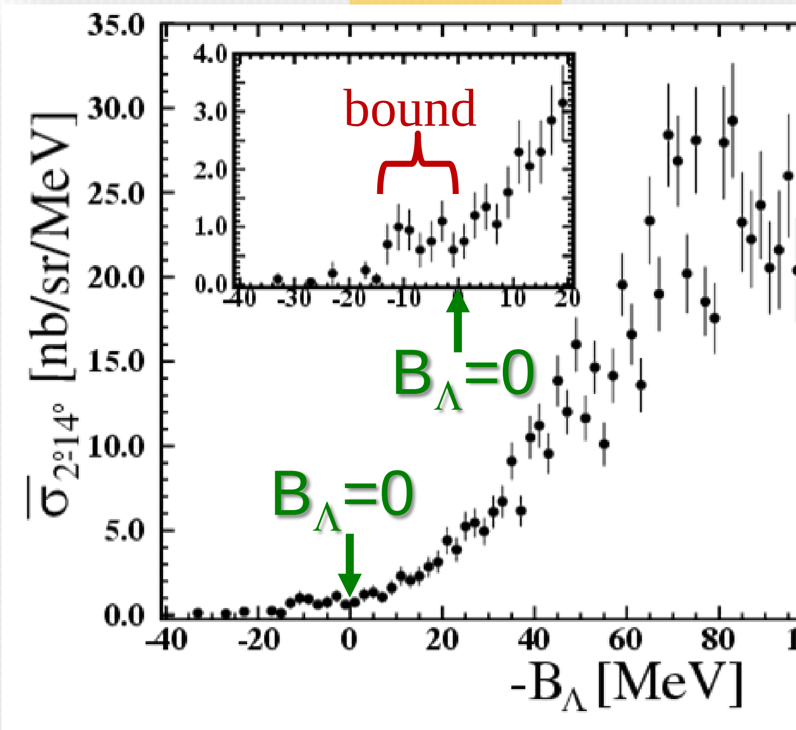
- **KEK E521**: P.K. Saha et al. PRL 94 (2005) 052501
  - Study of the $^{10}B(\pi^-,K^+)$ reaction
    - Successfully produced $^{10}{}_{\Lambda}Li$
    - Almost background free
  - Promising production method
    - Employed in J-PARC E10
  - Tiny production cross section

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX},{}^{10}_{\Lambda}\mathrm{Li}) \approx 10\mathrm{nb/sr}$$

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}) \Big/ \frac{d\sigma}{d\Omega}(\mathrm{NCX}) \approx 10^{-3}$$

- High-intensity pion beams are necessary

$^{10}B(\pi^-,K^+)^{10}_{\Lambda}Li$



Reaction mechanism of (π^-,K$^+$) reaction

- The (π^-,K$^+$) reaction basically has two-step nature
  - 2 nucleons participate in the elementary process

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

- Two possible reaction mechanisms
  - Simple two-step process
    - Sequential single charge-exchange reactions

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

  - "Single-step" process by ΛN-ΣN mixing

$$\pi^- pp \to K^+ \Sigma^- p \Leftrightarrow K^+ \Lambda n$$

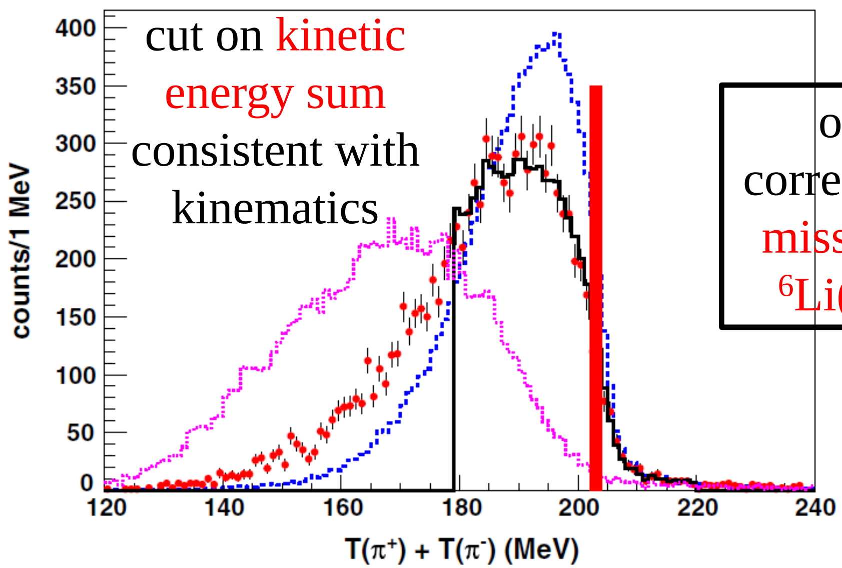
- ΛN-ΣN mixing appears also in reaction mechanism
  - KEK-E521 data favors "single-step" at least for $^{10}{}_{\Lambda}$Li

DCX: (K^-_{stop},π^+)
NCX: (K^-_{stop},π^-) for $^{12}{}_{\Lambda}C$

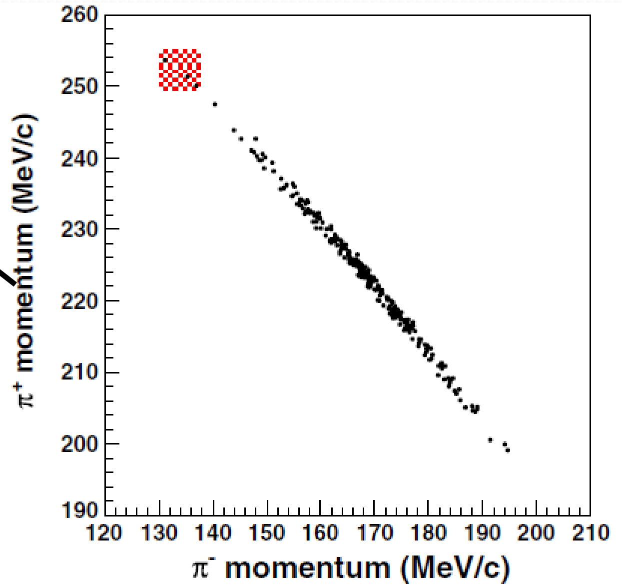
Recent status of studies by DCX (2)

- **FINUDA**: M. Agnello et al. PRL 108 (2012) 042501
  - Study of the $^{6}Li(K^-_{stop},\pi^+\pi^-)$ reaction

$$^{6}\mathrm{Li}(K^-_{\mathrm{stop}},\pi^+)^{6}_{\Lambda}\mathrm{H} \qquad ^{6}_{\Lambda}\mathrm{H}\to{}^{6}\mathrm{He}+\pi^-$$



one to one correspondence to missing-mass of $^{6}Li(K^-_{stop},\pi^+)X$

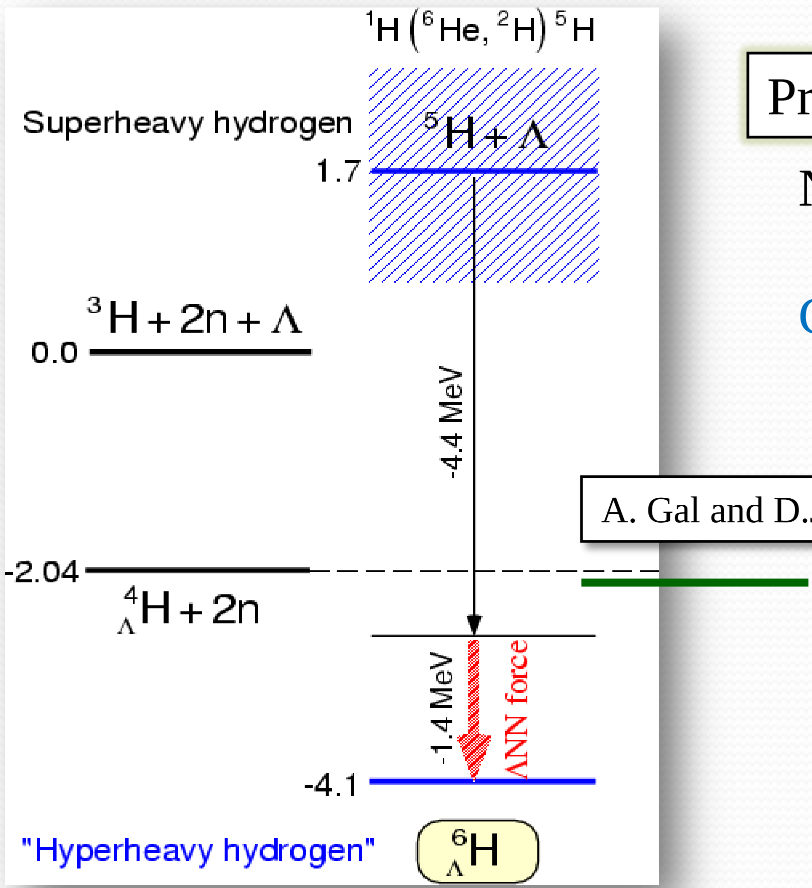


  - Reported 3 candidate events of $^{6}{}_{\Lambda}H$ production

$$\mathrm{BR}(\mathrm{DCX},{}^{6}_{\Lambda}\mathrm{H})/\mathrm{BR}(\mathrm{NCX}) \approx 2\times10^{-3}/\mathrm{event}$$

${}^{6}_{\Lambda}$H hypernucleus and ΛN-ΣN mixing

- Possible observation of mixing effect in ${}^{6}_{\Lambda}$H structure



Y. Akaishi and T. Yamazaki, Frascati Phys. Ser. XVI (1999) 59

Prediction of Akaishi and Yamazaki

Normal ΛN interaction (glue-like role)
$B_{\Lambda} \sim 4.4$ MeV

Coherent ΛN-ΣN mixing (3-body int.)
$B_{\Lambda} \sim 4.4 + 1.4$ MeV

A. Gal and D.J. Millener, Phys. Lett. B 725 (2013) 445

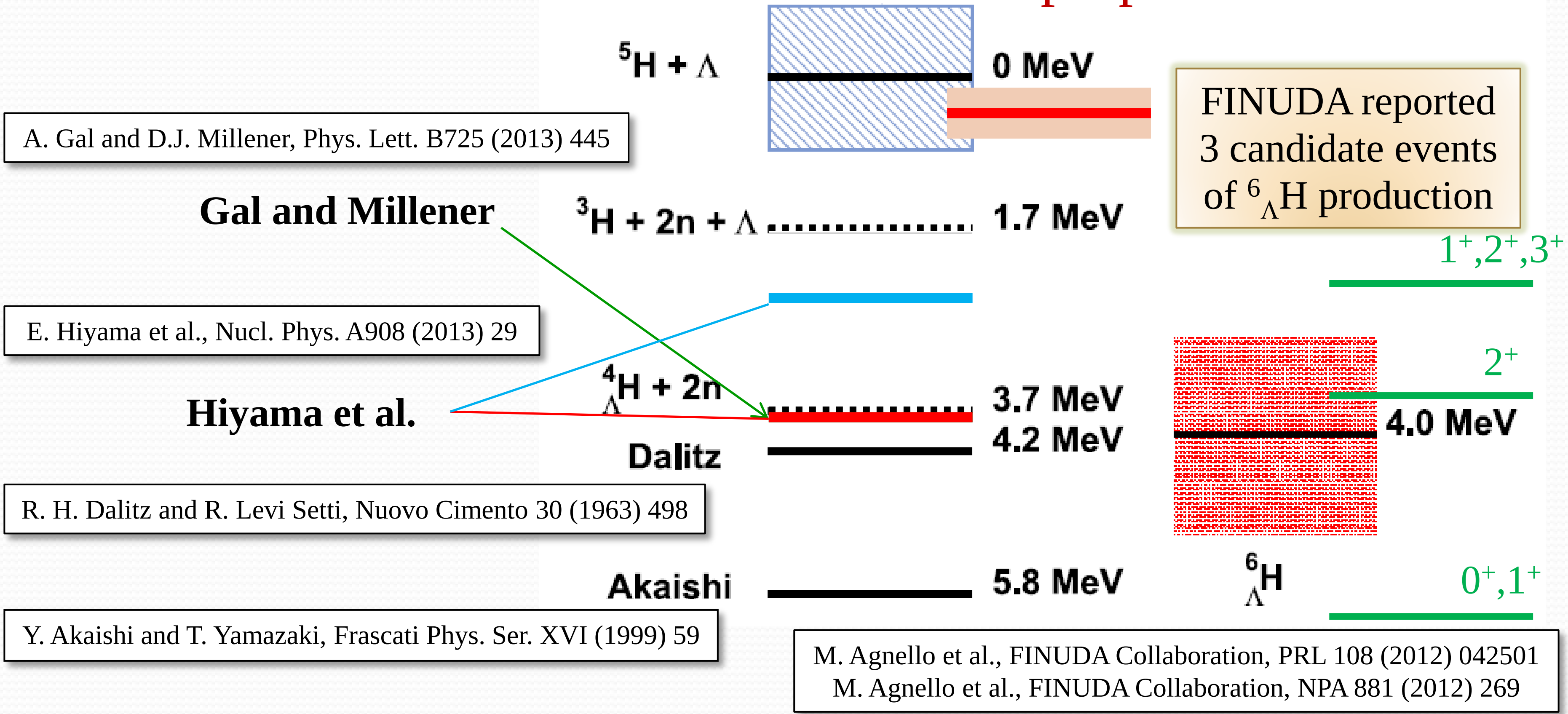
Prediction of Gal and Millener

Coherent ΛN-ΣN mixing
$\Delta B_{\Lambda N\text{-}\Sigma N} \sim 0.1$ MeV

Structure of ${}^{6}_{\Lambda}$H should be investigated experimentally

Possible structure of $^{6}_{\Lambda}$H hypernucleus

- FINUDA reported 3 candidate events of $^{6}_{\Lambda}$H production
- Sensitive to ΛN interaction and also properties of ^{5}H



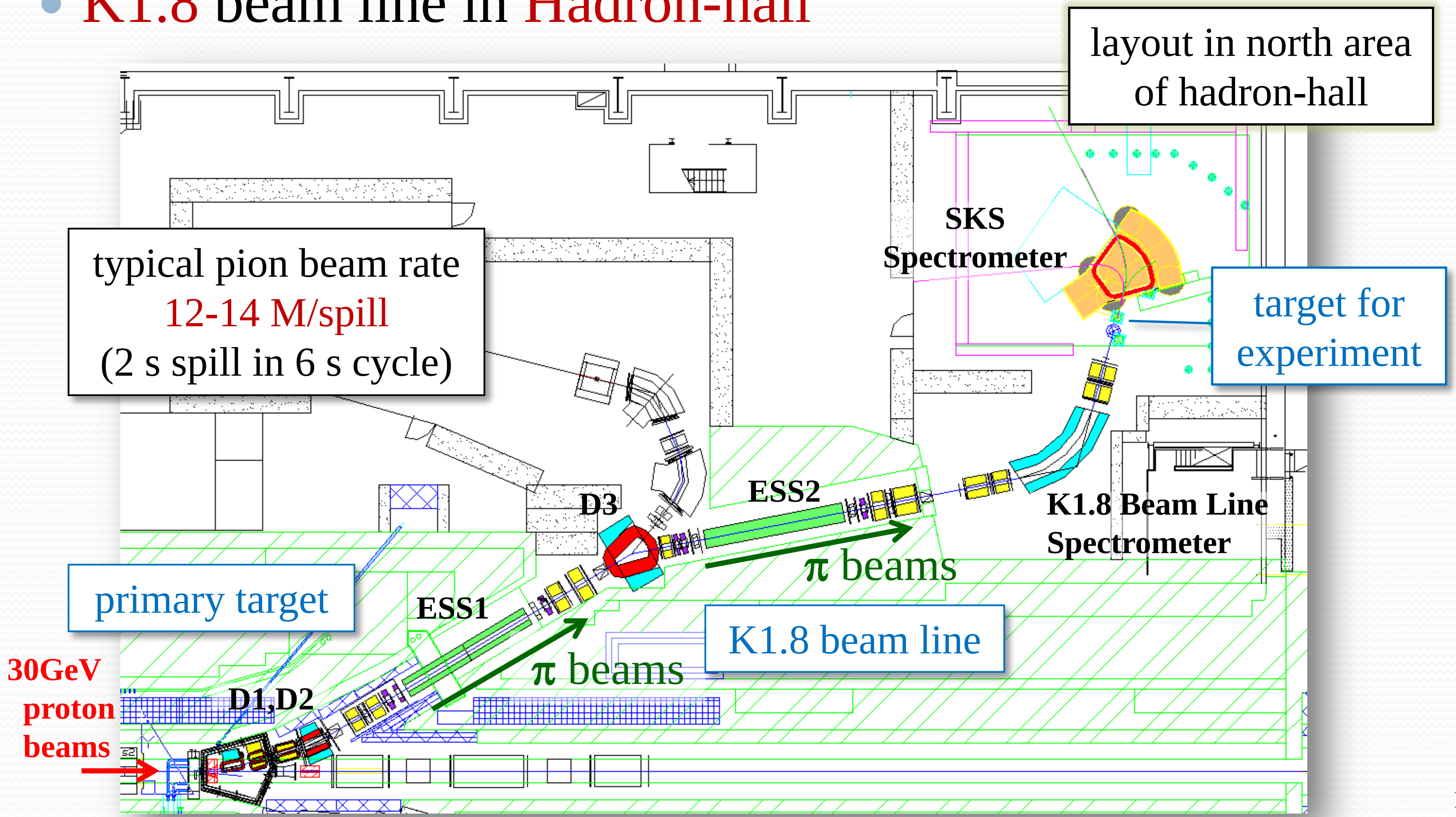
FINUDA data still have ambiguities. Complementary measurement is necessary.

Aims of J-PARC E10 experiment

- **Aim 1**: Λ hypernuclei close to the neutron drip-line
  - E10 may produce highly neutron-rich Λ hypernuclei
    - $^{6}_{\Lambda}H$ (1p, 4n and 1Λ), $^{9}_{\Lambda}He$ (2p, 6n and 1Λ)
    - Exotic hypernuclei we have never seen clearly
  - Glue-like role of Λ hyperon is critical in such loosely bound hypernuclei
- **Aim 2**: ΛN interaction at the extreme condition
  - Effect of ΛN-ΣN mixing may be observed in structures of neutron-rich hypernuclei
    - Neutron-rich Λ hypernuclei are good laboratories to study these effects
- Search for $^{6}_{\Lambda}H$ was performed as phase-1 of J-PARC E10

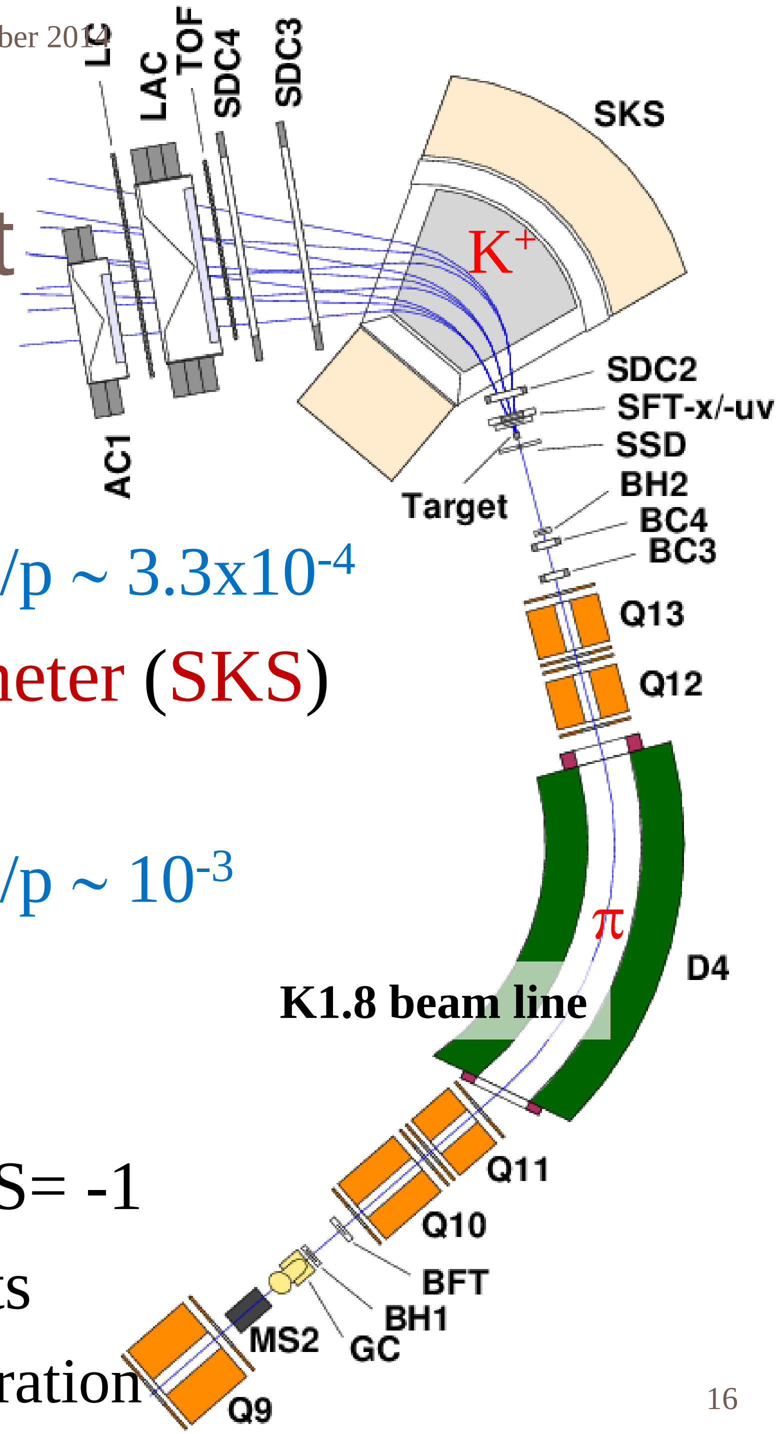
Phase-1 of J-PARC E10 Experiment

- Location in J-PARC 50GeV PS
  - K1.8 beam line in Hadron-hall



Setup of E10 experiment

- K1.8 beam line spectrometer
  - Selected 1.2 GeV/c pion beams
  - Good momentum resolution: dp/p ~ 3.3×10^{-4}
- Superconducting Kaon spectrometer (SKS)
  - 0.9 GeV/c K^+ was produced
  - Good momentum resolution: dp/p ~ 10^{-3}
  - Large acceptance: dΩ ~100 msr
- Missing-mass spectroscopy
  - ^{6}Li (π^-,K^+)X, X has Z=1, A=6, S= -1
  - Search for $^6_\Lambda$H production events
    - $\Sigma^\pm$ and $^{12}_\Lambda$C production for calibration



Run conditions proposed and achieved

- High intensity pion beams to override tiny cross section
- Obtained 50% of requested beamtime

E10 proposal

Run conditions	Values
Pion beam momentum	1.2 GeV/c
Pion beam intensity	10M/spill
Beamtime for production run	500 hours
Total number of pions	3T pions
Target thickness (^{6}Li)	3.5 g/cm^2
DCX cross section (assumed)	10 nb/sr
SKS acceptance	100 msr
K decay loss	0.5
Analysis efficiency	0.5
Estimated $^{6}_{\Lambda}$H yield	265

E10 achievements

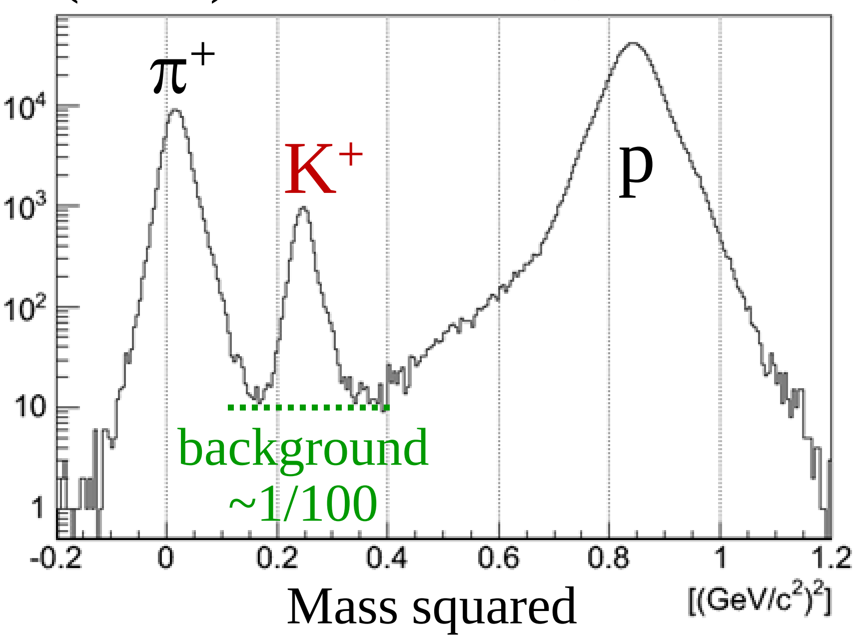
Values
1.2 GeV/c
12-14M/spill
240 hours
1.4T pions
3.5 g/cm^2
10 nb/sr
100 msr
0.5
0.3
90

Sensitivity
~ 0.1 nb/sr

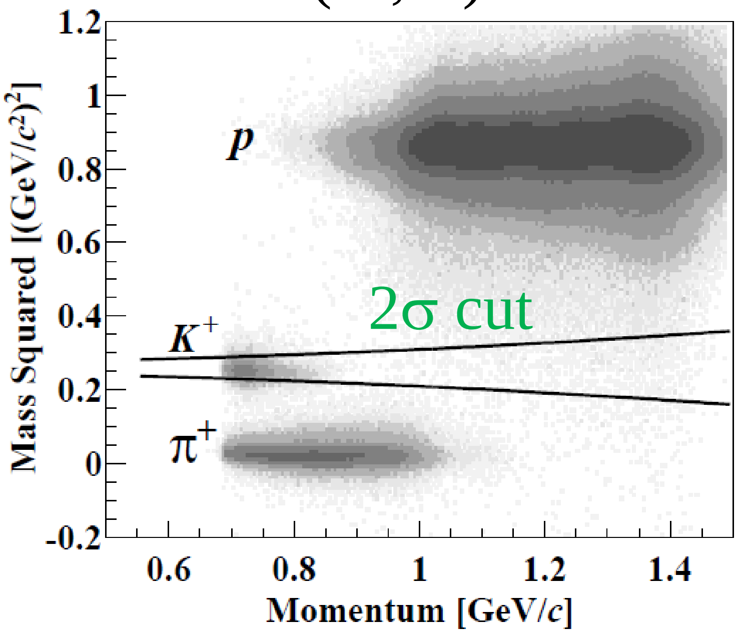
Particle identification (PID) of produced K^+

- Important for DCX to see small cross section
  - No physical background, source of BG is miss-PID
  - Background level at kaon peak ~ 1/100
  - Tight (2σ) and momentum dependent cut for K^+

$^6Li(\pi^-,h^+)X$ (π^-,K^+) trigger, p<1.1GeV/c



$^6Li(\pi^-,h^+)X$

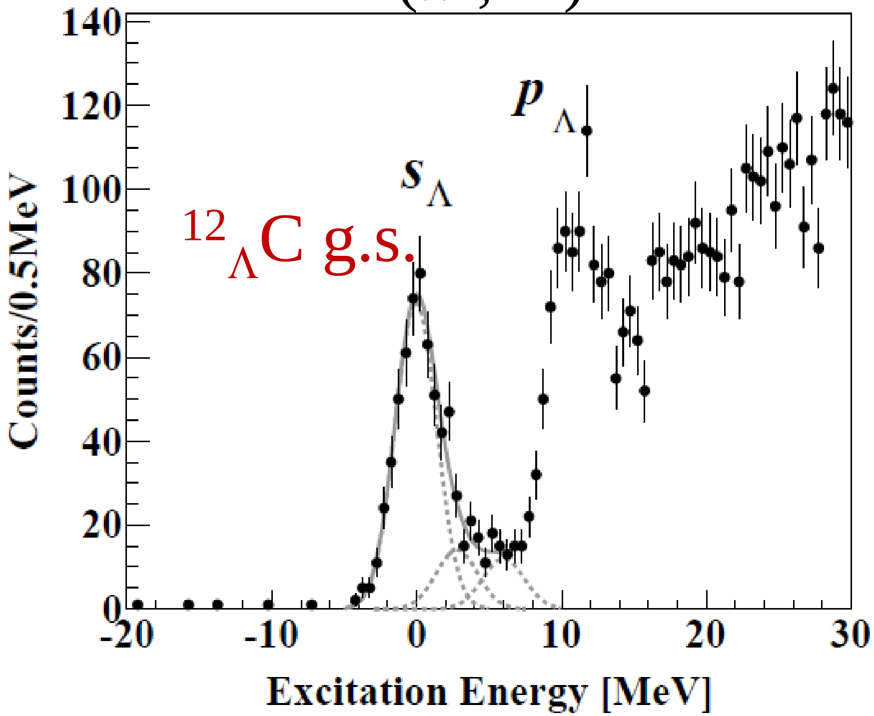


Missing-mass resolution

- Resolution of ΔM_X(=$\Delta Ex/c^2$) was estimated by $^{12}_{\Lambda}C$
  - NCX reaction on C (graphite) target at p_π=1.2GeV/c
  - Estimated resolution was ΔEx=3.2MeV (FWHM)

good enough to see states in $^{6}_{\Lambda}H$

$^{12}C(\pi^+,K^+)X$



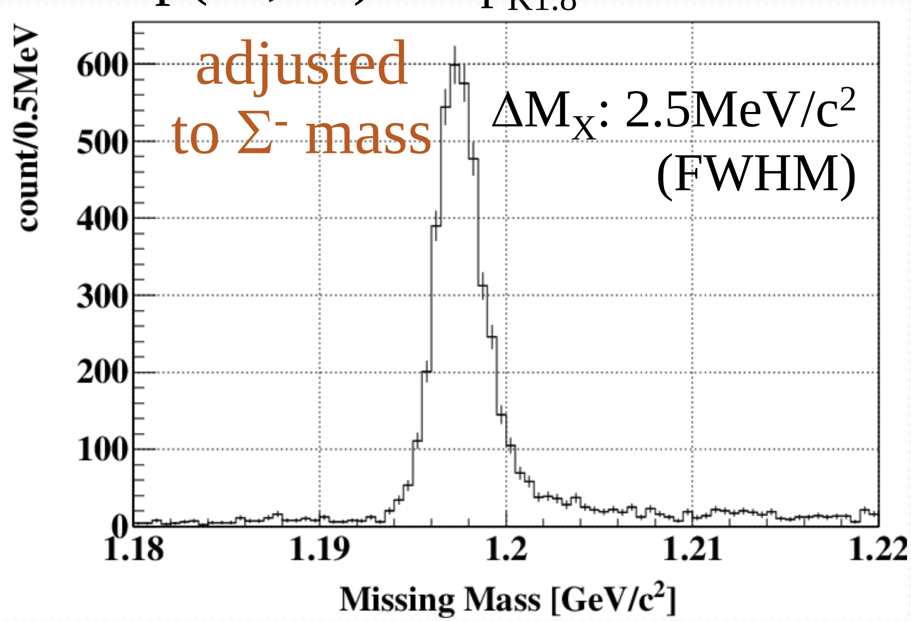
3 Gaussian functions
Known low-lying states
Ex = 0 MeV
Ex = 2.833 MeV
Ex = 6.050 MeV
Common width

Calibration of spectrometers

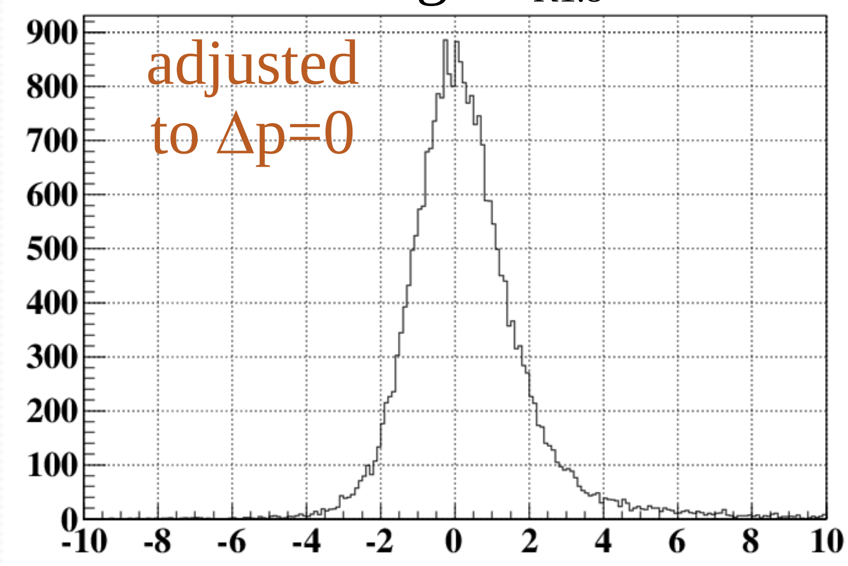
- Momentum calibration of spectrometer was done by
  - $\Sigma^{\pm}$ production reactions at 1.37 GeV/c
  - Beam through run at 0.9 GeV/c
  - Systematic error of momentum 1.34MeV/c

} momenta in SKS ~0.9 GeV/c

$p(\pi^-,K^+)\Sigma^-$ $p_{K1.8}$=1.37 GeV/c



π^+ beam through $p_{K1.8}$=0.9 GeV/c



$\Delta p = p_{K1.8} - p_{SKS}$ [MeV/c]

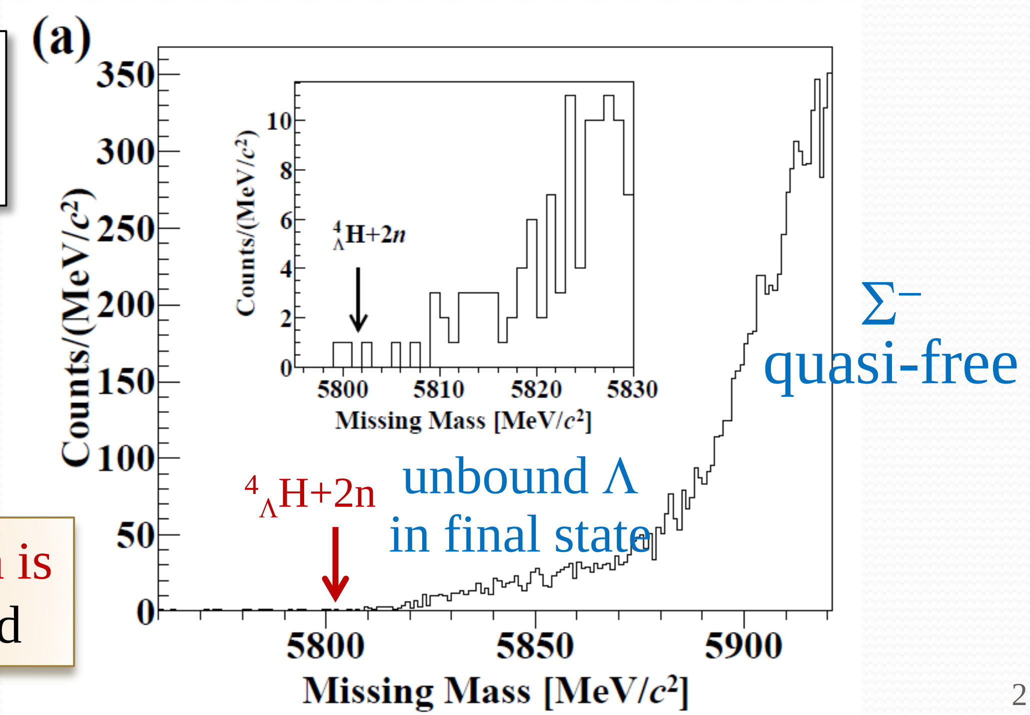
Results of $^{6}_{\Lambda}$H search

- Missing-mass spectrum of the ^{6}Li(π^{-},K^{+})X reaction
  - Systematic error of missing-mass 1.26 MeV/c^2
  - Tentative angle cut was made: 2-14 degrees
    - Same as KEK-E521 and SKS acceptance is well known

^{6}Li(π^{-},K^{+})X
θ_{LAB}=2-14 deg.

We saw no clear peak of $^{6}_{\Lambda}$H production in threshold region

At least we have to say cross section is extremely smaller than we expected



Results of $^{6}_{\Lambda}$H search

- Estimation of upper-limit of production cross section
  - Calculation of double differential cross section

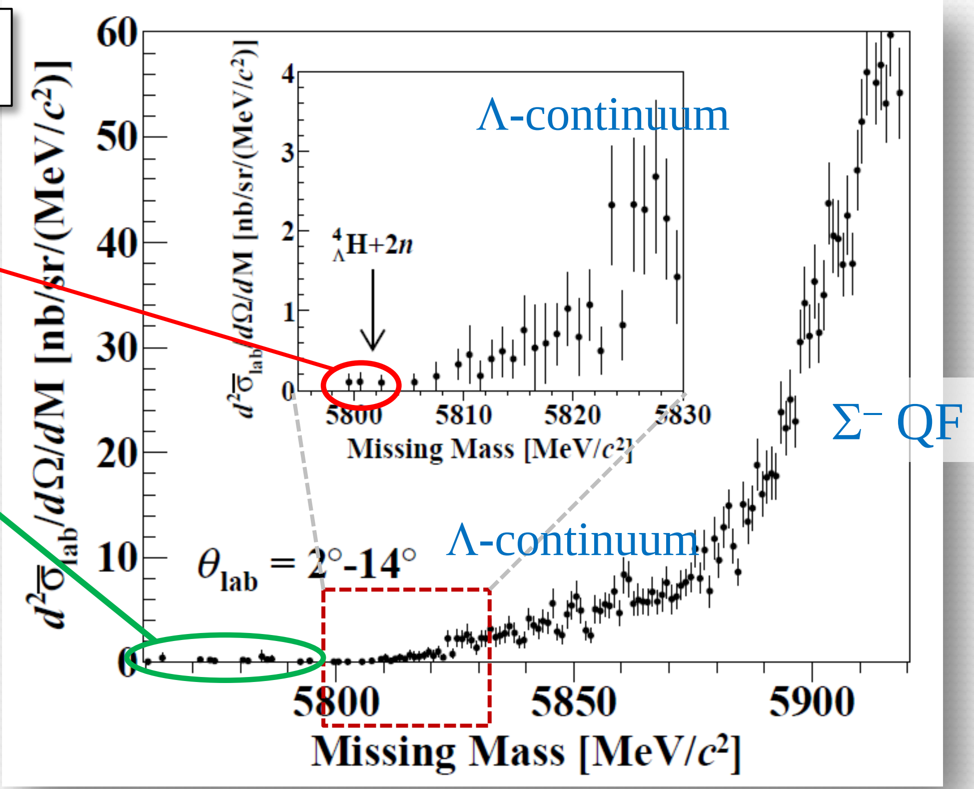
^{6}Li(π^{-},K^{+})X

3 events around $^{4}_{\Lambda}$H+2n threshold

Background due to miss-PID
0.39±0.05 event/(MeV/c^{2})

Expected number of background is ~2 events

1 event ~ 0.18 nb/sr



- $d\sigma_{2^\circ\text{-}14^\circ}/d\Omega$ <1.2 nb/sr (90% confidence level)

Possible interpretations of results

- Small cross section come from reaction mechanism?
  - Spin-flip amplitude is vanishing in the (π^-, K^+) reaction?
    - Transition from $^6Li(1^+)$ to $^6_\Lambda H(0^+)$ needs spin-flip
    - But, transition to $^6_\Lambda H^*(1^+)$ is possible without spin-flip. Why no population of 1^+ state?
  - Very small ΛN-ΣN mixing for $^6_\Lambda H$?
    - Population of $^6_\Lambda H(0^+)$ and $^6_\Lambda H^*(1^+)$ is sensitive to mixing
- Structure of $^6_\Lambda H$?
  - Core nucleus ^5H may affect largely to $^6_\Lambda H$ structure
- Smallness of cross section is not easy to understand
  - Information of other hypernuclei ($^9_\Lambda He$ etc.) necessary

Study of unbound Λ production

- DCX reaction has two-step nature in Λ production
  - "Single-step" looks dominant in the (π^-,K^+) reaction

$$\pi^- pp \to K^+ \Sigma^- p \Leftrightarrow K^+ \Lambda n$$

  - Unbound Λ production may be treated in same manner
    - Information of coupling between ΛN and ΣN channels
- Theoretical framework
  - Description of the $\pi^- pp \to K^+\Sigma^-(\Lambda)N$ reaction by Green's function method
  - Model parameters are U_Σ (real) and iW_Σ (imaginary)
  - Made comparison of missing-mass spectra

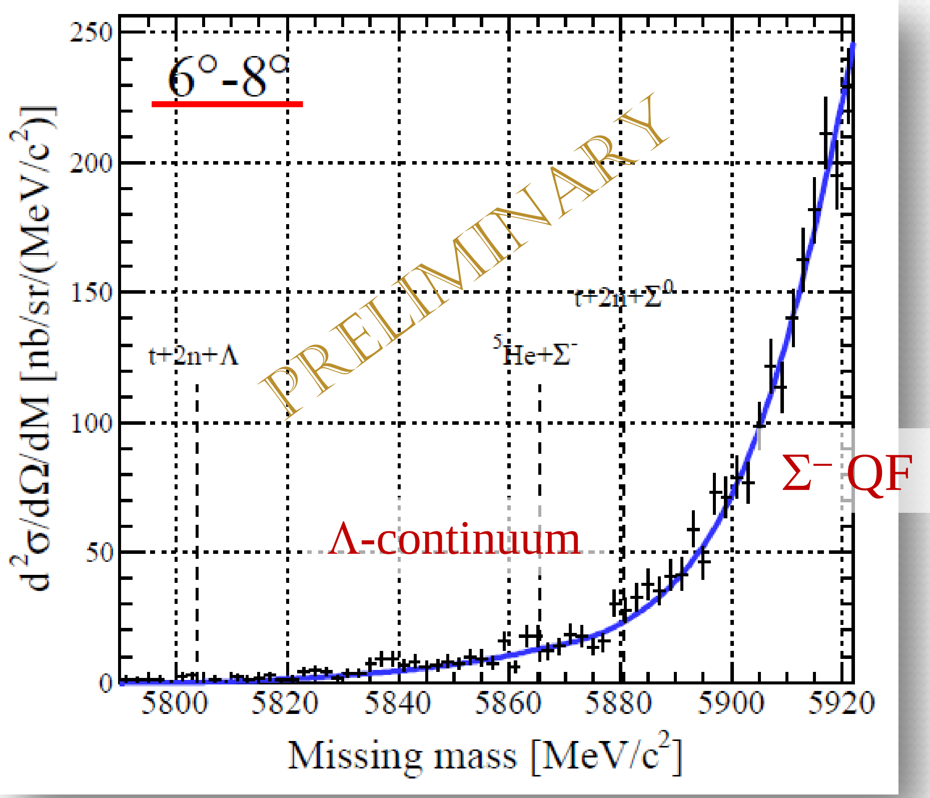
Study of unbound Λ production

- Simultaneous reproduction of Λ-continuum and Σ-QF
  - Missing-mass spectrum was reproduced well
  - This type of comparison can be made angle by angle

Analysis is still in progress

Information of U_{Σ} and W_{Σ}

Consistent picture of ${}^{6}_{\Lambda}H$, unbound-Λ and quasi-free Σ production reactions



Summary

- Study of Λ hypernuclei close to neutron drip-line
  - Glue-like effect may extend boundary of stability
  - ΛN-ΣN mixing and neutron-rich hypernuclei
- Several studies by DCX reactions are in progress
- J-PARC E10 experiment
  - Search for ${}^{6}_{\Lambda}H$ was done as phase-1 of E10 experiment
    - Cross section was extremely small, $d\sigma/d\Omega < 1.2$ nb/sr
    - Several possible interpretations. Need further information.
  - Study of unbound-Λ production reaction
    - Reproduced by model calculation. Estimate U_Σ and W_Σ.
    - Consistent picture of ${}^{6}_{\Lambda}H$, unbound-Λ and Σ-QF reactions