Study on Λ-hypernuclei at J-PARC with intense pion beams

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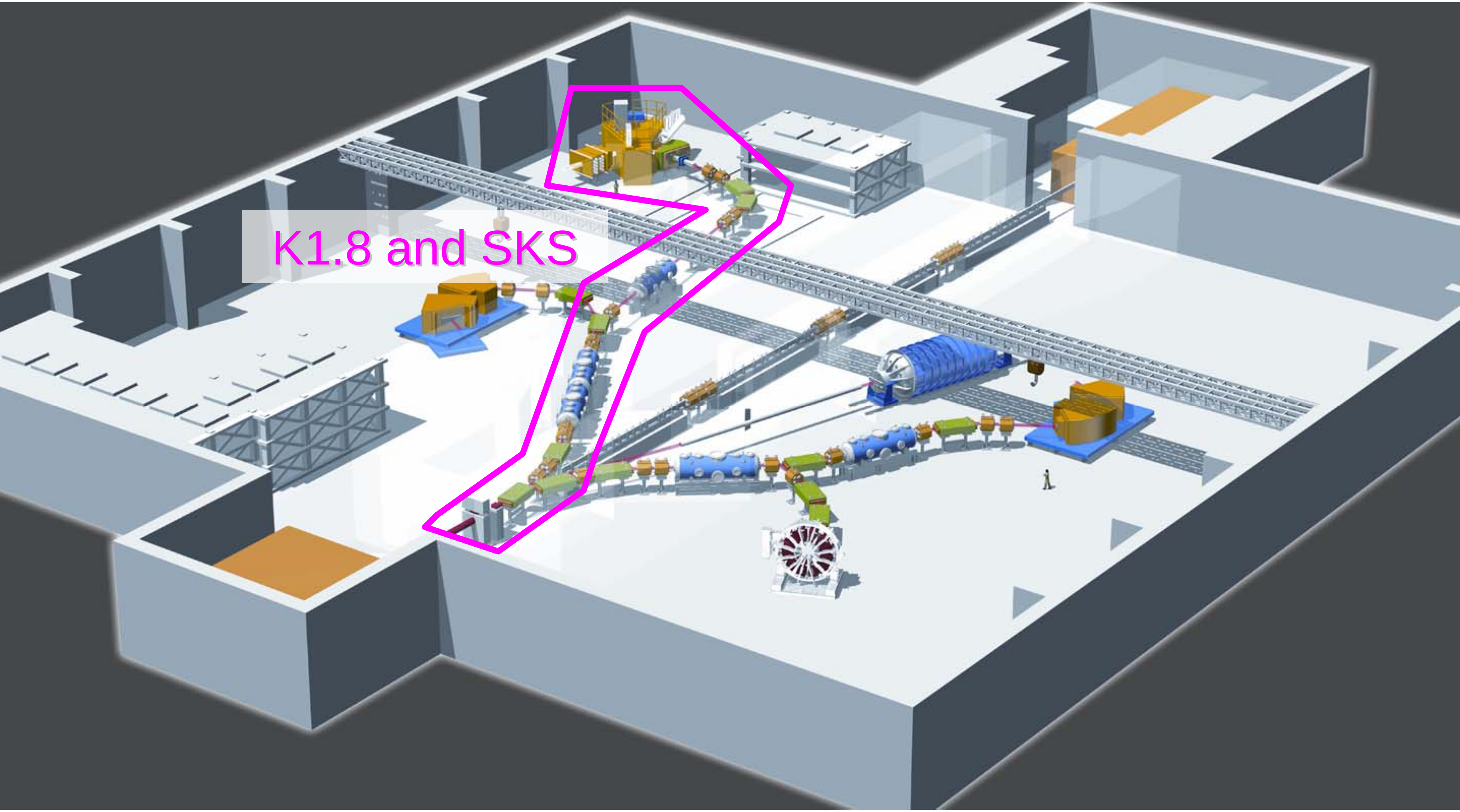
Collaboration

Motivation

- Intense kaon beams will be available
  - beam intensity is a few X 10^6 kaons/spill
    - with 30GeV, 9μA primary proton beams
- Provide us also very intense pion beams
  - roughly X1000 higher than kaons
    - a few X 10^7 pions/spill with conventional detectors
    - one order higher than experiments in the past
- experiments with intense pion beams
  - available even at the beginning of J-PARC

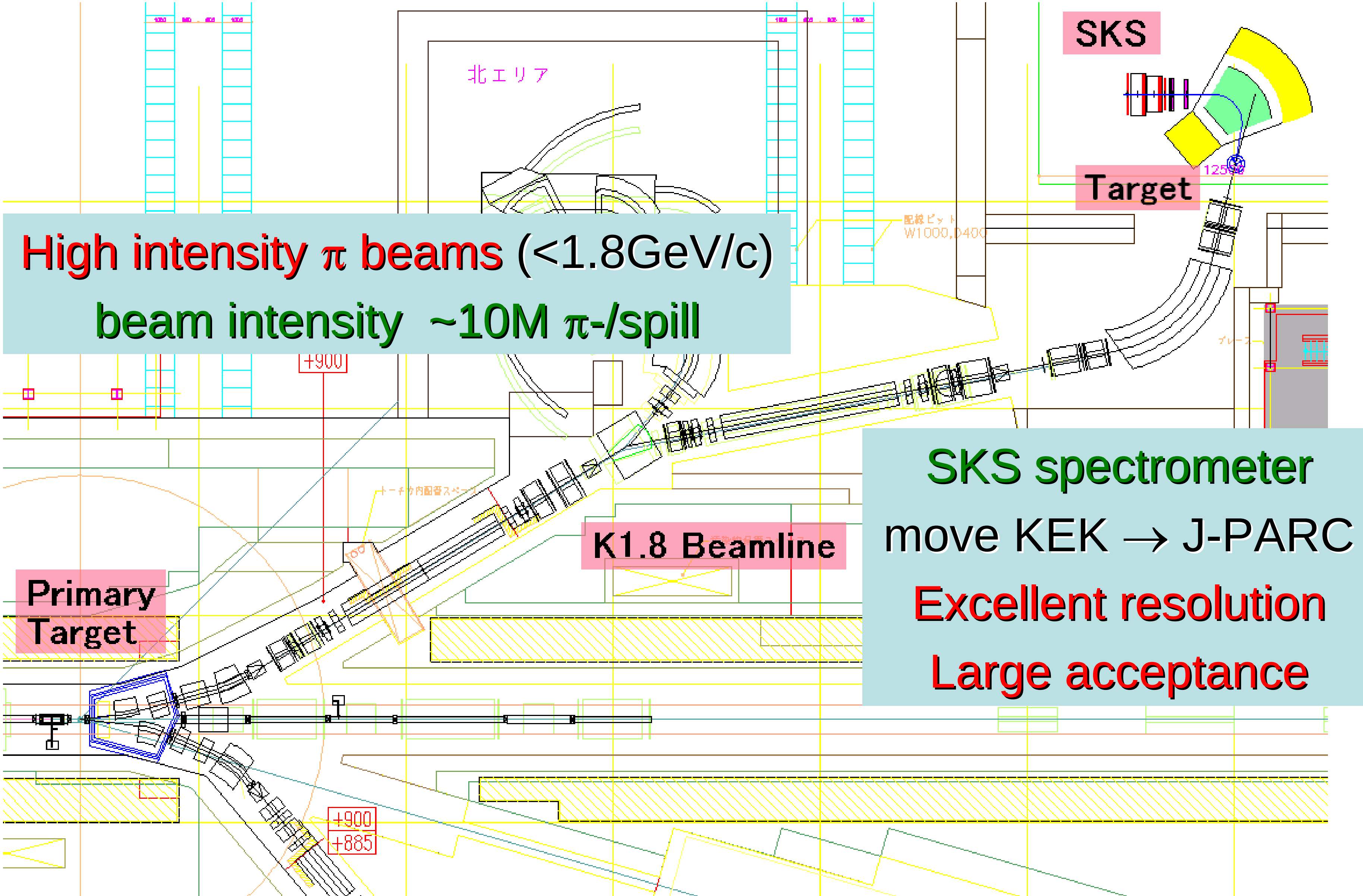
Hadron Experimental Hall



K1.8 beam line and SKS

High intensity π beams (<1.8GeV/c)

beam intensity ~10M π-/spill



SKS spectrometer

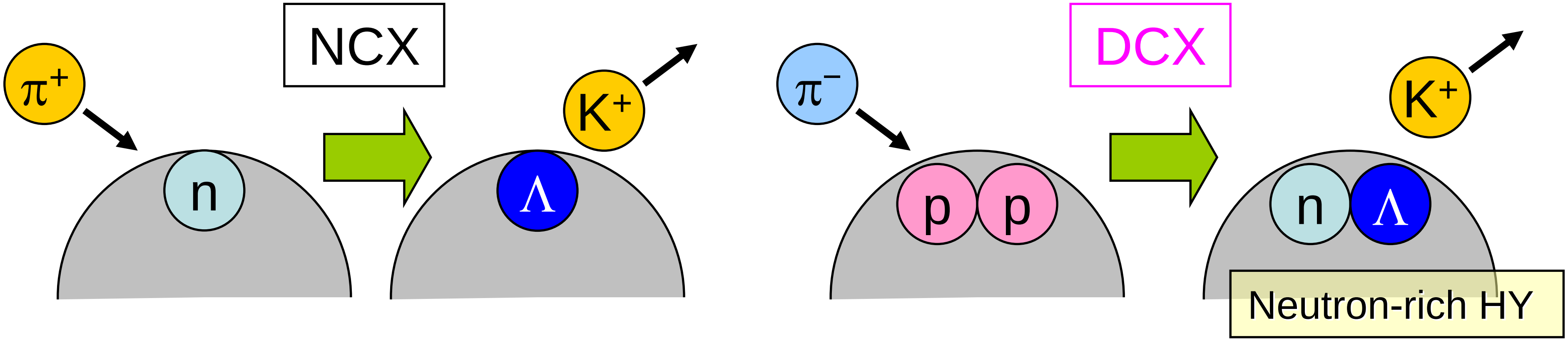
move KEK → J-PARC

Excellent resolution

Large acceptance

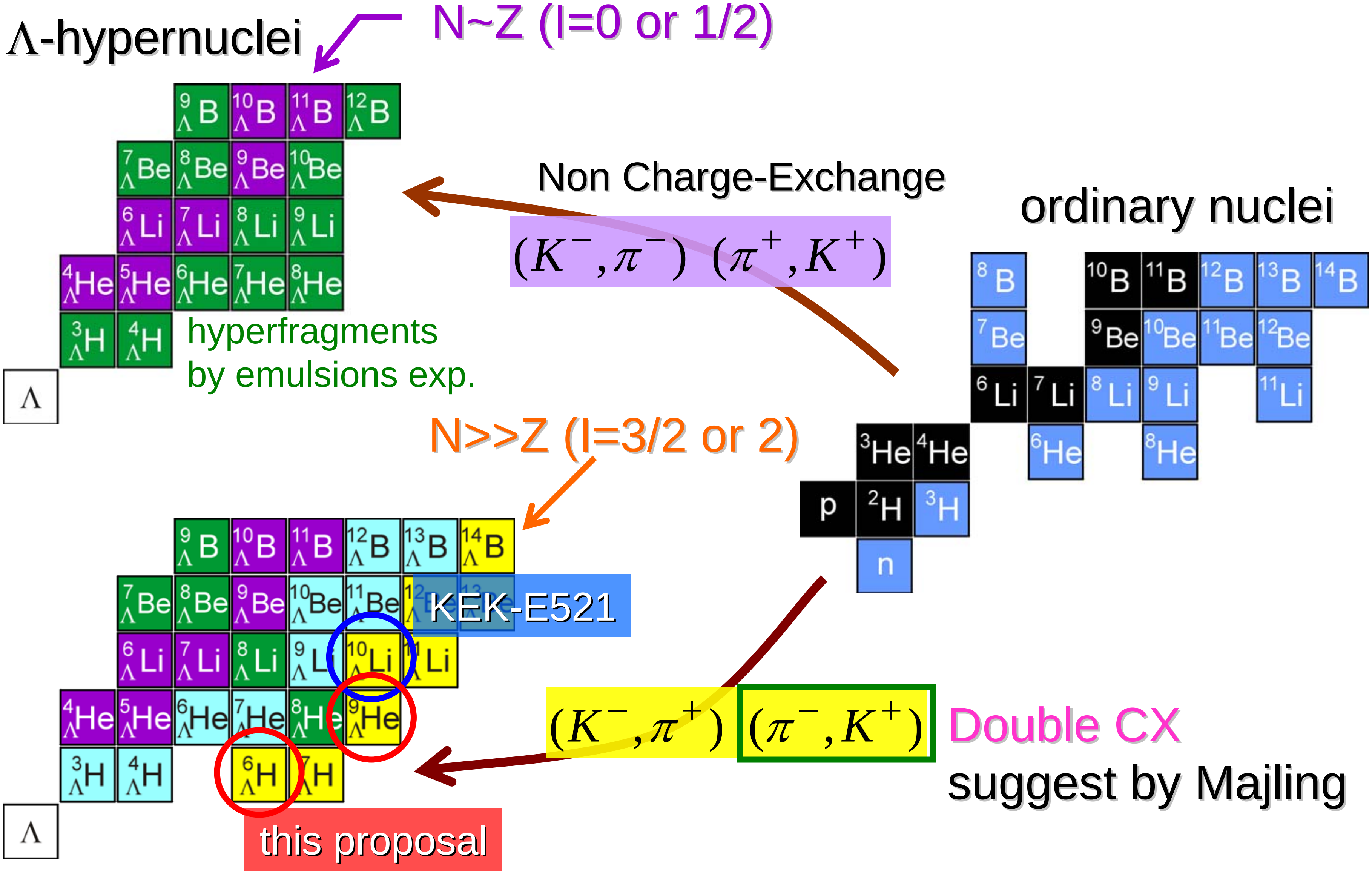
Proposing 2 experiments at J-PARC E10 and E22

- Production of neutron-rich hypernuclei
  - Double Charge-eXchange (DCX) reaction



- Study on non-mesonic weak decay
  - Weak decay of A=4 hypernuclei ($^{4}_{\Lambda}He$, $^{4}_{\Lambda}H$)
  - Precise determination of decay amplitudes

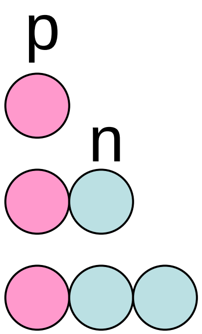
E10: Neutron-rich hypernuclei



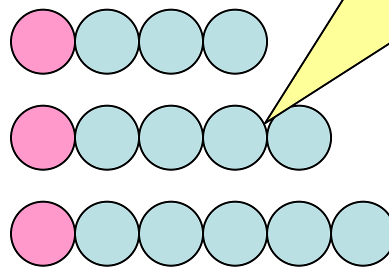
Exotic Λ-hypernuclei

- Example of “hydrogen”

Super Heavy Hydrogen

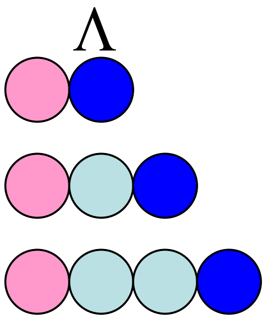


^{1}H	Stable
^{2}H	Stable
^{3}H	Stable

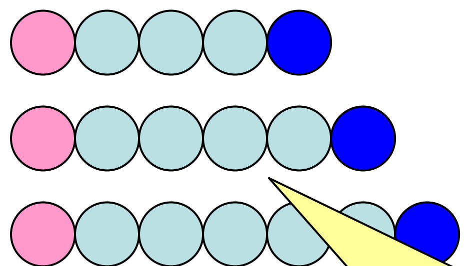


^{4}H	No evidence
^{5}H	Resonance
^{6}H	No evidence

glue like role of Λ



$^{2}_{\Lambda}$H	Not bound
$^{3}_{\Lambda}$H	Stable
$^{4}_{\Lambda}$H	Stable



$^{5}_{\Lambda}$H	No evidence
$^{6}_{\Lambda}$H	Stable ?
$^{7}_{\Lambda}$H	Stable ?

We can produce at J-PARC

Hyper Heavy Hydrogen

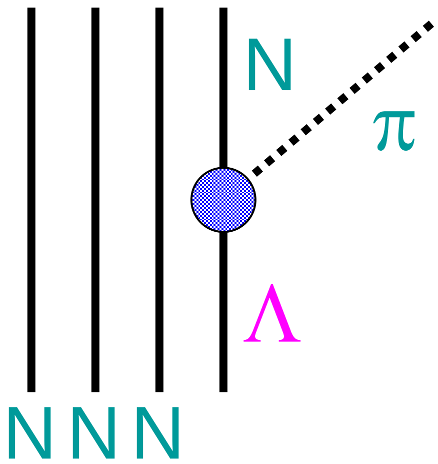
Yield estimation: $^{9}_{\Lambda}He$ production

– Cross section ~10nb/sr (1/1000 of NCX)
– Major difficulty in this experiment

Parameters	Values
π^- beam momentum	1.2 GeV/c
π^- beam intensity	1 x 10^7 /spill ← High intensity beams
PS acceleration cycle	3.4 s/spill
^{9}Be target thickness	3.5 g/cm^2
Reaction cross section	10 nb/sr
Spectrometer solid angle	0.1 sr ← Large acceptance
Spectrometer efficiency	0.5
Analysis efficiency	0.5

– 310 events in 3 weeks
  - 7 times larger ← KEK-E521 (47 events)
  - Discussion on level structure possible

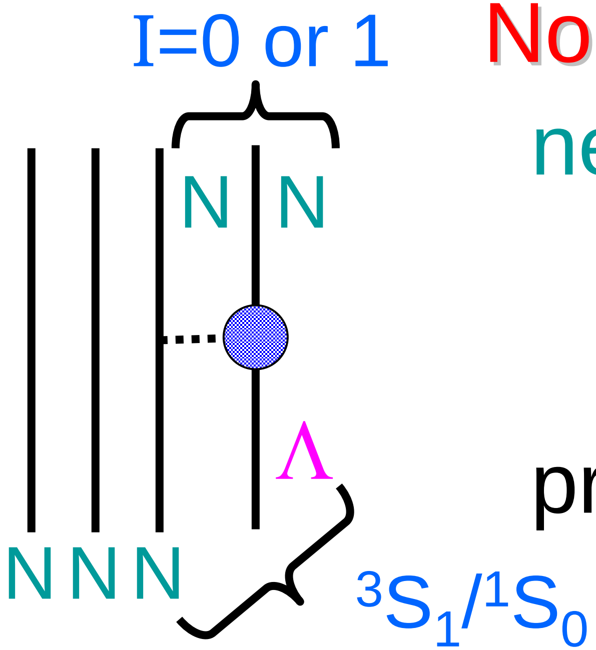
E22: Non-mesonic weak decay



Mesonic weak decay (MWD)

similar with free decay of Λ

properties are predictable



Non-Mesonic weak decay (NMWD)

new decay mode in hypernuclei

proton- and neutron-stimulated

$$\Lambda p \rightarrow np, \quad \Lambda n \rightarrow nn$$

properties are not well known yet

Decay amplitudes

- Block and Dalitz approach
  - Initial Λ-N in S-wave (s-shell hypernuclei)
  - Introduced 6 independent amplitudes (a ~ f)
    - Initial spin ($^1S_0$ or $^3S_1$)
    - Final isospin (0 or 1)
    - Parity change (yes or no)

spin isospin parity

Branching Ratios

Initial	Final	Matrix element	Rate	I_f	Parity change
$^1S_0$	$^1S_0$	a	a^2	1	no
	$^3P_0$	$\frac{b}{2}(\sigma_1 - \sigma_2)q$	b^2	1	yes
$^3S_1$	$^3S_1$	c	c^2	0	no
	$^3D_1$	$\frac{d}{2\sqrt{2}}S_{12}(q)$	d^2	0	no
	$^1P_1$	$\frac{\sqrt{3}}{2}e(\sigma_1 - \sigma_2)q$	e^2	0	yes
	$^3P_1$	$\frac{\sqrt{6}}{4}f(\sigma_1 + \sigma_2)q$	f^2	1	yes

$^1S_0(I=1)$ (rates a^2, b^2)

$^3S_1(I=0)$ (rates c^2, d^2, e^2)

$^3S_1(I=1)$ (rate f^2)

Status of amplitudes

Status of measurements

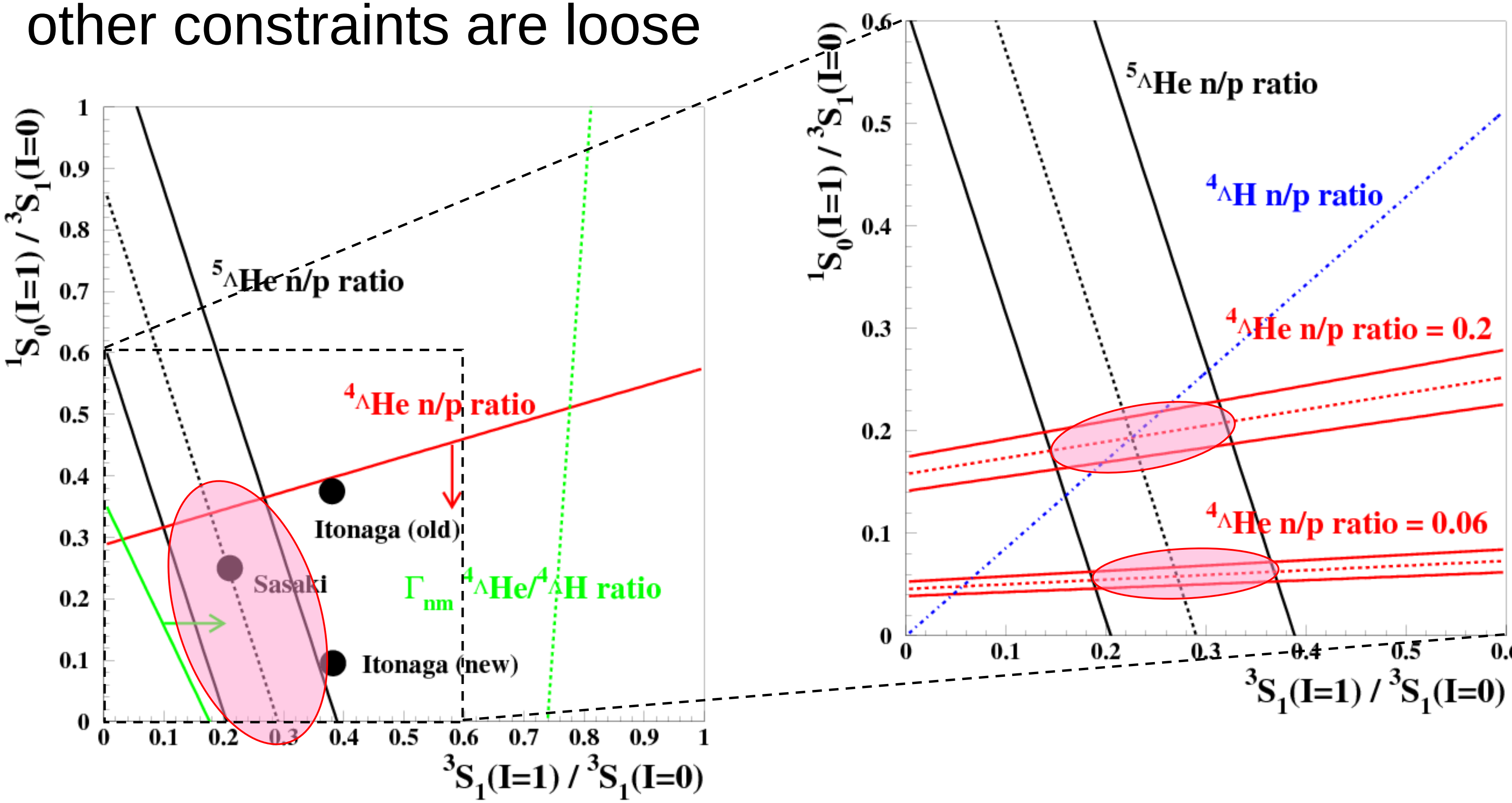
A=4 and 5 ($^4_\Lambda$H, $^4_\Lambda$He, $^5_\Lambda$He)

strong constraint from $^5_\Lambda$He

other constraints are loose

Our prospects

new measurement of $^4_\Lambda$He np-ratio with 15% accuracy



Estimation of $^{4}_{\Lambda}$He Yield

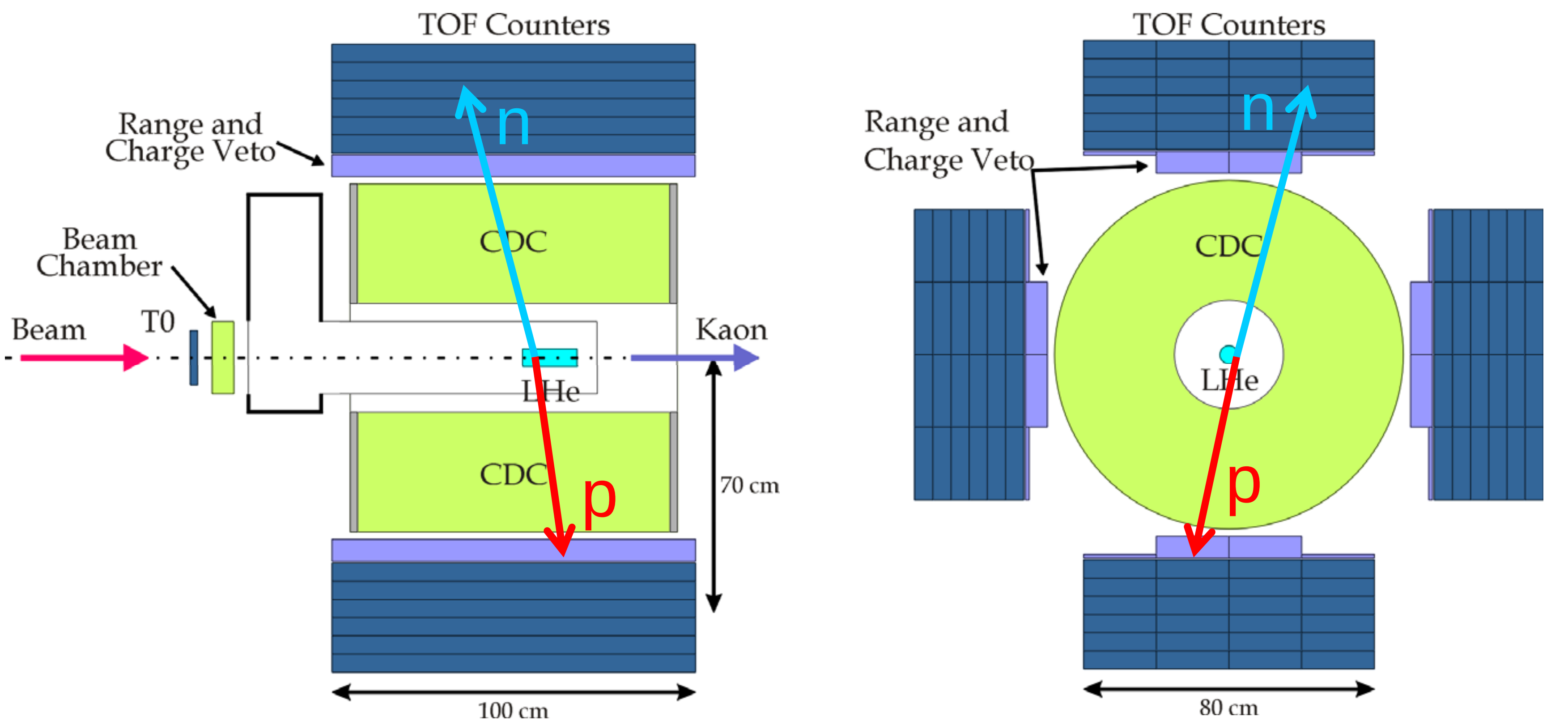
- Important factor in design of experiment
  - Tiny branching ratio of $\Lambda n \rightarrow nn$ channel
  - BR($^{4}_{\Lambda}$He,$\Lambda n \rightarrow nn$) ~ 0.01 (?)
  - BR($^{4}_{\Lambda}$He,$\Lambda p \rightarrow np$) = 0.16 ± 0.02

- Produce $^{4}_{\Lambda}$He as much as possible
  - use ^{4}He(π^{+},K^{+})$^{4}_{\Lambda}$He reaction ($d\sigma/d\Omega$~10μb/sr)
  - high intensity pion beams (K1.8 beam line)
  - large acceptance spectrometer (SKS)
- 19,000 $^{4}_{\Lambda}$He/day $\rightarrow$ 0.5M $^{4}_{\Lambda}$He in 4 weeks

Setup for decay measurement

– Large acceptance and high efficiency for NN

– Good PID capability (n/p/π/γ)



$\text{neutron}: \Omega/4\pi \approx 0.4,\ \varepsilon \approx 30\%$ $\text{proton}: \Omega/4\pi \approx 0.25,\ \varepsilon \approx 80\%$

Estimation of yield of NMWD

Parameters	Values
Acceptance for decay proton	0.25
Acceptance for decay neutron	0.4
Efficiency for proton	0.8
Efficiency for neutron	0.3
Branching ratio of $\Lambda p \rightarrow np$ process	0.01
Branching ratio of $\Lambda n \rightarrow nn$ process	0.1

large acceptance and high efficiency

- 1,300 $\Lambda p \rightarrow np$ and 75 $\Lambda n \rightarrow nn$ in 4 weeks
  in case of 10% BR — in case of 1% BR
- We can achieve 15% statistical error

Summary

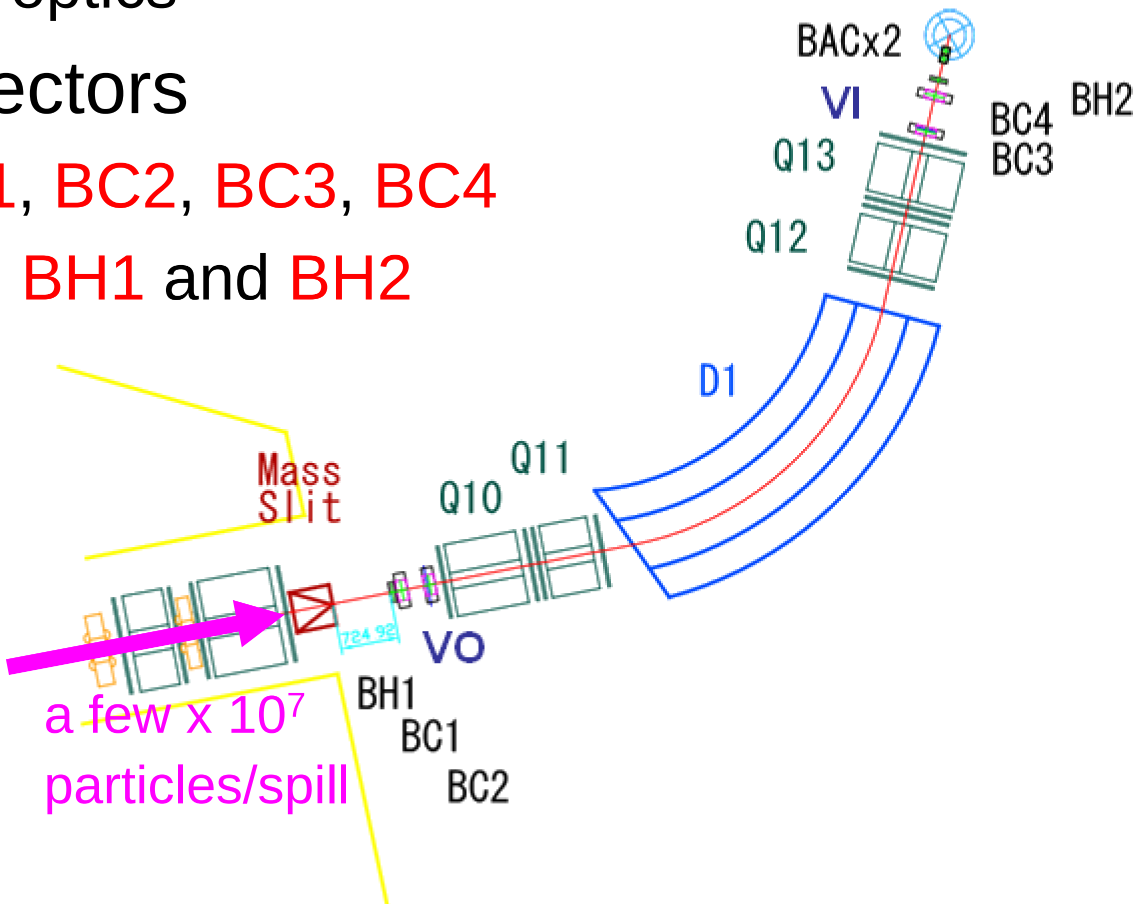
- Experiments with intense pion beams
  - Feasible even very early stage of Day-1
- Two experimental proposals
  - Production of neutron-rich hypernuclei
    - New neutron-rich hypernuclei ($^{9}_{\Lambda}He$ and $^{6}_{\Lambda}H$)
    - Information on ΛN interaction in n-rich hypernuclei
    - Production of exotic hypernucleus $^{6}_{\Lambda}H$
  - Study on non-mesonic weak decay
    - Detailed study on A=4 hypernuclei ($^{4}_{\Lambda}He$ and $^{4}_{\Lambda}H$)
    - Precise determination of decay amplitudes

Backup Slides

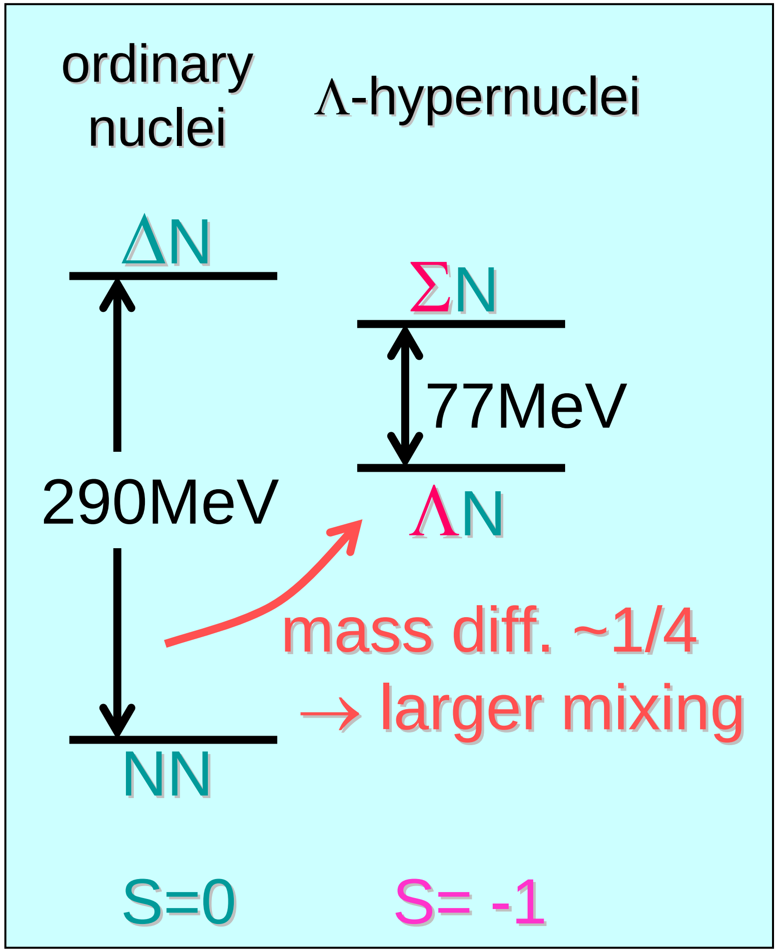
Beam Line Spectrometer

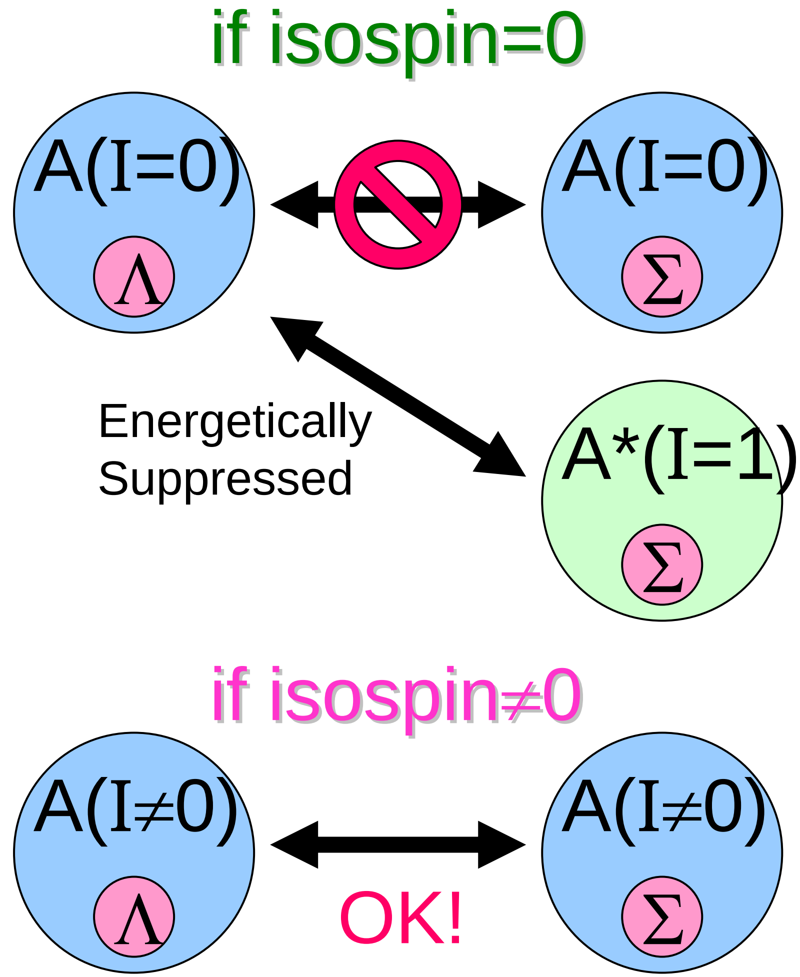
- Basic design
  - QQDQQ configuration
    - Point-to-point optics
  - Beam line detectors
    - Tracking: BC1, BC2, BC3, BC4
    - Time-of-flight: BH1 and BH2

E05 design	
BC1,BC2	1mm MWPC
BC3, BC4	3mm DC
BH1	11 segments
BH2	5 segments



ΛN-ΣN mixing effect

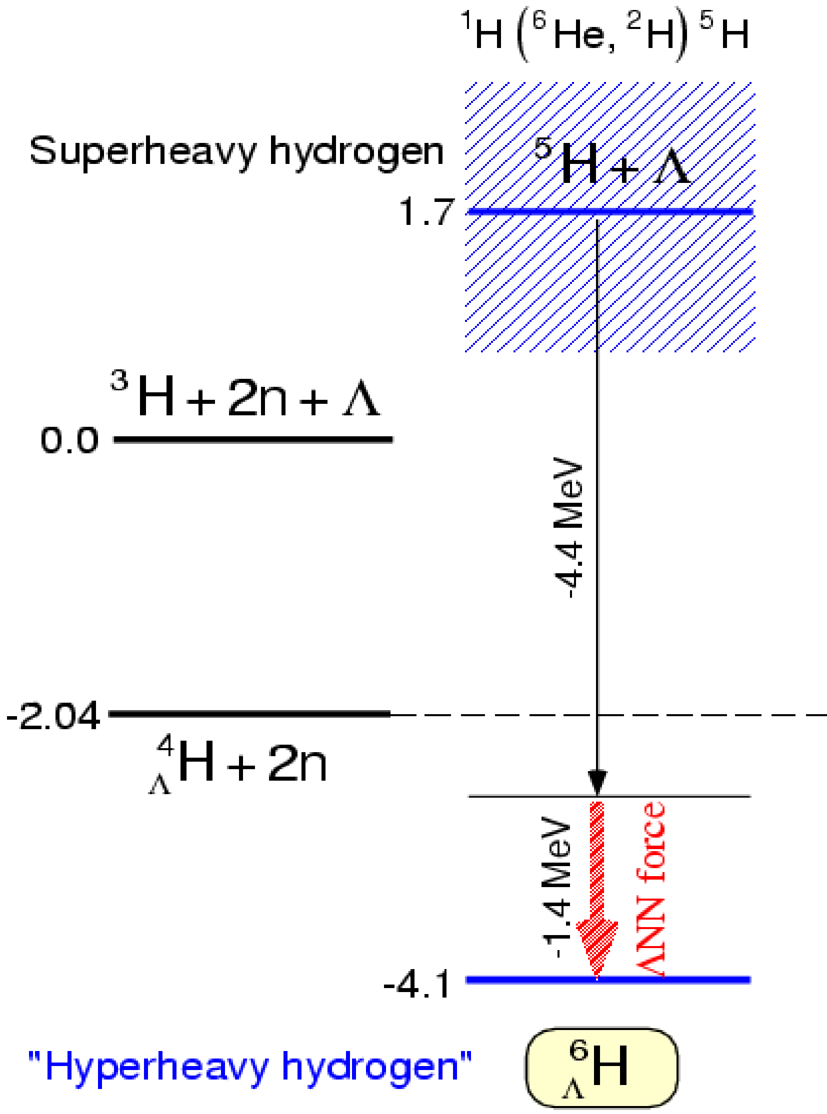




important in neutron-rich Λ-hypernuclei (large isospin)

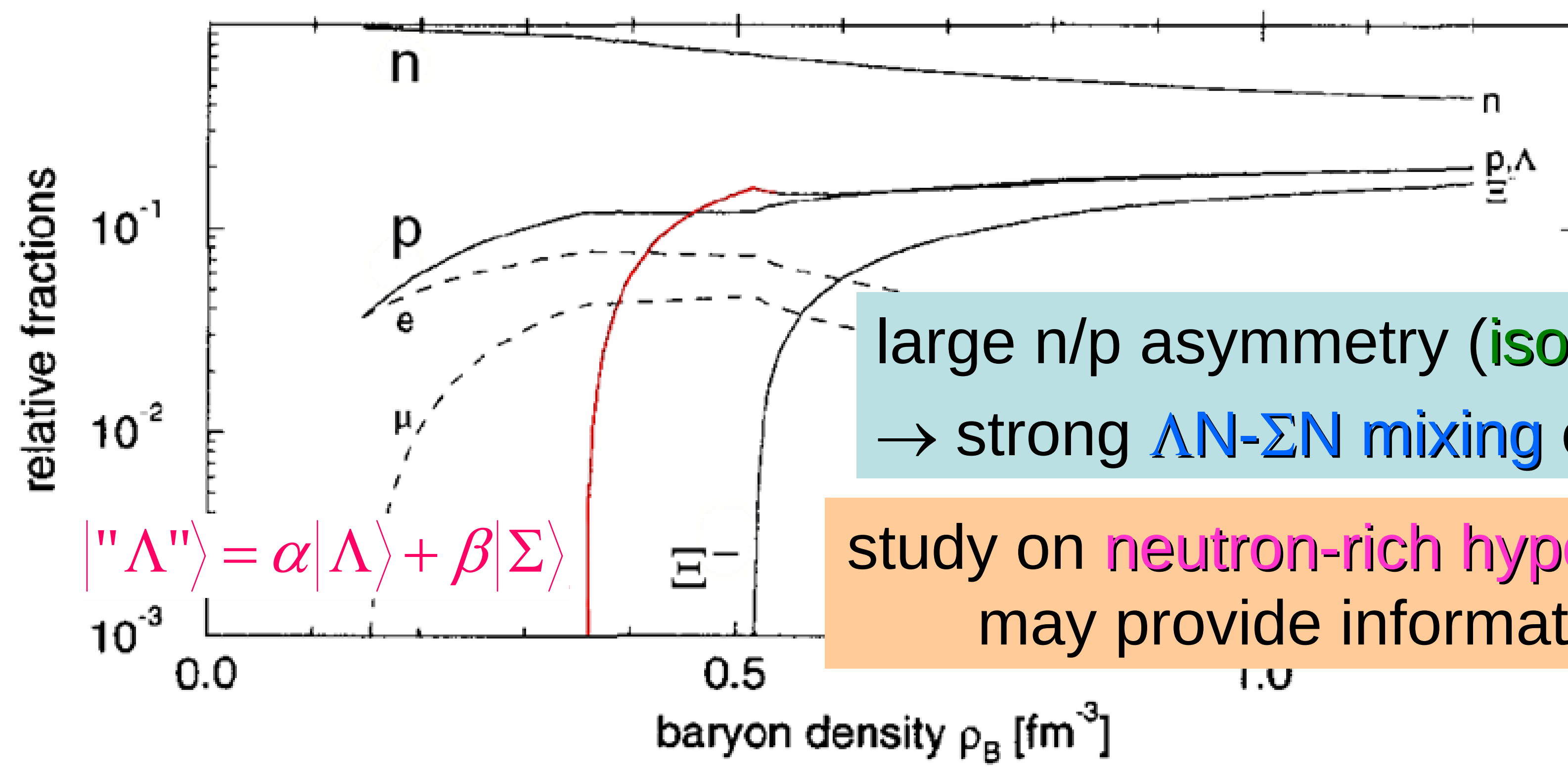
Structure of $^{6}_{\Lambda}H$ hypernucleus

- Unbound ^{5}H
  - 1.7 MeV unbound
  - Exist as resonance
  - "Superheavy Hydrogen"
- Bound $^{6}_{\Lambda}H$?
  - glue-like role of Λ
  - B_{Λ}= 0.5~2 MeV ?
  - "Hyperheavy Hydrogen"



EoS of matter in neutron stars

- Strangeness degree of freedom inevitable
  – What kinds of strangeness appear ?
  – Controlled by mass, charge and interaction.



$$|"\Lambda"\rangle = \alpha|\Lambda\rangle + \beta|\Sigma\rangle$$

large n/p asymmetry (isospin≫1)
→ strong ΛN-ΣN mixing expected

study on neutron-rich hypernuclei may provide information

Production of n-rich Λ-hypernuclei

- KEK-E521 experiment established
  - $^{10}B\left(\pi^-,K^+\right)^{10}_{\Lambda}Li$ reaction
  - Clean reaction

K6 beamline @KEK-PS

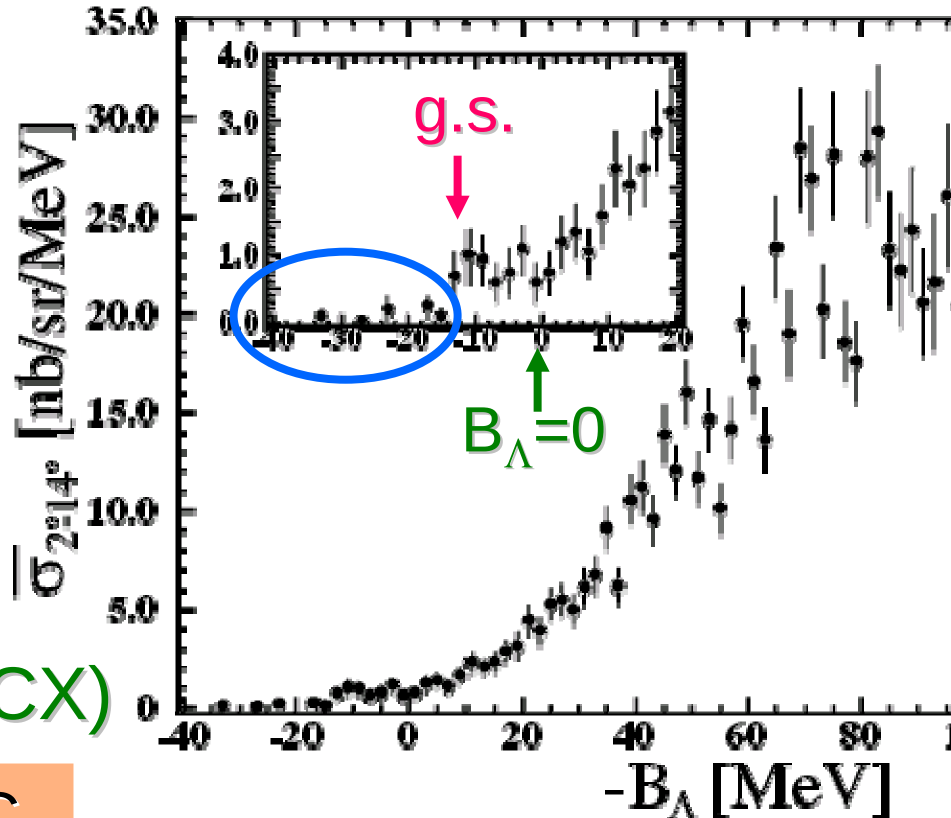
SKS spectrometer

good energy resolution

ΔB_Λ = 2.5MeV (FWHM)

~45 events in bound region

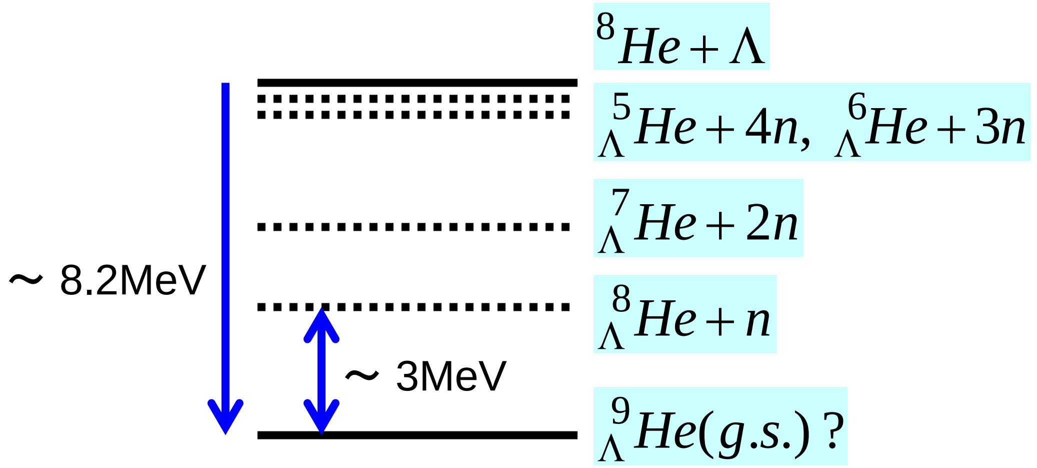
dσ/dΩ~10nb/sr (1/1000 of NCX)



Increase yield ×10 at J-PARC

Structure of $^{9}_{\Lambda}$He hypernucleus

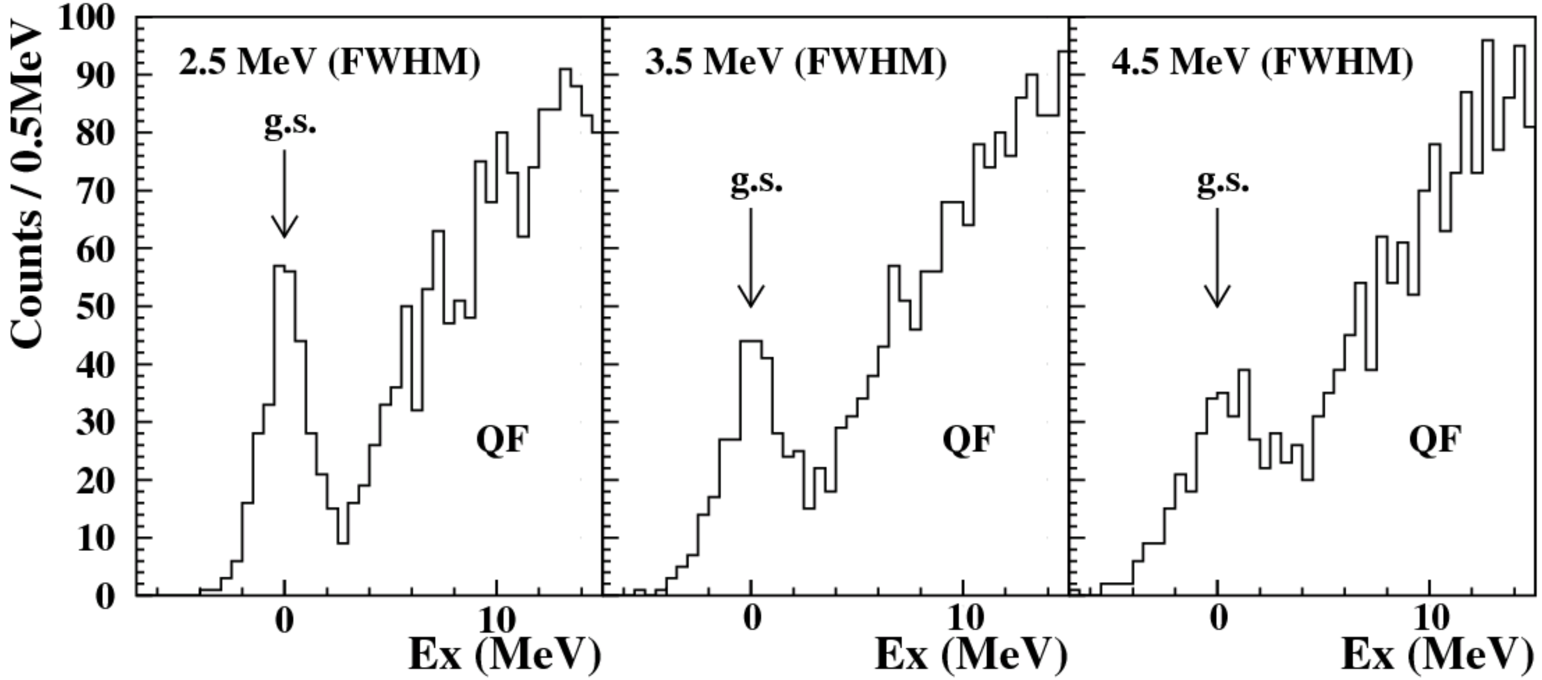
- Expected to be particle stable
  - Core nucleus ^{8}He is particle bound
- Practical decay thresholds
  - Naive extrapolation of B_Λ tells B_Λ~8MeV
  - $\rightarrow$ 3 MeV more bound than $^{8}_{\Lambda}$He+n threshold



Requirement: Resolution (1)

- Clear identification of hypernuclei
  - Binding energy (guess) : ${}^{9}_{\Lambda}$He ~8MeV, ${}^{6}_{\Lambda}$H ~3MeV
  - Strong quasi-free Λ-production background

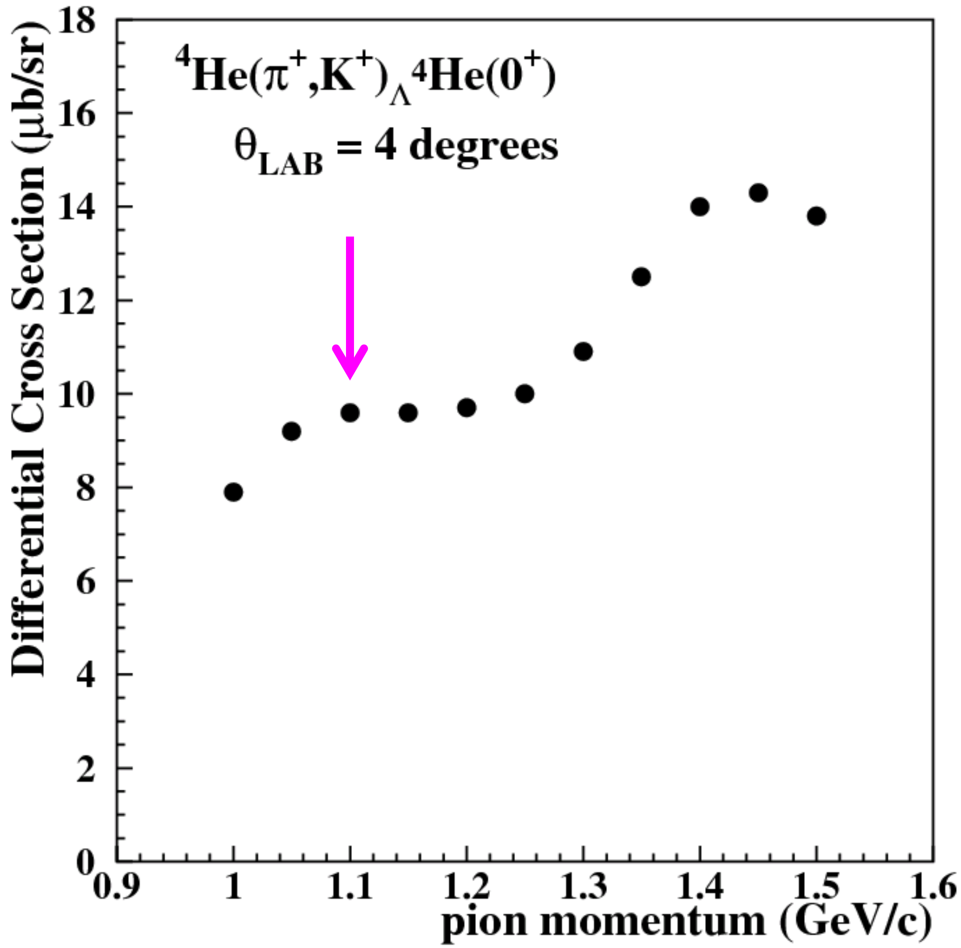
In the case of ${}^{6}_{\Lambda}$H hypernucleus



Energy resolution ≤ 2.5MeV (FWHM)

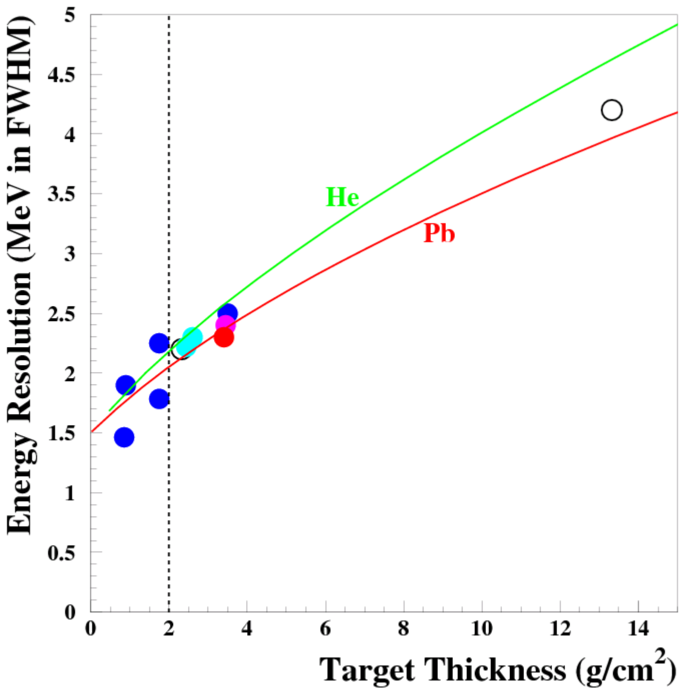
Production cross section

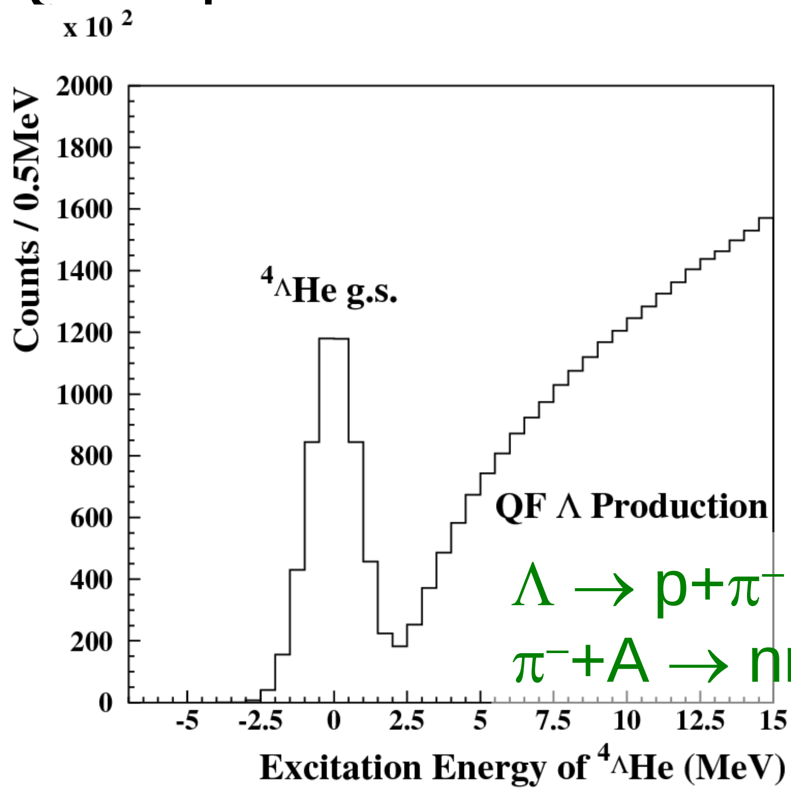
– ${}^{4}_{\Lambda}$He(g.s., 0+) production
– estimation with DWIA by T. Harada



Energy resolution

- K1.8 beam line + SKS $\rightarrow$ excellent resolution
  - Liquid ^{4}He 2 g/cm^2 $\rightarrow$ ΔEx ~ 2 MeV
  - BE($^4{}_\Lambda$He) = 2.42 $\pm$ 0.04 MeV
- Separation from QF Λ production essential





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

$\pi^-+A \rightarrow nnX, npX$

Estimation of $^{4}_{\Lambda}$He Yield

- use $^{4}He(\pi^{+},K^{+})^{4}_{\Lambda}He$ reaction

Parameters	Values
π^{+} beam momentum	1.1 GeV/c
π^{+} beam intensity	1 x 10^{7} /spill
PS acceleration cycle	3.4 s/spill
^{4}He target thickness	2 g/cm^{2}
Reaction cross section	10 μb/sr
Spectrometer solid angle	0.1 sr
Spectrometer efficiency	0.5
Analysis efficiency	0.5

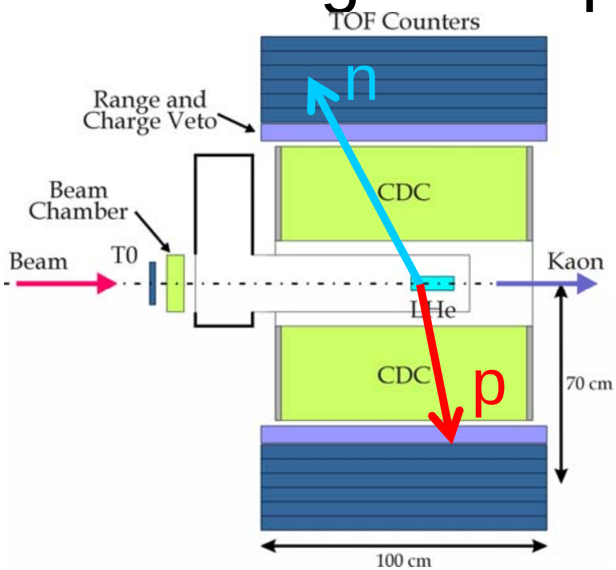
← High intensity beam (π⁺ beam intensity)

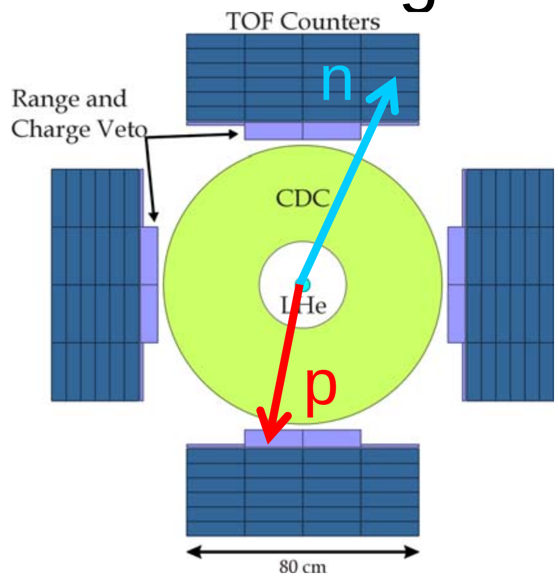
← Large acceptance (Spectrometer solid angle)

- 19,000 $^{4}_{\Lambda}$He/day → 500,000 $^{4}_{\Lambda}$He in 4 weeks

Detector setup for decay

– Large acceptance and high efficiency for NN





$\Omega(n) \approx 0.4$

$\varepsilon(n) \approx 30\%$

$\Omega(p) \approx 0.25$

$\varepsilon(p) \approx 80\%$

– Good PID capability (n/p/π/γ)

n/γ TOF
p/π E/ΔE/range
n/p charge-veto