Proposal for J-PARC 50GeV PS

Study on Λ-Hypernuclei with the Charge-Exchange Reactions

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Abstract

- Studies on Λ-hypernuclei
  with Charge-Exchange (CX) reactions

- Proposal of experiments (at Day-1)

Exp.1: Production of neutron-rich hypernuclei

Production of exotic hypernuclei

⇒ Λ–N interaction in neutron-rich environment

⇒ EoS and structure of neutron stars

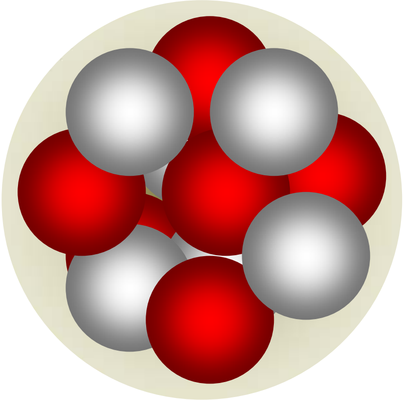
Exp.2: Non-mesonic weak decay(NMWD) of $^4_\Lambda$He

Spin-isospin structure of Λ-Nucleon weak int.

⇒ "ΔI=1/2 rule" in NMWD of hypernuclei

Atomic Nuclei

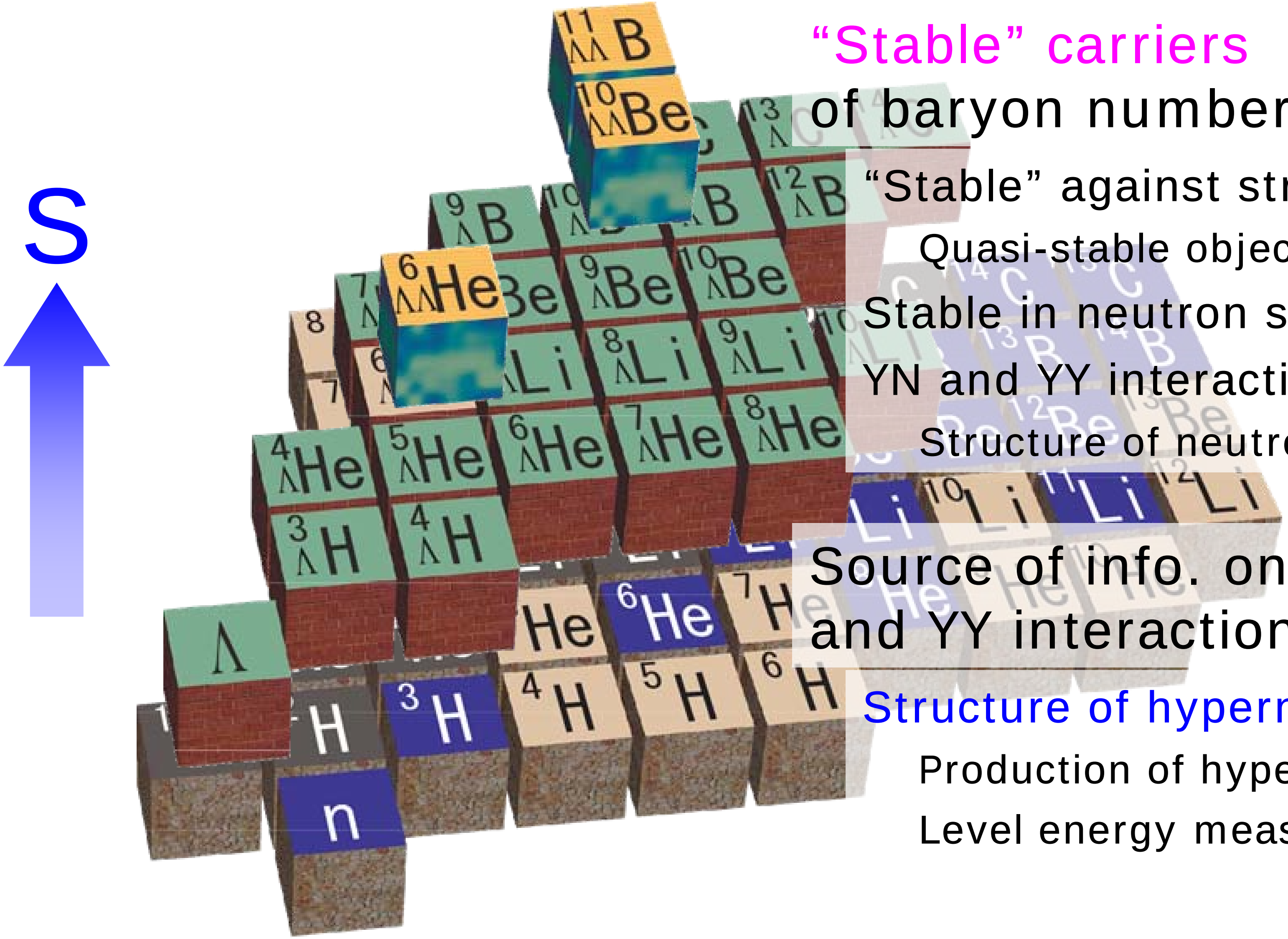
- Stable carriers of baryon numbers



  - Attractive NN int.
    - ⇒ Guarantees formation of “Matter”
  - Repulsive NN int.
    - ⇒ Avoids collapse to black hole
  - Interplay of NN interactions
    - ⇒ Drives evolution of stars and the universe

- Knowledge on NN interaction
  - Nuclear structure
  - NN scattering data

Hypernuclei



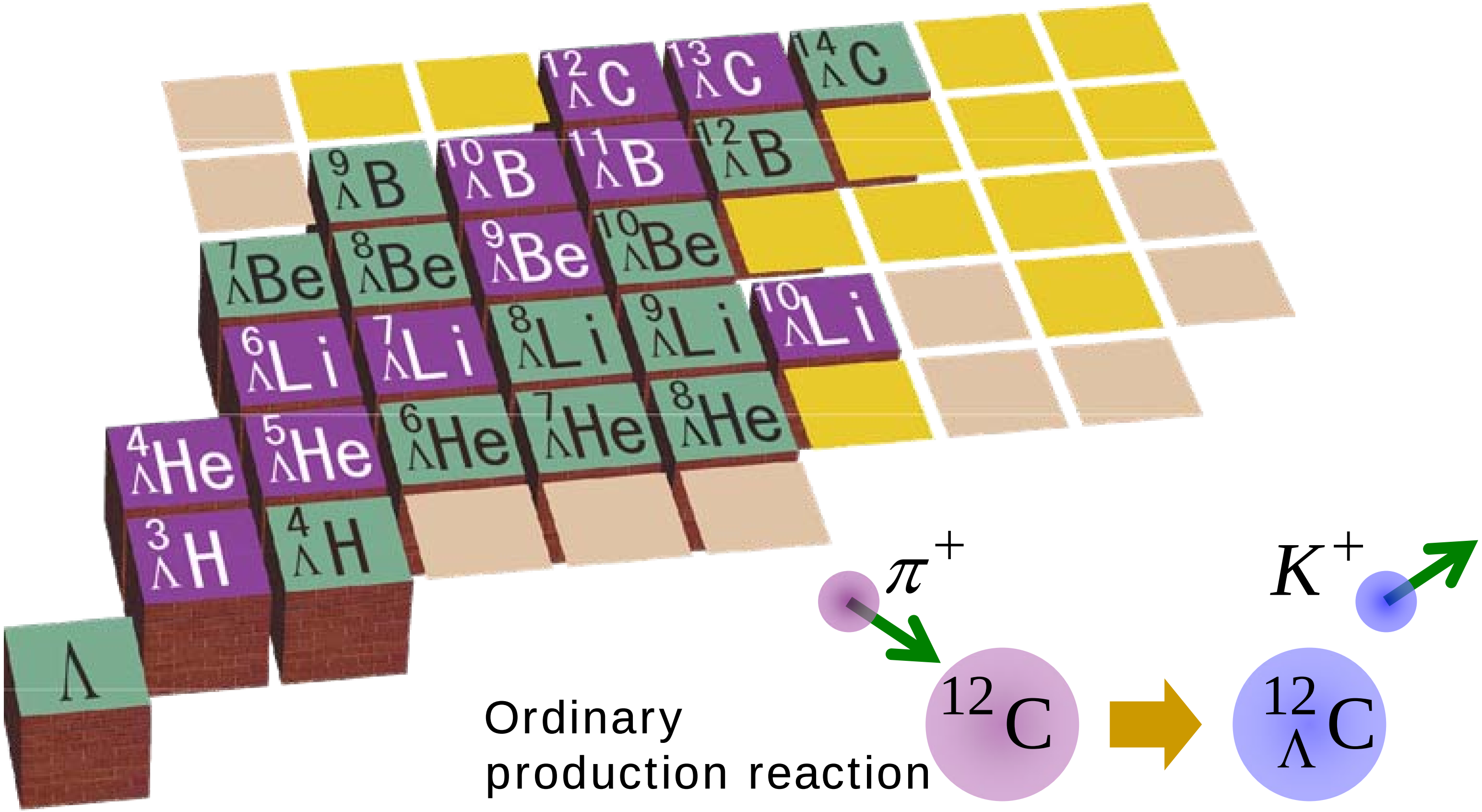
"Stable" carriers of baryon numbers

- "Stable" against strong int.
  - Quasi-stable objects
- Stable in neutron stars
- YN and YY interaction
  - Structure of neutron stars

Source of info. on YN and YY interaction

- Structure of hypernuclei
  - Production of hypernuclei
  - Level energy measurement

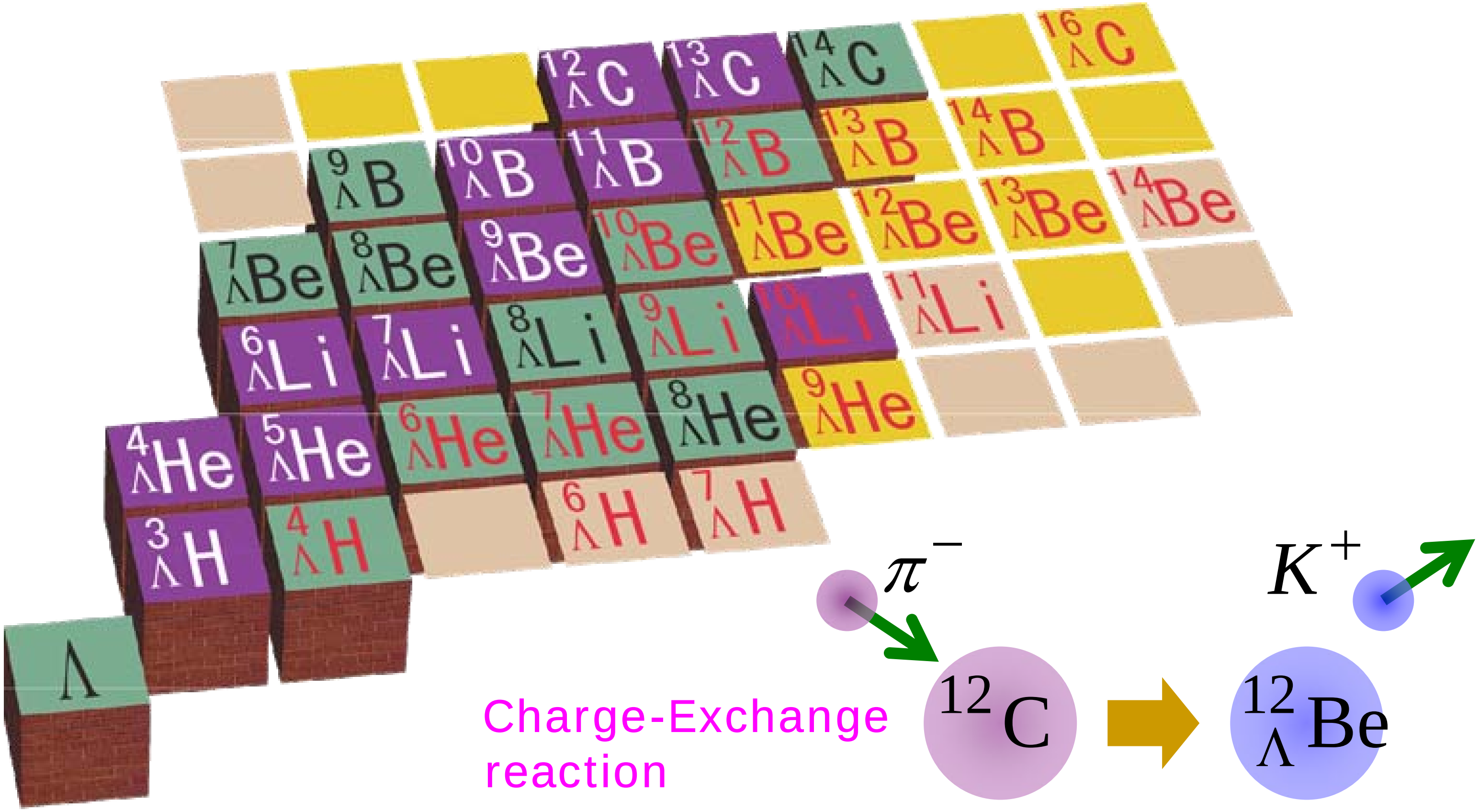
- Structure study on hypernuclei
  - Survey only limited region of isotopes
  - Lack of spectroscopic tools



Ordinary production reaction

Charge-Exchange Reactions

- New category of production reaction
  - New hypernuclear species
  - Mirror and neutron-rich hypernuclei



Charge-Exchange reaction

Exotic Objects

- Heaviest stable hydrogen ?
  - Triton

    $^{3}\mathrm{H}$ Heaviest stable hydrogen
  - Only with nucleons

    $^{5}\mathrm{H}$ Super-heavy hydrogen

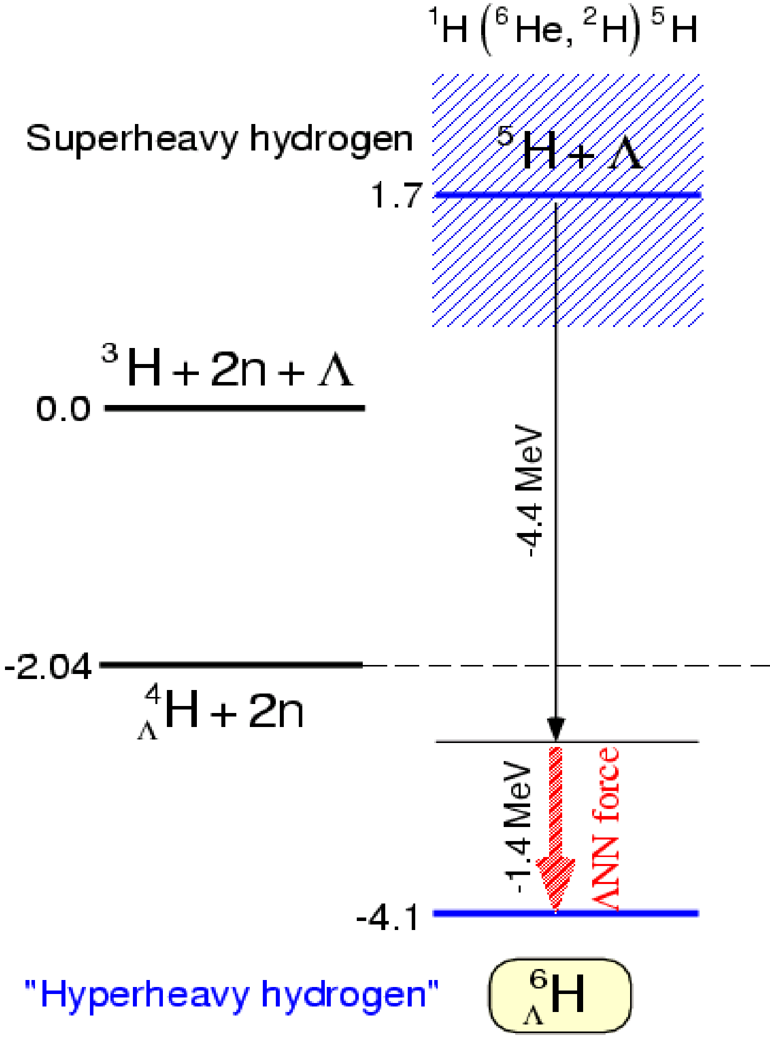
    1.7 MeV unbound
  - Addition of Λ hyperon

    $^{6}_{\Lambda}\mathrm{H}$ Hyper-heavy hydrogen

    ~ 4 MeV bound

    Heaviest stable hydrogen

    Double of ^{3}H

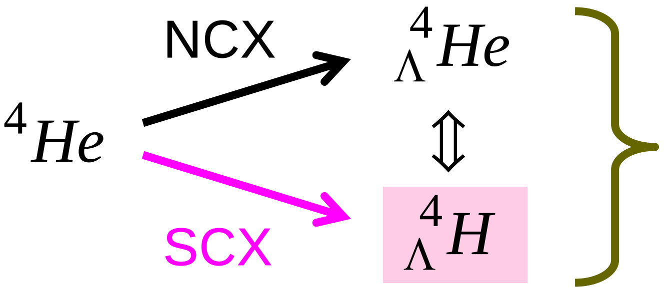


Our Strategy

- Develop charge-exchange reactions
  - Single charge-exchange (SCX) reactions

$\left(\pi^-, K^0\right)$

Suitable to produce mirror-hypernuclei



^4He

NCX

$^4_\Lambda He$

$\Updownarrow$

SCX

$^4_\Lambda H$

Systematic study of hypernuclei

  - Double charge-exchange (DCX) reactions

$\left(\pi^-, K^+\right)$ $\left(K^-, \pi^+\right)$

Production of neutron-rich hypernuclei

- Practical problems

  $\left(\pi^{-}, K^{0}\right)$

  - Small detection efficiency for SCX: ⬇ 10^{-1}~10^{-2}
  - Small reaction cross section for DCX: ⬇ 10^{-3}

- High-intensity beam line for CX reaction
  - Pion beam intensity ~ 10^{9}/spill: ⬆ 10^{2}

    Override small yield

    High-resolution achievable at the same time
  - A long-range plan

    Construction of new beam line and spectrometer

- Experiments at Day-1
  - Start study with available infrastructure

Experiments at Day-1 (1/2)

- Production of n-rich hypernuclei with DCX
  - Structure of neutron-rich hypernuclei
  - What we can learn ?

    ΛN strong interaction in N$\gg$Z environment

    Close connection to EoS in neutron stars

- Non-mesonic weak decay of ${}^4{}_{\Lambda}$He
  - Measurement of $\Lambda n \to nn$ weak process
  - Complementary with $\Lambda p \to pn$ in ${}^4{}_{\Lambda}$H
  - What we can learn ?

    Spin-isospin structure of ΛN weak interaction

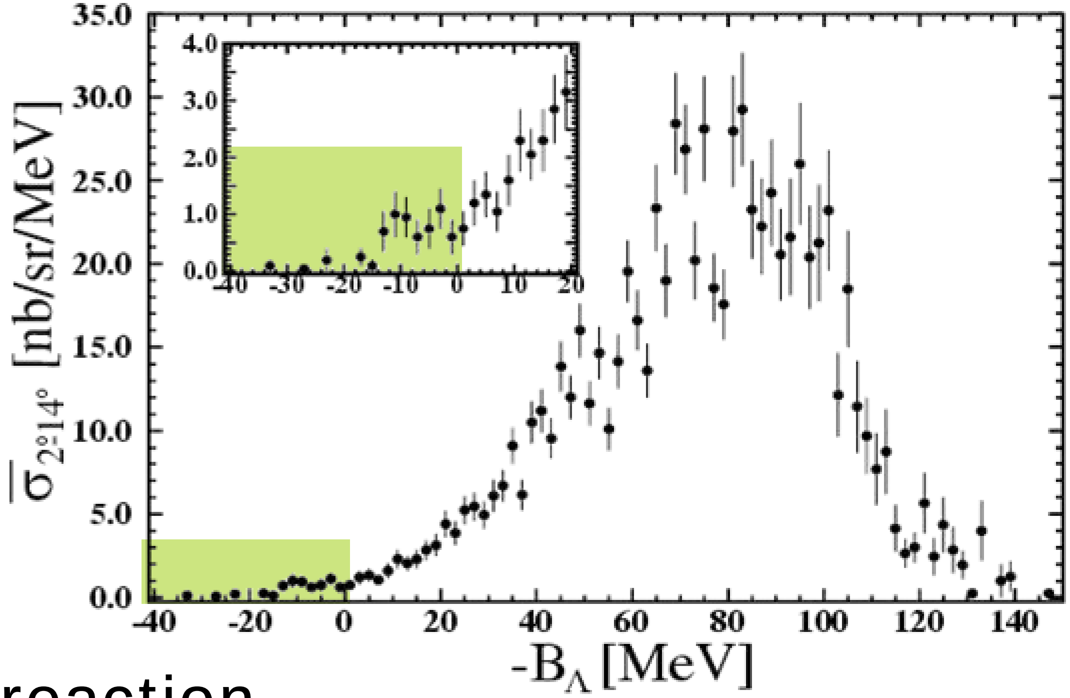
    Test of “$\Delta I=1/2$ rule”

Neutron-Rich Hypernuclei

- KEK-PS-E521
  - First successful experiment

    n-rich hypernuclei

    DCX reaction



Reaction studied

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

Cross section

~10 nb/sr

small cross section

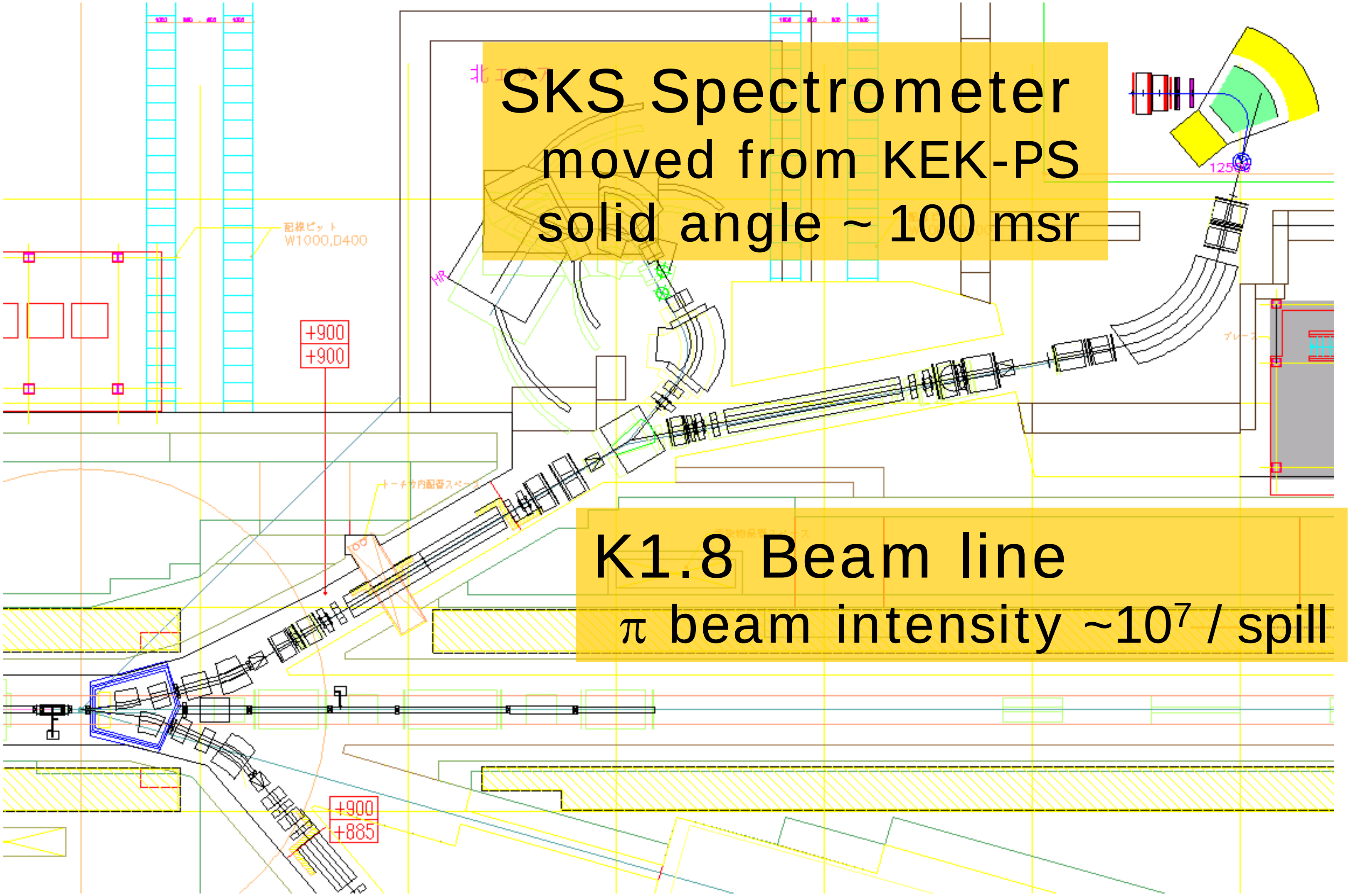
~10^{-3} of ordinary reaction

Experimental

No problem except for the small cross section

We need good beam line and good spectrometer

- Experimental setup



SKS Spectrometer

moved from KEK-PS

solid angle ~ 100 msr

K1.8 Beam line

π beam intensity ~10^7 / spill

- Proposed experiment
  - Reaction mechanism of DCX reaction

    Production of typical n-rich hypernuclei

$$ {}^{10}\mathrm{B}\left(\pi^{-},K^{+}\right){}^{10}_{\Lambda}\mathrm{Li} \qquad {}^{12}\mathrm{C}\left(\pi^{-},K^{+}\right){}^{12}_{\Lambda}\mathrm{Be} $$

  - Another option

    Study on structure of n-rich hypernuclei

    Production of exotic hypernuclei

$$ \underbrace{{}^{10}_{\Lambda}\mathrm{Li} \qquad {}^{9}_{\Lambda}\mathrm{He}}_{\text{Similar reaction and structure}} \qquad {}^{6}_{\Lambda}\mathrm{H} $$

Cross section and structure may differ

Expected yield

- Production of $^{9}_{\Lambda}$He
  - Assume similar cross section as $^{10}_{\Lambda}$Li

$$Yield = N_{Beam} \times \frac{N_{Target}}{9} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{SP} \times \varepsilon_{SP} \times \frac{Time}{T_{Cycle}}$$

⇒ ~400 events/2weeks

Parameters	Values	
π^- beam momentum	1.2 GeV/c	
π^- beam intensity	10^7 /spill	N_{Beam}
PS acceleration cycle	3.4 sec	T_{Cycle}
^{9}Be target thickness	3.5 g/cm^2	N_{Target}
Reaction cross section	10 nb/sr	$d\sigma/d\Omega$
Spectrometer solid angle	0.1 sr	Ω_{SP}
Spectrometer efficiency	0.5	ε_{SP}

- Requested beamtime for this study

2 weeks for $^{9}_{\Lambda}$He and 2 weeks for $^{6}_{\Lambda}$H (4 weeks in total)

+ Beam tuning and energy/efficiency calibration

Experiments at Day-1 (2/2)

- Production of n-rich hypernuclei with DCX
  - Structure of n-rich hypernuclei
  - What we can learn ?

    ΛN strong interaction in N≫Z environment

    Close connection to EoS in neutron stars

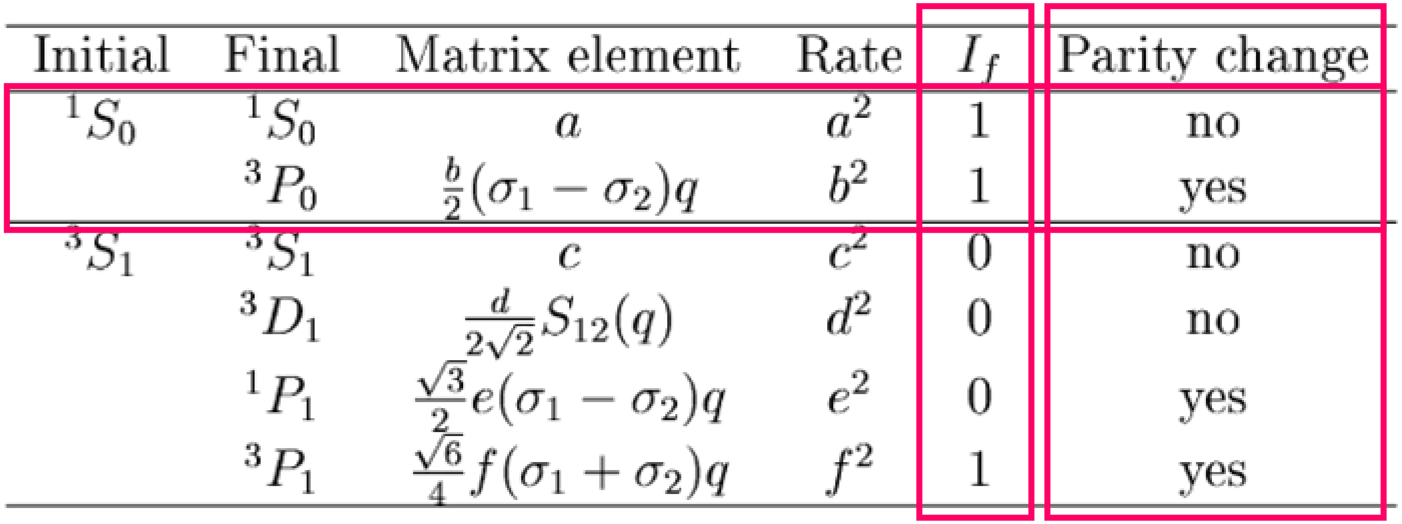
- Non-mesonic weak decay of ${}^{4}_{\Lambda}$He
  - Measurement of Λn→nn weak process
  - Complementary with Λp→pn in ${}^{4}_{\Lambda}$H ⟵Need SCX
  - What we can learn ?

    Spin-isospin structure of ΛN weak interaction

    Test of "ΔI=1/2 rule"

Non-Mesonic Weak Decay

Spin-isospin structure of NMWD



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

$$\frac{\Gamma(\Lambda n \to nn)}{\Gamma(\Lambda p \to np)}$$

$$\sigma_0(1+\alpha\cos\theta_p)$$

- Branching ratio tell $d \approx f \;>>\; others$
- Decay asymmetry tell $d >> f \quad or \quad d << f$
- Possible answer: $^1S_0$ amplitude (a and/or b)
- Observable sensitive to $^1S_0$

$$\Gamma\left(\Lambda n \to nn;\ {}^4_\Lambda\mathrm{He}\right)\quad \Gamma\left(\Lambda p \to np;\ {}^4_\Lambda\mathrm{H}\right)$$

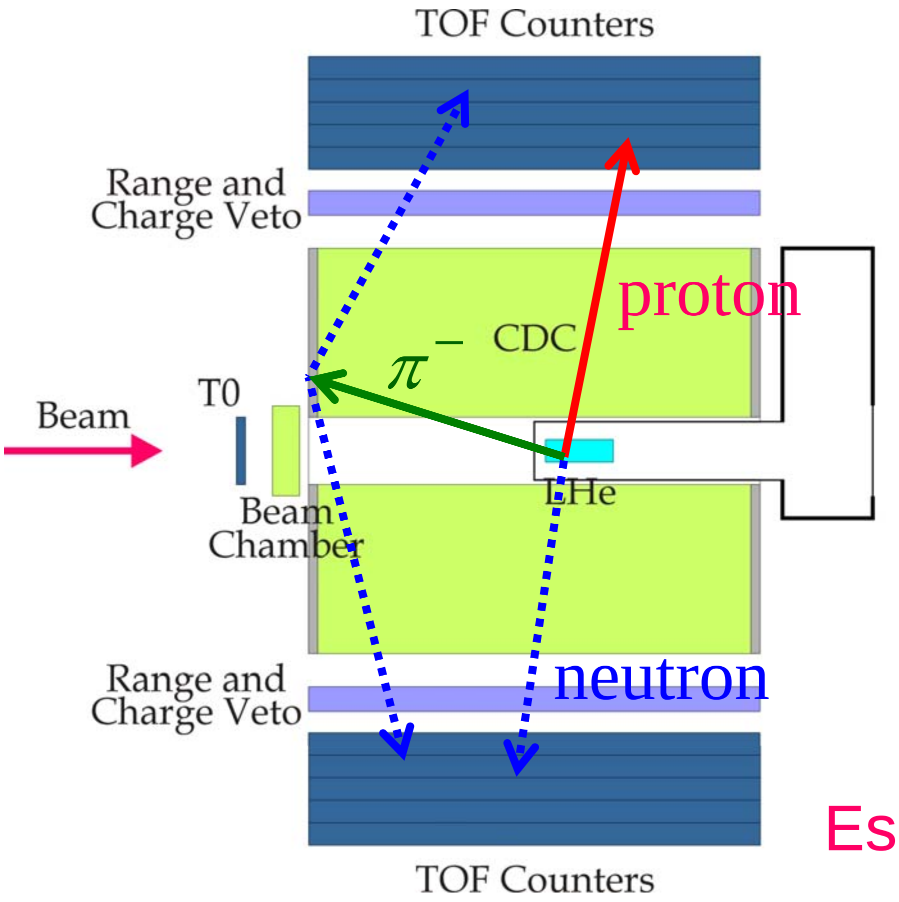
- Beam line and spectrometer
  - K1.8 beam line: 1.1GeV/c π^+ beam ~10^7/spill
  - SKS spectrometer: ~100 msr
- Expected yield of ${}^4_\Lambda$He(0^+)

Parameters	Values	
π^+ beam momentum	1.1 GeV/c	
π^+ beam intensity	10^7 /spill	N_{Beam}
PS acceleration cycle	3.4 sec	T_{Cycle}
Liquid ^{4}He target thickness	2 g/cm^2	N_{Target}
Reaction cross section	10 μb/sr	ds/dΩ
Spectrometer solid angle	0.1 sr	Ω_{SP}
Spectrometer efficiency	0.5	ε_{SP}

$$Yield = N_{Beam} \times \frac{N_{Target}}{4} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{SP} \times \varepsilon_{SP} \times \frac{Time}{T_{Cycle}}$$

  - Yield ~ 38k ${}^4_\Lambda$He(0^+)/day

Decay particle detector



Direct measurement

Detect nn and np pairs

$$\begin{matrix} Yield\,(n) \\ Yield\,(p) \end{matrix} \;\cancel{\Longrightarrow}\; \begin{matrix} Yield\,(nn) \\ Yield\,(np) \end{matrix}$$

Back-to-back kinematics

Selection of ΛN→NN process

Remove ΛNN→NNN process

Veto for negative pion BG

Rejection with CDC

MC study tells $S/N \gg 10$

Estimated yields

Λn→nn: ~120 events/2weeks

Λp→np: ~3200 events/2weeks

Summary

- We propose studies on Λ-hypernuclei with Charge-Exchange (CX) reactions
- Proposal of experiments (at Day-1)

Exp.1: Production of neutron-rich hypernuclei

$^{9}_{\Lambda}\mathrm{He}$ $^{6}_{\Lambda}\mathrm{H}$ Production of exotic hypernuclei

Exp.2: Detailed study on NMWD of $^{4}_{\Lambda}\mathrm{He}$

$\Gamma\left(\Lambda n \to nn;\ ^{4}_{\Lambda}\mathrm{He}\right)$ pin down $^{1}S_{0}$ contribution

- Outputs expected
  - ΛN strong int. in neutron-rich environment
  - Spin-isospin structure of ΛN weak interaction