J-PARC HI meeting
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(Hadron Physics at J-PARC HI project) Comments on hypernuclei

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2. Magnetic moments
3. B(M1) by Coulomb excitation
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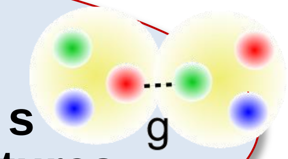
Motivations of strangeness nuclear physics

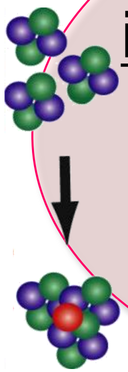
BB interactions



Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures

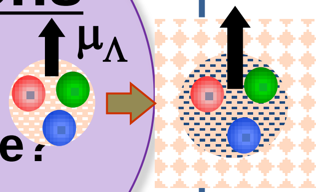
Test lattice QCD calculations

Impurity effect in nuclear structure



Changes of size,
deformation, clustering,
Appearing new symmetry,
…

Properties and behavior of baryons in nuclei



μ, size, structure change?
Baryon-mixing,
BBB forces (ρ dependence)

Clues to understand
hadrons and nuclei
from quarks

Cold and dense
nuclear matter
with strangeness

Production rates of hypernuclei

$\sqrt{s_{\mathrm{NN}}} = 2 - 6$ GeV for J-PARC

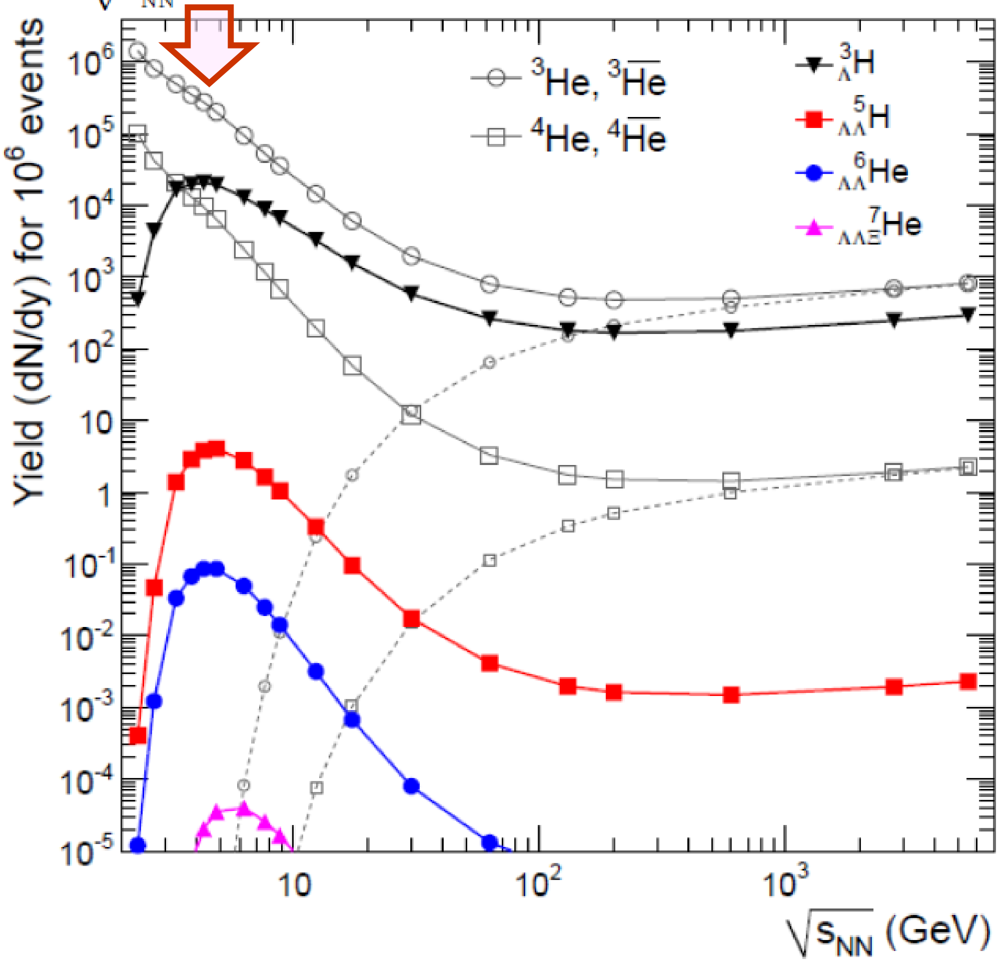


Figure 18: Hypernuclear yields at the mid-rapidity of $^{3}_{\Lambda}$H, $^{5}_{\Lambda\Lambda}$H, $^{6}_{\Lambda\Lambda}$He, and $^{7}_{\Lambda\Lambda\Xi}$He calculated by a thermal model as functions of $\sqrt{s_{\mathrm{NN}}}$ (GeV) [89].

Detection/identification is a problem rather than production.

Characteristics of hypernuclear studies via HI collisions

Previous data

$^{4}_{\Lambda}$H: (7Li, 4He on ^{12}C) JINR

$^{3}_{\Lambda}$H: (11.5 GeV/A Au on Pt) BNL-AGS

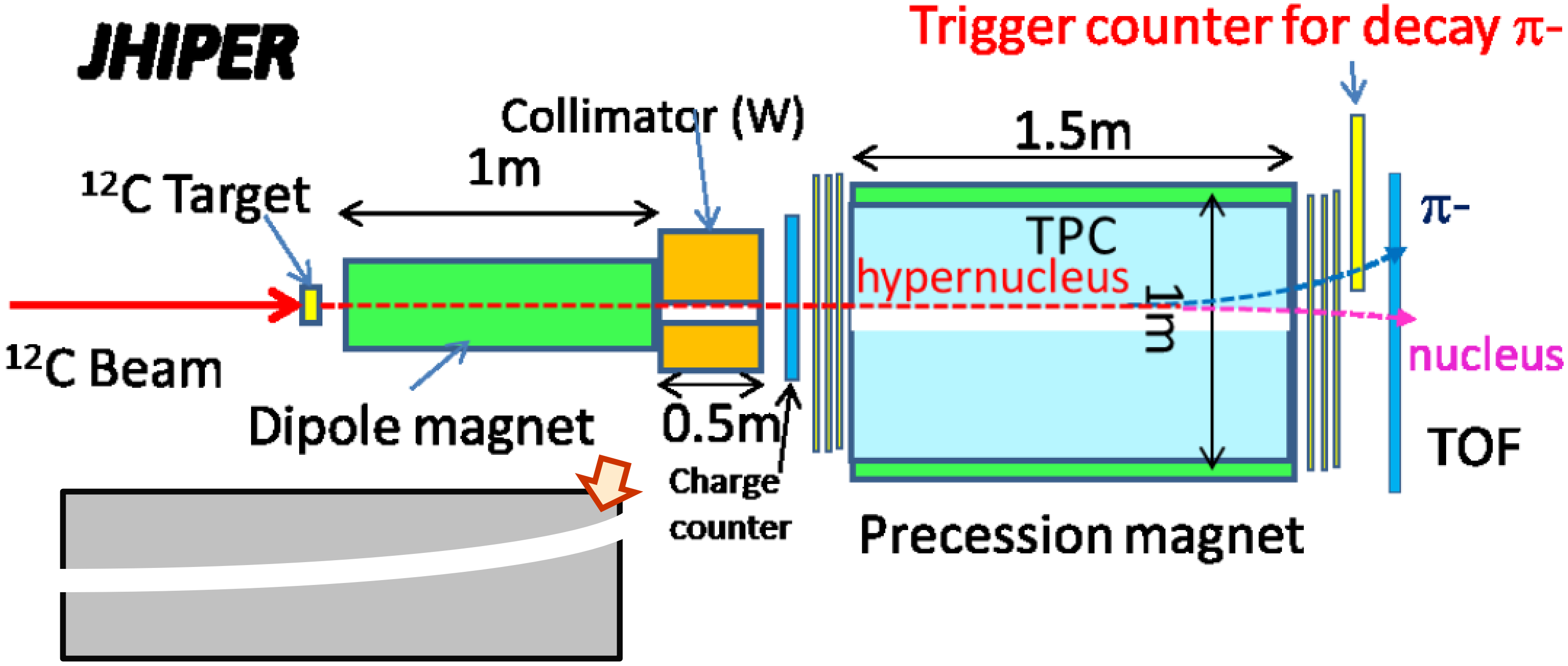
$^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H: (2 GeV/A ^{6}Li on ^{12}C) GSI (HypHI)

$^{3}_{\Lambda}$H, $\overline{^{3}_{\Lambda}\text{H}}$: (200 GeV Au+Au) RHIC(STAR), (2.76 TeV Pb+Pb) LHC(ALICE)

- Identification of heavier hypernuclei (A>10) is extremely difficult. More nonmesonic decays, emission of more than one neutrons.
- For light hypernuclei (A<10), ab-initio calculations provide direct connection to BB and BBB interactions.
- μ, nuclear radius, and B(M1)/B(E2) (some cases) cannot be measured by conventional (K-,π), (π,K+), (e,eK+) methods.
- “Closed geometry” to select rigidity of the tracks is essential, particularly powerful for n-rich/multi-strange large-rigidity hypernuclei

Closed geometry setup

JHIPER

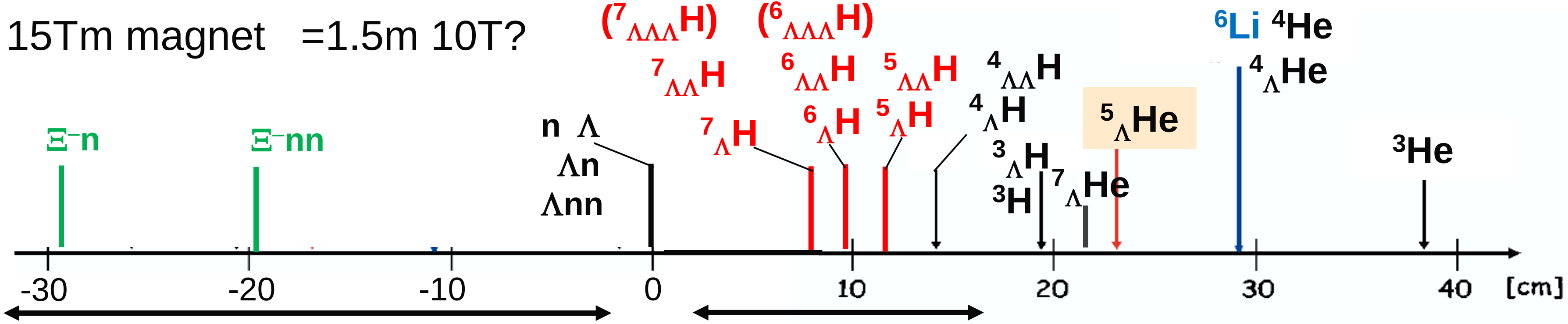


Collimator in the magnet

6Li + 12C at 15 A GeV $\beta\gamma c\tau \sim 1.2\ m$

15Tm magnet =1.5m 10T?

Projectile fragments with hyperons



No contamination from non-strange nuclei

Figure 7: Separation of hypernuclei at the exit of the superconducting magnet, which are by the ^{6}Li projectiles at 20 A GeV.

Hypernuclear physics program

- **Magnetic moment and B(M1)**

  => Baryon properties in a nucleus

  ΛN-ΣN mixing, Baryon structure change? Effect of chiral symmetry restoration?

  - Magnetic moment of ${}^{5}_{\Lambda}$He, ${}^{7}_{\Lambda}$He, …
  - Λ-spin-flip B(M1) of ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He… by Coulomb excitation
- **Neutron-rich/ Multi-strange hypernuclei**

  => BB/BBB interactions, ΛN-ΣN / $\Lambda\Lambda$-ΞN mixing

  - Λnn, ${}^{6}_{\Lambda}$H, ${}^{4}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$H, … (strangelet)
  - Ξ^{-}n, Ξ^{-}nn, Ω^{-}n,.. (strangelet) “Weakly-decaying negatively-charged nuclei”
- **Lifetimes, weak decay branching ratios**

  => baryonic weak interaction, hypernuclear structure

  - ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, (${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He,), …, Ξ^{-}n -> Σ^{-}n
- **Interaction cross section in matter** => Nuclear radius, neutron halo
  - Size of ${}^{3}_{\Lambda}$H, ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$He,..
- **Gamma decays, B(E2) by Coulomb excitation**

  => Impurity effect: changes of deformation, halo, collective motion,…

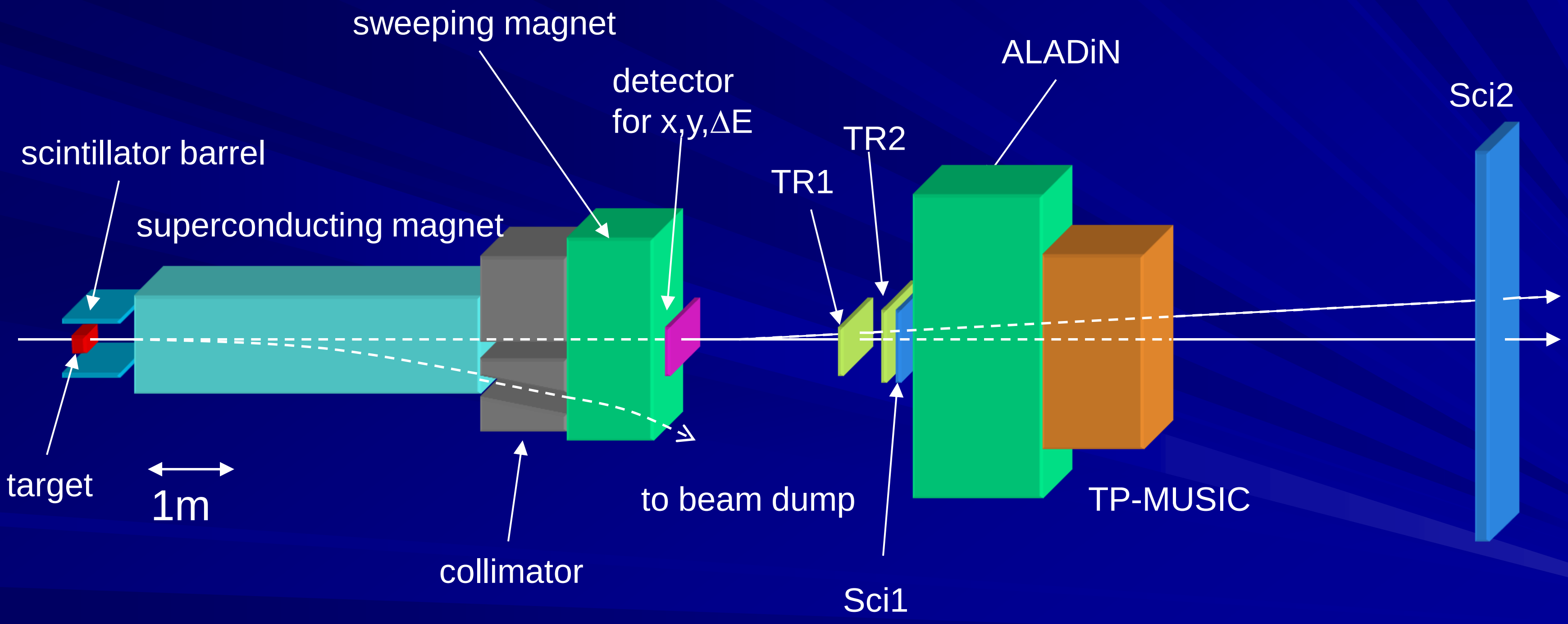
  - ${}^{7}_{\Lambda}$He, ${}^{9}_{\Lambda}$Be, ${}^{13}_{\Lambda}$C,..

Slide by T.R. Saito

Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

HypHI Phase 3



Removing light hadrons from the hypernuclear decay before the sweeping magnet.

Interests of μ_Λ in nucleus

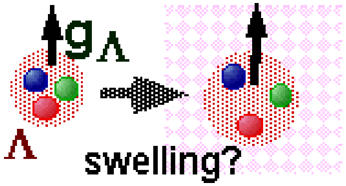
- ## Baryon properties in nuclear medium

⇒ Can be investigated only by a Λ (free from Pauli) in 0s orbit.

Structure change? Swelling?

Effect of partial restoration of chiral symmetry??

How μ_N changes? -- Clue to understand the **origin of baryon magnetic moment**



Constituent quark: μ_B looks OK with $\mu_q = \frac{e\hbar}{2m_q c}$

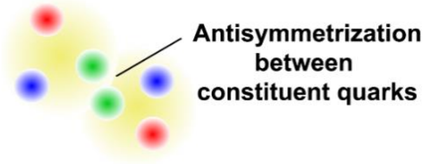
Current quark: *nucleon spin = quark spin (~0.2) + gluon spin + L*

How to understand μ_B ?

- ## Pauli effect between quarks ("quark exchange current")

changes μ_B in nucleus

sensitive to baryon size (b)



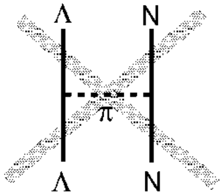
- Quark Cluster Model Takeuchi et al., N.P. A481(1988) 639

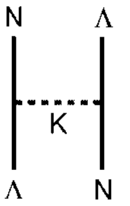
$\delta\mu/\mu$: ${}^{4}_{\Lambda}$He(1^+) -1% ~ -2%, larger by Σ mixing

${}^{4}_{\Sigma^+}$Li(1^+) -40% ~ -100%

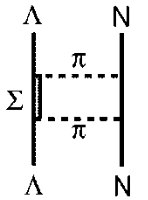
b = 0.6 fm -> 0.8 fm, μ becomes twice large.

- ## Meson exchange current





${}^{5}_{\Lambda}$He : -9%



${}^{6}_{\Lambda}$Li : -2%

T≠0 only

Saito et al., N.P. A625 (1997) 95

- ## Sigma mixing effect

~ +2--5 % for ${}^{5}_{\Lambda}$He (Dover-Gal)

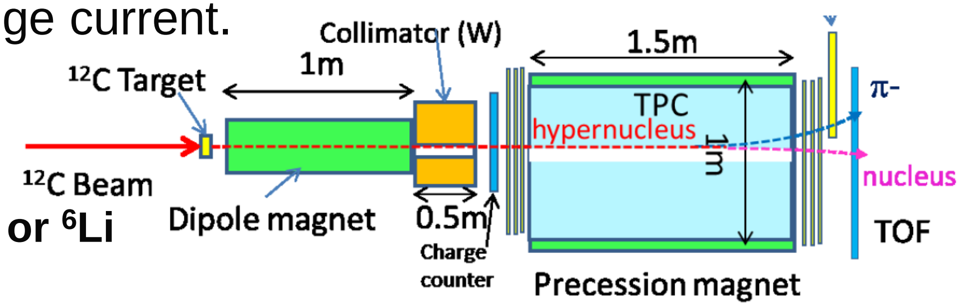
Measurement of a few % is desired.

Systematic study of ρ and T dependence (${}^{3}_{\Lambda}$H, ${}^{5}_{\Lambda}$He, ${}^{7}_{\Lambda}$He) **will discriminate these effects.**

Magnetic moment of $^{5}_{\Lambda}$He

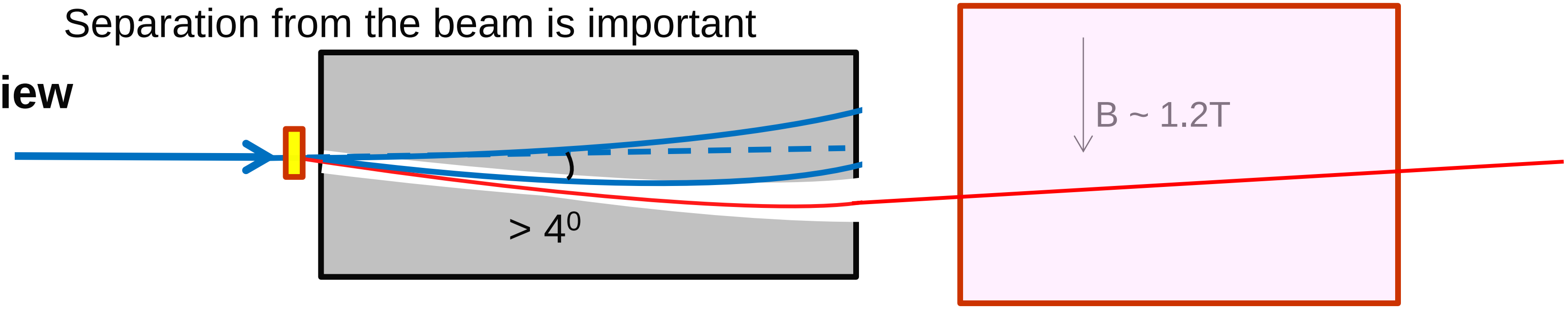
$^{5}_{\Lambda}$He: ab-initio calculation possible.
Core polarization small.
Effects of Σ mixing, meson exchange current.

15 GeV/A
10^{10}/spill
$\beta\gamma c\tau(\Lambda) \sim 1.2\ m$



Separation from the beam is important

Side view



Production Cross section:
σ ~0.1 ub/sr (projectile rapidity region) for 7Li+12C (20 GeV/A)
After separator (> 4^0) x 0.02 ?
Λ–Polarization: > 0.1 for p_T > 1 GeV/c
Decay rate in the decay volume: ~ 0.6
Pionic decay ($^{5}_{\Lambda}$He -> ^{4}He p π-) branch: 0.44
Decay reconstruction eff. ~0.1

Estimate based on JHF LOI (2000)

=> 600 / day

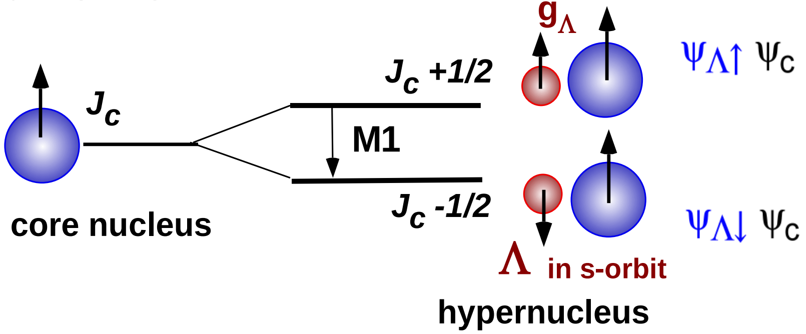
Precession: 1.2T, 1.5m => 37 deg

=> ~3% for 100 days

With 10^{11}/spill beam, other hypernuclei ($^{3}_{\Lambda}$H, $^{7}_{\Lambda}$He) can be also measured.

Λ-Spin-flip B(M1) for g_Λ in nucleus

g_Λ in a nucleus can be also obtained from B(M1) of Λ spin-flip transition



$$B(M1) = (2J_{up}+1)^{-1}\,|\langle\,\Psi_{low}\,\|\,\mu\,\|\,\Psi_{up}\,\rangle|^2$$

$$= (2J_{up}+1)^{-1}\,|\langle\,\psi_{\Lambda\downarrow}\,\psi_c\,\|\,\mu\,\|\,\psi_{\Lambda\uparrow}\,\psi_c\,\rangle|^2$$

$$\mu = g_c \boldsymbol{J}_c + g_\Lambda \boldsymbol{J}_\Lambda = g_c \boldsymbol{J} + (g_\Lambda - g_c)\boldsymbol{J}_\Lambda$$

$$= \frac{3}{8\pi}\,\frac{2J_{low}+1}{2J_c+1}\,(g_\Lambda - g_c)^2 \quad [\,\mu_N^2\,]$$

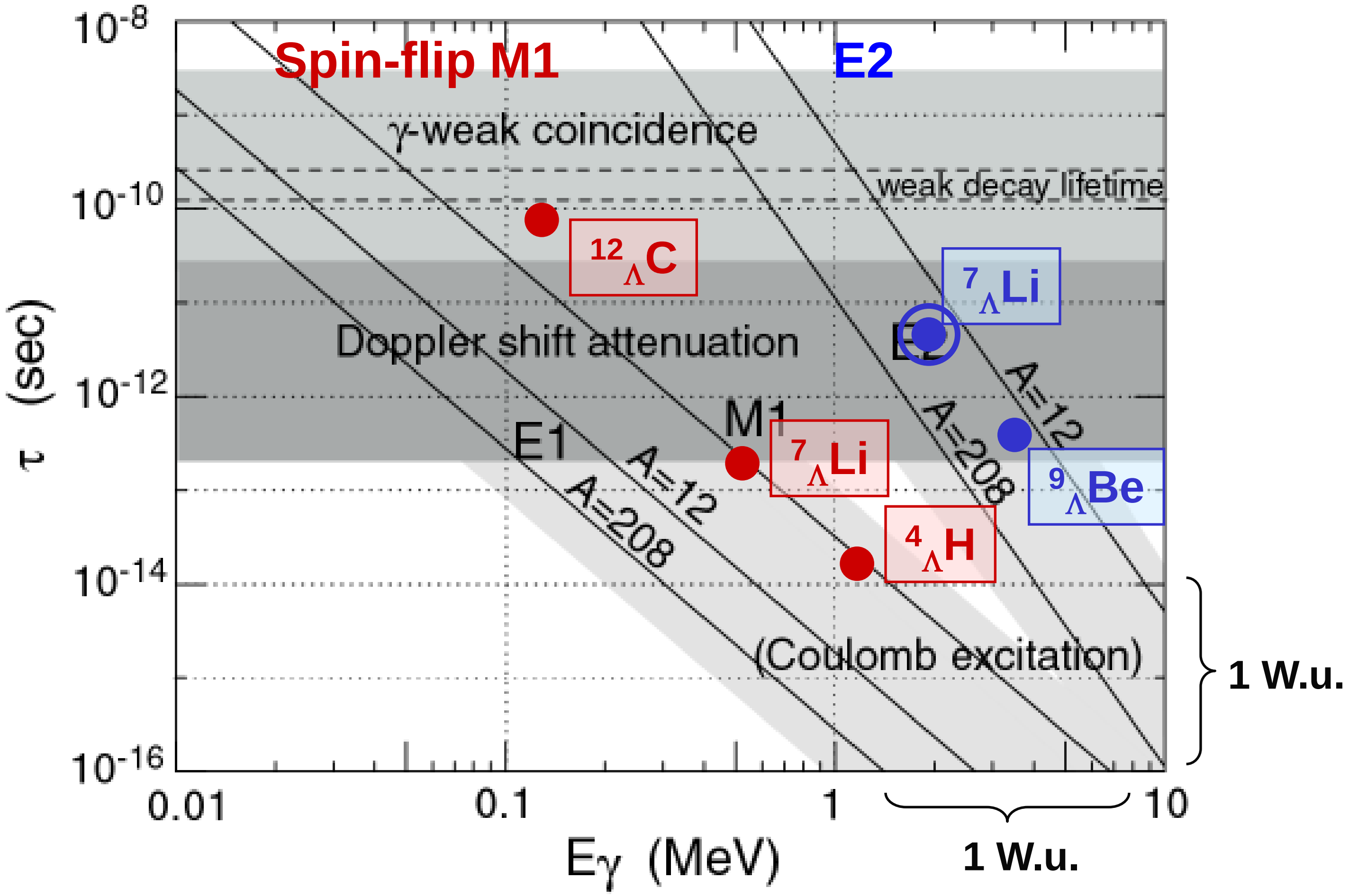
(weak coupling limit)

Methods

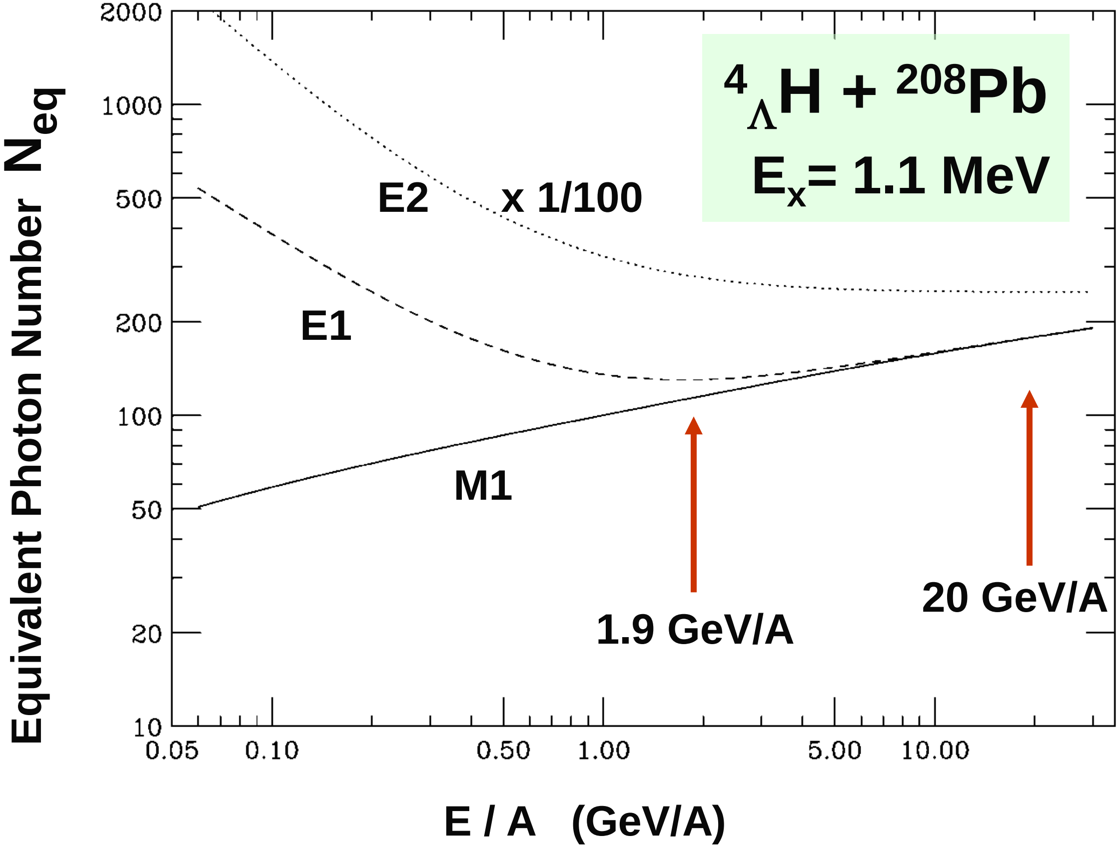
- **Doppler shift attenuation method ($\tau \sim t_{stop}$) :**
  τ –> B(M1) **(K,π), J-PARC E63 for $^7{}_\Lambda$Li**
- **γ-weak coincidence method ($\tau \sim \tau_{weak}$) :**
  τ –> B(M1) (K,π), To be proposed at J-PARC
- **Coulomb excitation**
  σ –> B(M1) J-PARC-HI

Established for
"hypernuclear shrinkage"
in $^7{}_\Lambda$Li from B(E2)
PRL 86 ('01)1982

How to measure lifetimes for hypernuclear γ transitions



M1 Coulomb excitation for $^{4}_{\Lambda}\mathrm{H}\ (0^{+}\text{->}1^{+})$



$B(M1) \sim 2.6\ \mu_N^2$

HypHI LOI:
$^{4}_{\Lambda}$He yield ~2×10^{5} / week

Reaction cross section
$\sim \pi\,[R(^{4}_{\Lambda}\mathrm{H})+R(^{208}\mathrm{Pb})]^2$
= 2.5 b
(Nuclear spin-flip excitation should be estimated with lighter target nuclei.)

Should be studied

$$\sigma\ (0^{+}\text{->}1^{+})\ [\mathrm{mb}] = 4.43\times10^{-2} * N_{eq}(M1) * B(M1)\ [\mu_N^2]$$

$$= \left.\begin{array}{l} 20\ \mathrm{mb}\ (E/A=20\ \mathrm{GeV/A}) \\ 13\ \mathrm{mb}\ (E/A=1.9\ \mathrm{GeV/A}) \end{array}\right\}$$

Study of Ξ^-n bound system

In general, Ξ hypernuclei decay via Ξ^-p -> $\Lambda\Lambda$ at the same vertex point as production

=> Identification extremely difficult

Ξn (S=1, I=1) is predicted to be bound, deuteron analog in {10*}, BE= 3.6 MeV from ESC08a

Kiso event and recent E05 pilot data suggest a rather deep Ξ-nulcear attractive potential

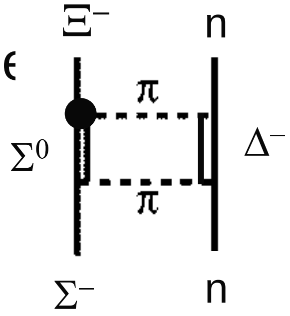
=> Weakly-decaying Ξ hypernuclei? Ξ^-n, Ξ^0p, Ξ^-nn(?),

Ξ^-n -> $\Lambda\,\pi^-$ n   (Ξn (S=0, I=1) is predicted to be strongly repulsive)

Weakly-decaying negatively-charged nuclei can be easily separated and identified. Ξ^-n, Ξ^-nn, (Σ^-n), Ω^-n

d (K-,K+) [Ξ^-n] => Accurate binding energy

HI => Lifetime and Decay mode (Ξ^-n-> Σ^-n: suppressed?), size

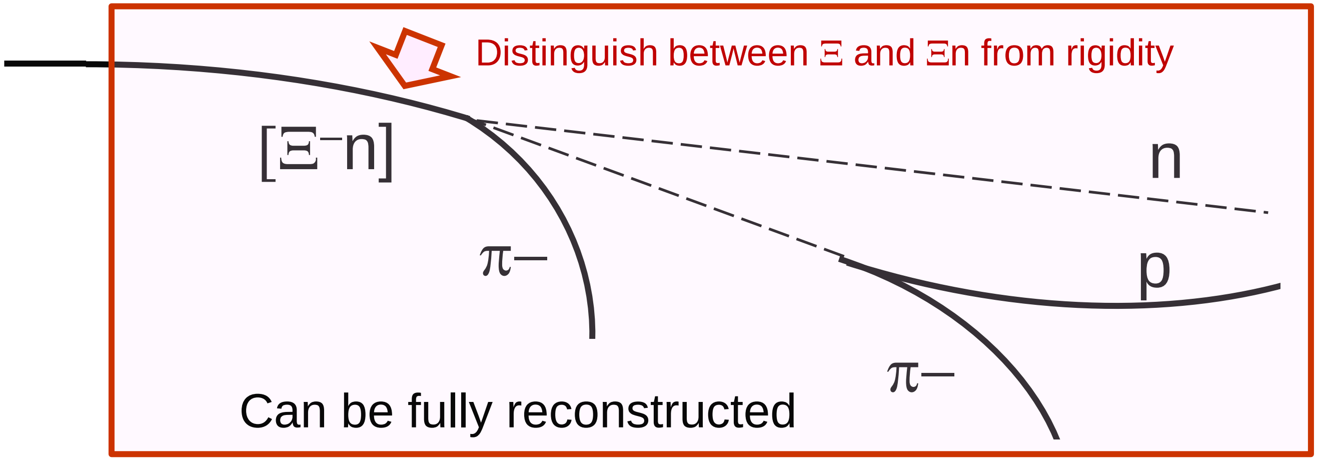


σ ~1 nb (peripheral)

~1 μb (central)

(Sano, Wakai)

Probably, no problem in yield



Distinguish between Ξ and Ξn from rigidity

Can be fully reconstructed

Other subjects of personal interest

- B-B correlation
  => ΛΣ, ΣΣ, ΞΛ, ΩN interactions ?
  -- Feasibility should be studied
- BB correlation data for various A and collision energy
  => density dependence of in-medium BB forces??
  -- Theoretical support necessary
- Meson mass spectrum for various A and collision energy
  => density dependence of chiral symmetry restoration??
  -- Theoretical support necessary