Experimental studies of baryon modification in nuclei using hyperons

plum liquor

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plum liquor

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1. Introduction

– baryon modification in medium

Challenges in high density matter in NS

- **Hyperon puzzle (How to support heavy NS's?)**
- **Quark matter exists? (Where and how hadronic matter changes to QM?)**

Our experimental strategy (at J-PARC + JLab + SPring-8)

See Aoki (Wed. pl.), Gogami (Thu.F)

- **Determine YN, YY interactions**
  both **in free space** ← $\Sigma^{\pm}$p scattering (E40), Λp scattering (E86,Spring-8) + Femtoscopy
  and **in nuclear matter** (at ρ_0) ← Λ hypernuclei (E13,63,73,94,Jlab), $\Lambda\Lambda/\Xi$ hypernuclei (E05,07,70,75,96)
- **Study** ρ **(>ρ_0) dependence** of YN int. (YNN 3-body force)
  ← Precise Λ hypernuclear spectroscopy (P84)

⇒ Investigate whether NS properties can be microscopically described in terms of hadrons in accordance with all the experimental data and lattice QCD calculations.
If not => indirect evidence for QM presence in NS.

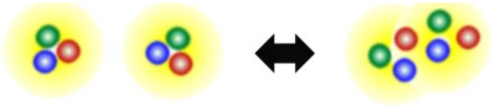
- Ab-initio (variational, BHF, …) approaches are necessary to extrapolate to higher densities ($\rho > \rho_0$).
  (Phenomenological calc. based on nuclear data at $\rho \sim \rho_0$ do not work!)
- But they assume that properties of nucleons (baryons) and nuclear force (BB forces) are unchanged.

・Nucleons (baryons) are modified even at ρ_0, and may be further modified at higher ρ!
・Nucleon modification could be related to partial deconfinement (crossover transition)??

"Modification" of baryons in nuclear matter

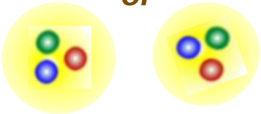
■ **EMC effect (Change of structure function in DIS)**

-- Experimentally established but not well understood.
Short Range Correlation data at JLab give suggestions.



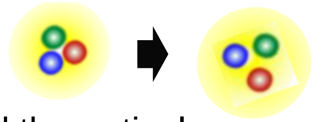
short range correlation

or



Always modified in nuclei?

■ **Nucleon swelling?**



-- Various experimental and theoretical suggestions/conjectures but no clear evidence

TABLE I. The magnitudes of nucleon swelling inferred from experiments and predicted from various models.

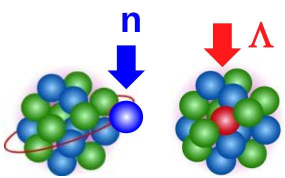
Experiment/model	Size of nucleon swelling
Quasielastic scattering [49]	<3–6% for ^{3}He
K^{+}-nucleus scattering [50]	10–30% for ^{12}C and ^{40}Ca
nIMParton [20]	2.0–8.1% for ^{3}He-^{208}Pb
QMC [48]	5.5% for typical nuclei
Binding potential [54]	A few % for typical nuclei
Skyrmion model [55]	3–4%
Quark-*N* interaction [56]	≈2% for nuclear matter
Chiral quark-soliton [57]	≈2.4% for heavy nuclei
Chiral symmetry [58]	<10% for nuclear matter
N-*N* overlapping [37]	4.7–22% for ^{3}He-^{208}Pb
Weak stretching [59]	4.5–9.4% for ^{4}He-^{208}Pb
PLC suppression [60]	1–3%
Statistical model [61]	2.2–5.0% for ^{4}He-^{197}Au
Quark-quark correlation [62]	15%
Chiral quark-meson [63]	≈19% for nuclear matter
String model [64]	40%

PRC 99 (2019) 035205

-- What are good probes sensitive to "baryon modification" in low energy phenomena ?

Modification of N cannot be separated from properties of nuclear matter.
Effects of N modification could be seen for valence nucleons, but they are located at a low density region.

Hyperon: Distinguishable from nucleons in NM.
Free from Pauli blocking from nucleons and can stay in the 0s orbit
=> a suitable probe



What probes should be used?

- Compare electro/weak properties of hyperons in free space and in nuclear matter
  - **Magnetic moment of Λ** => *On-going:* Λ's spin-flip B(M1) (J-PARC E63)
  - Electromagnetic decay of $\Sigma^0 \to \Lambda \gamma$
  - Weak decays of Λ

- Avoid strongly interacting probes – Medium effects are hidden by FSI.
  - 😢 Mesonic weak decay ($\Lambda \to N\pi$)
  - 😢 Nonmesonic weak decay ($\Lambda N \to NN$)
  - 😊 **Beta decay ($\Lambda \to p\, e^- \nu^{bar}$)** => *Under detailed design*

- Discriminating "baryon modification" effects from hadronic effects (meson exchange current, baryon mixing...) and nuclear many-body effects is a key.
  Hadronic and nuclear effects should be small or reliably estimated.

2. Magnetic moment of Λ in nuclear matter

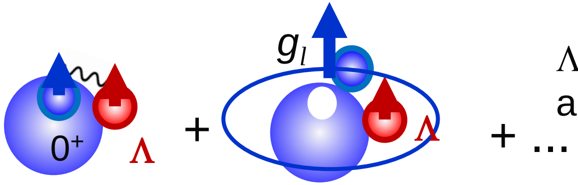
Modification of μ_Λ in nuclear medium?

can be estimated.

Nuclear level

- **Core polarization**

  Should be small for Λ.



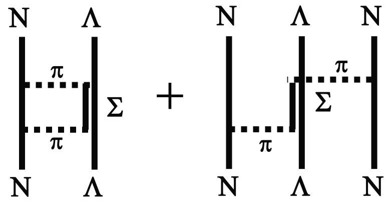
ΛN spin-dependent interactions are **weaker by <1/10** than NN

Hadron level

- **ΛN–ΣN mixing**:

  C.B. Dover, H. Feshbacj, A. Gal, PRC 51 (1995) 541.

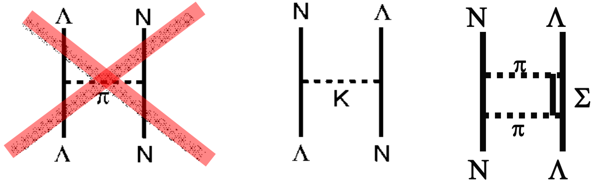
  $\Delta\mu_\Lambda$ = 2--5 % for $^4_\Lambda$He, smaller for T=0 hypernuclei



- **K, 2π exchange current:** *K. Saito, M. Oka, T. Suzuki, NPA 625 (1997) 95.*

  -9% for $^5_\Lambda$He

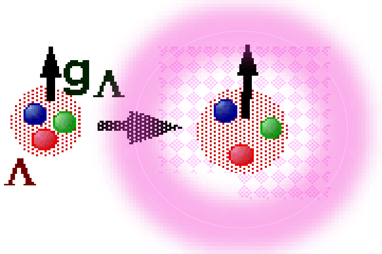
  -7% for $^7_\Lambda$Li



Quark level

- Structure change of a Λ in nuclear matter

  baryon swelling -> enhance μ_Λ ??



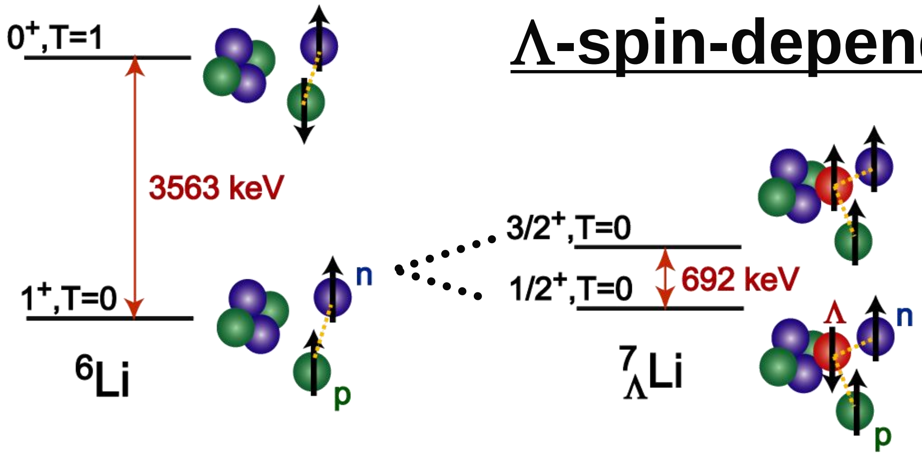
$$\mu_q = \frac{e\hbar}{2m_q c}$$

m_q : Constituent quark mass   How does it change?

Its change in nuclear matter gives a clue to understand origin of baryon spin

- "Quark exchange current" in QCM   *T. Takeuchi, K. Shimizu, K. Yazaki, NPA 481 (1988) 693*

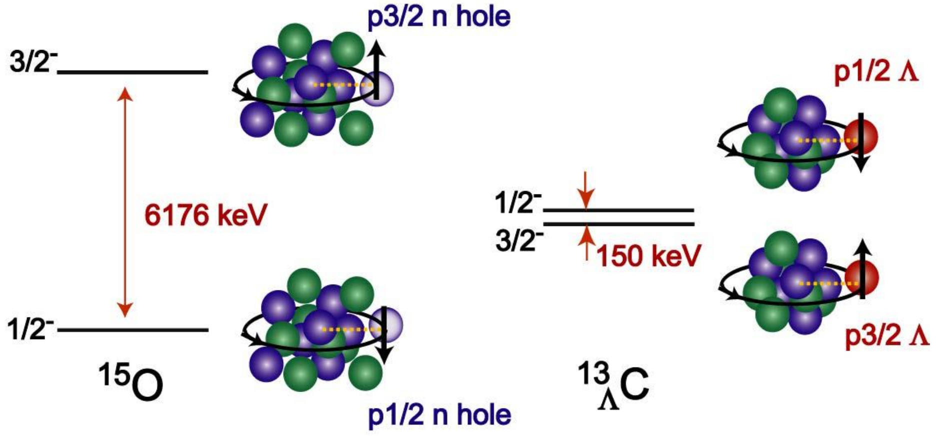
Λ-spin-dependent forces are weak



=> ΛN spin-spin force
~ 1/10 of NN spin-isospin force

($\Delta = 0.42$ MeV)

Tamura et al., PRL 84 (2000) 5963



=> ΛN spin-orbit force
~ 1/40 of NN spin-orbit force

($S_\Lambda = -0.01$ MeV)

Ajimura et al., PRL 86 (2001) 4255

=> Nuclear core polarization effects should be much smaller.

How to measure μ_Λ in a nucleus?

- Measurement of μ_Λ in a hypernucleus is very difficult => possible with Heavy Ion beams

- **Λ-spin-flip M1 transition: B(M1) -> g_Λ**

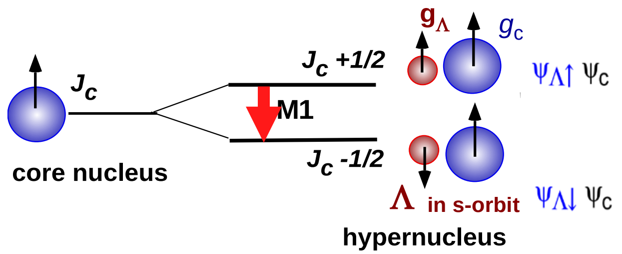
$$B(M1) = (2J_{up}+1)^{-1} \left| \langle \Psi_{low} \| \mu \| \Psi_{up} \rangle \right|^2$$
$$= (2J_{up}+1)^{-1} \left| \langle \psi_{\Lambda\downarrow} \psi_c \| \mu \| \psi_{\Lambda\uparrow} \psi_c \rangle \right|^2$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$$

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

: assuming **"weak coupling"** between a Λ and the core.

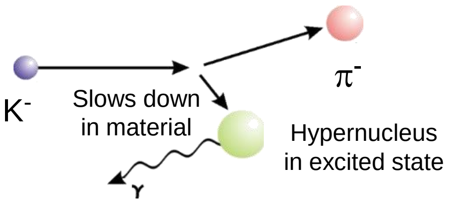
R.H. Dalitz and A. Gal, Annals of Phys. 116 (1978) 167.



$$\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 \, B(M1)$$

$^7_\Lambda$Li ~100%

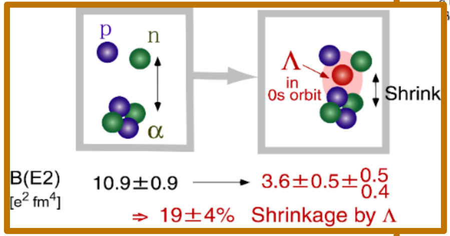
Doppler Shift Attenuation Method

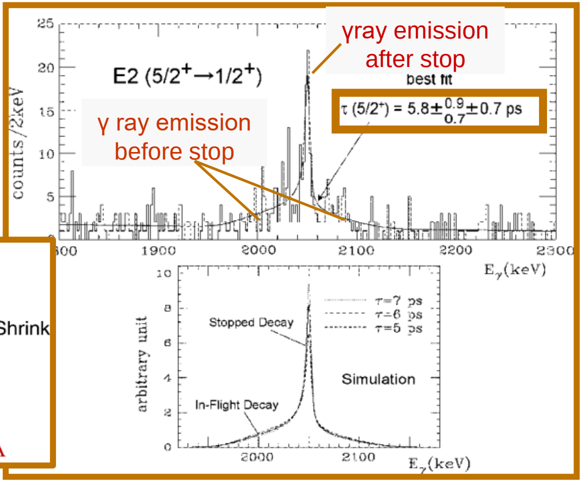


An example of Doppler Shift Attenuation Method

B(E2) of $^7_\Lambda$Li($5/2^+ \rightarrow 1/2^+$) was measured

Tanida et al., PRL 86 (2001) 1982





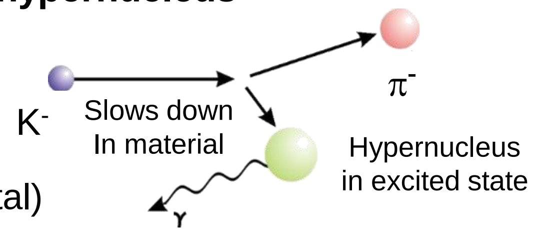
Experiment at J-PARC (E63)

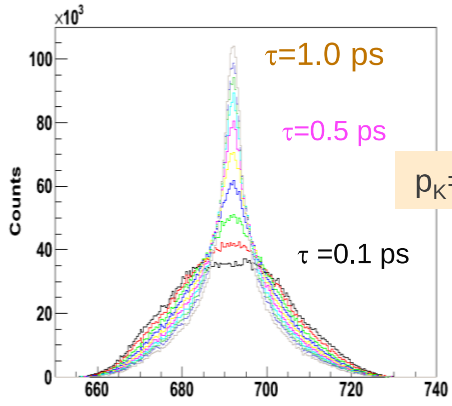
$^{7}_{\Lambda}$Li : the best-studied hypernucleus

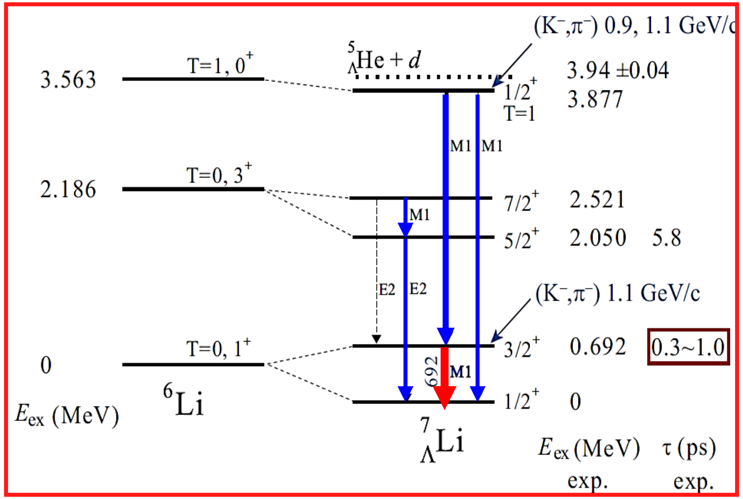
Doppler Shift Attenuation Method

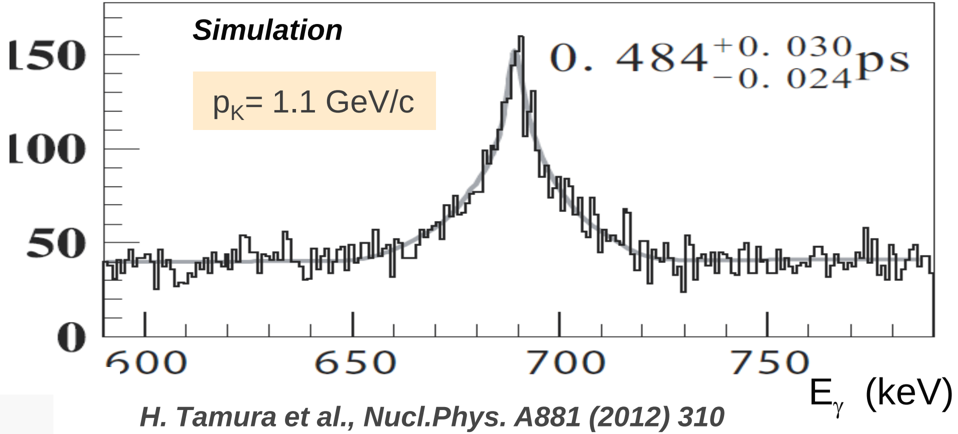
τ ~ 0.5 ps, t_{stop} ~ 2 ps

in Li_2O (2.01 g/cm^3, single crystal)









H. Tamura et al., Nucl.Phys. A881 (2012) 310

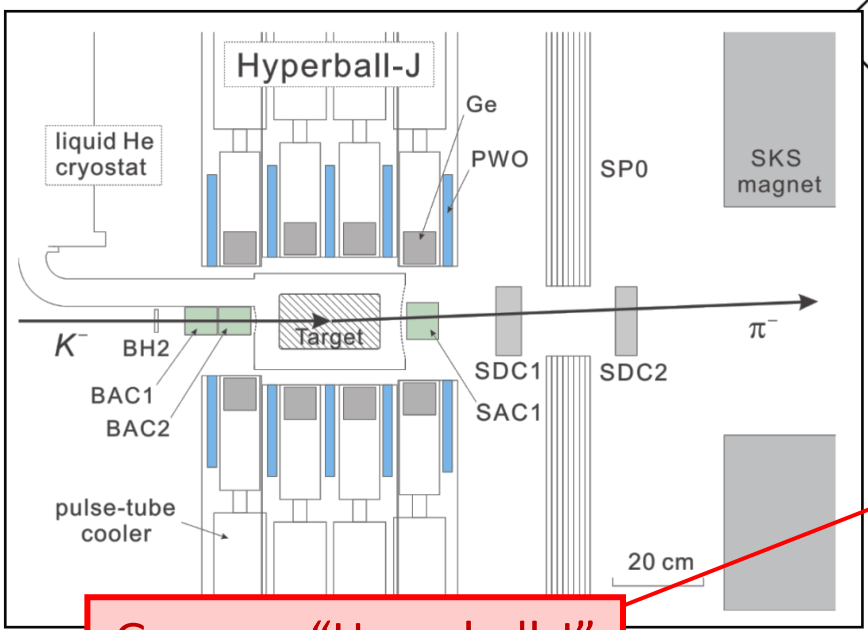
For 35 days for 50kW
Assuming 176k K^-/spill for 1.1 GeV/c

Stat. error
$\Delta\tau/\tau = 6\%$

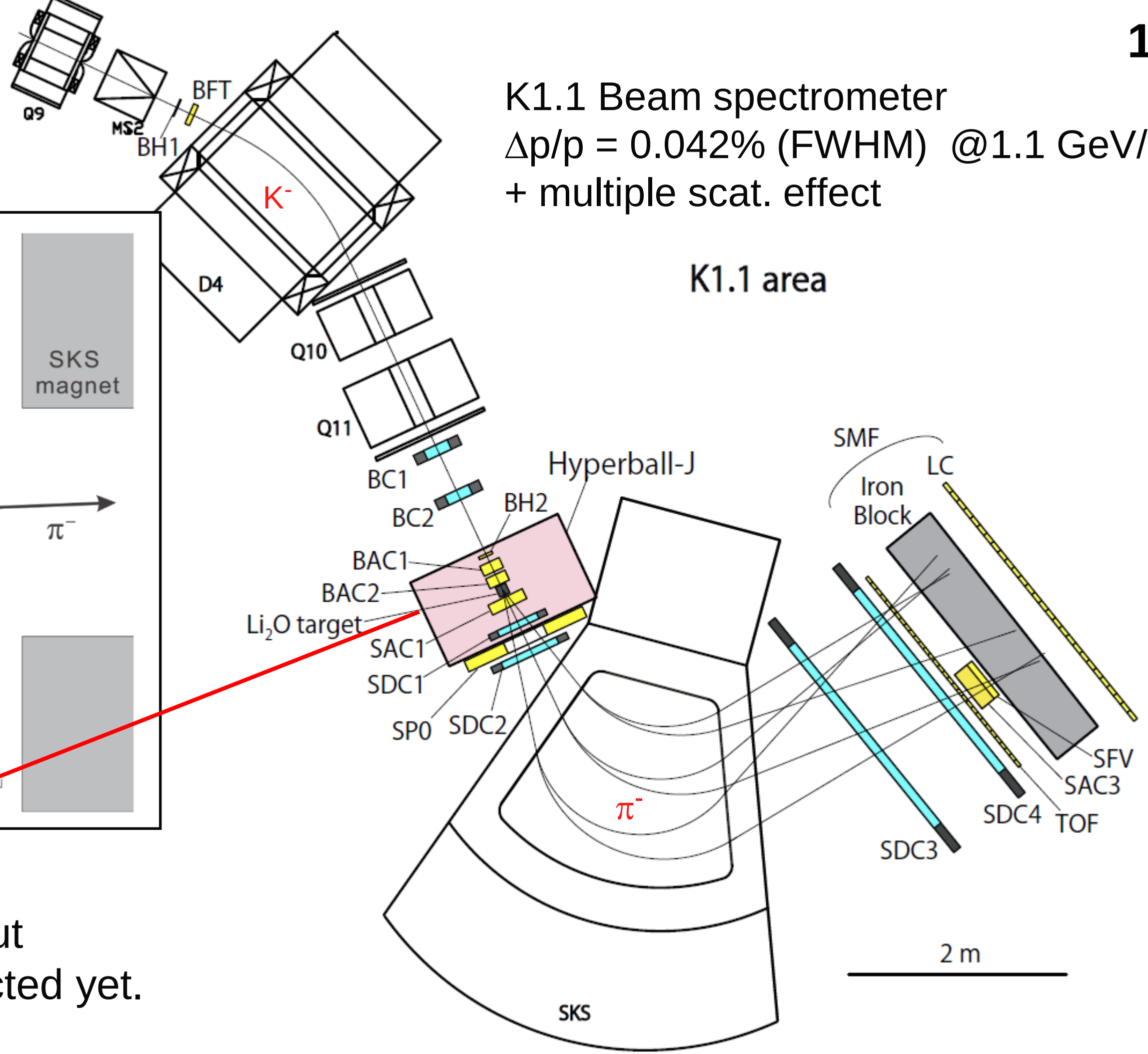
$$\Rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

E63 setup

K1.1 Beam spectrometer
$\Delta p/p$ = 0.042% (FWHM) @1.1 GeV/c
+ multiple scat. effect



Ge array "Hyperball-J"



All the detectors are ready, but
K1.1 beamline is not constructed yet.

Calculations for nuclear many-body effects

Experimental values:

^{6}Li: $g_c = 0.822047 \mu_N$

Λ: g_Λ (free) = $-1.226 \pm 0.008\ \mu_N$

=> If weak coupling is OK,

$^7_\Lambda$Li B(M1) = $0.334 \pm 0.003\ \mu_N^2$

Calculations

	$J_i, T_i \rightarrow J_j, T_f$	$B(M1)\ (\mu_N^2)$	
$^7_\Lambda$Li	$3/2^+, 0 \rightarrow 1/2^+, 0$	0.322	$^5_\Lambda$He+p+n cluster (Hiyama et al.) [a]
		0.352	^{4}He+d+Λ cluster (Motoba-Bando-Ikeda) [b]
		0.364	Shell model (Dalitz-Gal) [c]

-3.5% from weak coupling

+5.5% from weak coupling

[a] H. Hiyama et al., PRC 59 (1999) 2351.

[b] T. Motoba, H. Bando, K. Ikeda, T. Yamada, PTP Suppl. 81 (1985) 42.

[c] R.H. Dalitz and A. Gal, Annals of Phys. 116 (1978) 167.

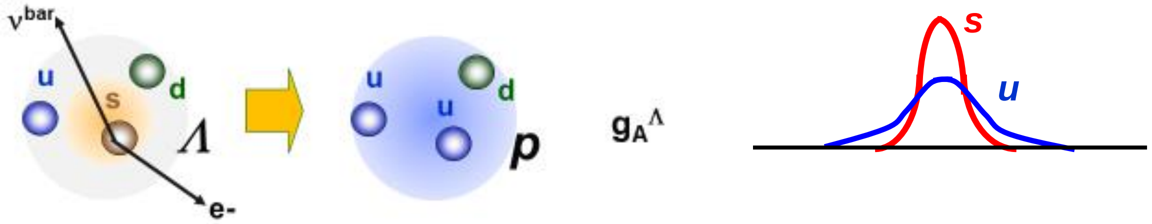
- *Suggesting that the weak coupling hypothesis holds well (<3.5%).*
- *Better calculation by Hiyama is going on.*
  ^{4}He+p+n+Λ cluster model with and without Λ–Σ coupling
- *Ab-initio 7-body calculations in future (if the measurement is done)*

3. Beta-decay of Λ in nuclear matter

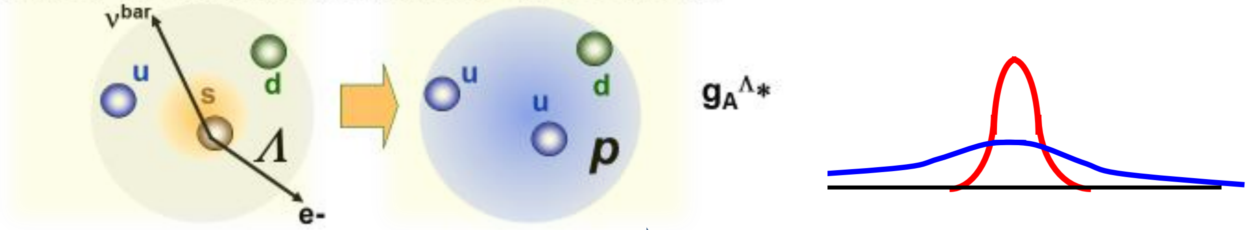
Modification of g_A^Λ due to baryon "swelling" in medium

$\Lambda \rightarrow p\, e^- \nu^{bar}$ **Sensitive to overlap of u and s quark w.f.**

In free space



In nuclear medium if u,d quarks are more spread, but s quark is not spread, then



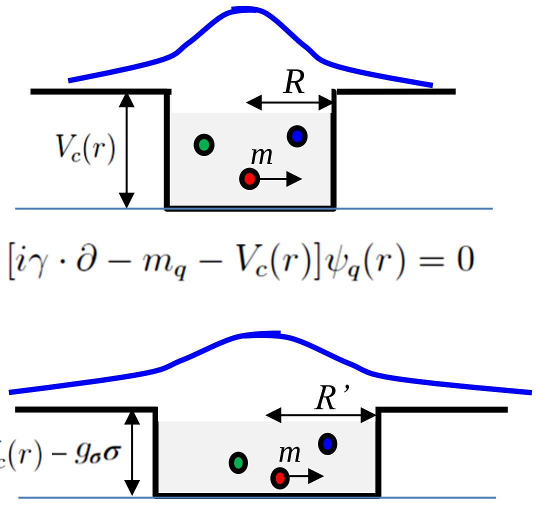
Less overlap between s and u quarks → *Reduction of beta decay rate in medium*

Prediction by Quark Meson Coupling Model

Lambda beta-decay in-medium

P.A.M. Guichon, A.W. Thomas / Physics Letters B 773 (2017) 332–335

QMC model: u,d quarks couple to σ, ρ, ω fields in a nucleus but s quark does not.



$$[i\gamma \cdot \partial - m_q - V_c(r)]\psi_q(r) = 0$$

$$[i\gamma \cdot \partial - \underbrace{(m_q - g_\sigma\sigma)}_{m^*} - V_c(r)]\psi_q(r) = 0(r) = 0$$

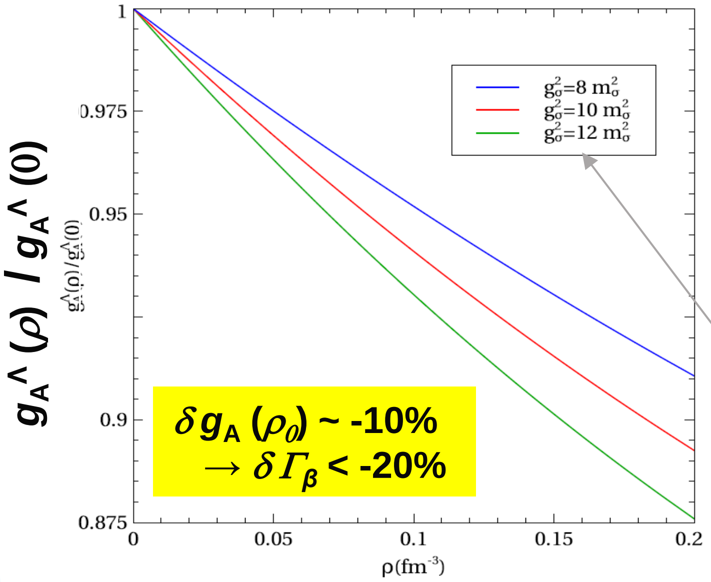


Fig. 1. Relative variation of the axial coupling as a function of density.

- $m^* = m - g_{q\sigma}\sigma$ and w,f. of u,d quarks in a baryon change due to scalar field σ.
- m^* and w.f. of s quark do not change.

$g_{q\sigma}$ determined from saturation density via various many-body theoretical treatments

Weak decay of Λ

Free Λ

Λ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p\pi^-$		(63.9 ±0.5) %		101
$n\pi^0$		(35.8 ±0.5) %		104
$n\gamma$		(1.75±0.15) × 10^{-3}		162
$p\pi^-\gamma$	[c]	(8.4 ±1.4) × 10^{-4}		101
$pe^-\overline{\nu}_e$		(8.32±0.14) × 10^{-4}		163
$p\mu^-\overline{\nu}_\mu$		(1.57±0.35) × 10^{-4}		131

$^5_\Lambda$He (best known)

	from τ	Λ→pπ⁻	Λ→nπ⁰	ΛN→NN
Experiment/Theory	$\Gamma_{tot}/\Gamma_\Lambda$	$\Gamma_{\pi^-}/\Gamma_\Lambda$	$\Gamma_{\pi^0}/\Gamma_\Lambda$	$\Gamma_{nm}/\Gamma_\Lambda$
Exp. (K^-,π^-), BNL [7]	1.03±0.08	0.44±0.11	0.18±0.20	0.41±0.14
KEK E462 Exp. (π^+,K^+), KEK [8, 9]	0.947±0.038	0.340±0.016	0.201±0.011	0.406±0.020
Theor. [10] (YNG)		0.393	0.215	
Theor. [11]		0.386	0.196	
Theor. [12]	0.966			0.358
Theor. [13] (NSC97f)			0.317	
Theor. [14]			0.43	

Γ_Λ: free Λ decay rate

[7] J.J. Szymanski et al., Phys. Rev. C43 (1991) 849.
[8] S. Kameoka et al., Nucl. Phys. A754 (2005) 173c.
[9] S. Okada et al., Phys. Lett. B 597 (2004) 249; S. Okada et al., Nucl. Phys. A754 (2005) 178c.
[10] T. Motoba, H. Bandō, T. Fukuda, J. Žofka, Nucl. Phys. A534 (1991) 597.
[11] I. Kumagai-Fuse, S. Okabe, Y. Akaishi, Phys. Rev. C 54 (1996) 2843.
[12] K. Itonaga, T. Motoba, Prog. Theor. Phys. Suppl. 185 (2010) 252.
[13] A. Parreno, A. Ramos, Phys. Rev. C 65 (2001) 015204.
[14] C. Barbero, C. De Conti, A.P. Galeao, F. Krmpotic, Nucl. Phys. A 726 (2003) 267.

What to measure?

Measure branching ratio BR_β and lifetime τ of a hypernucleus

$$\Gamma_\beta = BR_\beta/\tau \propto (g_V^\Lambda)^2 \, |\int 1|^2 + (g_A^\Lambda)^2 \, |\int \sigma|^2$$

Free Λ $\quad = (g_V^\Lambda)^2 + 3\,(g_A^\Lambda)^2 \sim 1 + 1.56$

$g_V^\Lambda = 1$

$g_A^\Lambda / g_V^\Lambda = -0.718 \pm 0.015$

Goal for statistical error: $\Delta BR_\beta / BR_\beta \sim 4\%$ and $\Delta\tau/\tau \sim 2\%$ => **$\Delta\Gamma_\beta / \Gamma_\beta \sim 5\%$ => $\Delta g_A^\Lambda / g_A^\Lambda \sim$ 4.1%**

Lifetime measurement of $\Delta\tau/\tau \sim 2\%$ possible (4% in KEK E463), but $\Delta BR_\beta / BR_\beta \sim 4\%$ is a challenge.

Light hypernuclei -> Little quenching of g_A from meson exchange current and nuclear effects.

$^5_\Lambda$He

^{4}He(0^+)

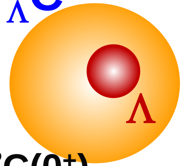
$^5_\Lambda$He($1/2^+$) → ^{4}He p e^- ν^{bar}

Λ w.f. widely spread -> lower ρ -> Effect may be reduced.

g_A quenching by hadronic / nuclear effects ~ 5% in ordinary β decay

Experiment feasible. Few-body calculation may be possible.

$^{13}_\Lambda$C



^{12}C(0^+)

$^{13}_\Lambda$C($1/2^+$) → " ^{13}N " e^- ν^{bar}

Λ w.f. not spread. -> Effect may not be reduced.

g_A quenching by hadronic / nuclear effects ~ 10--20% in ordinary β decay

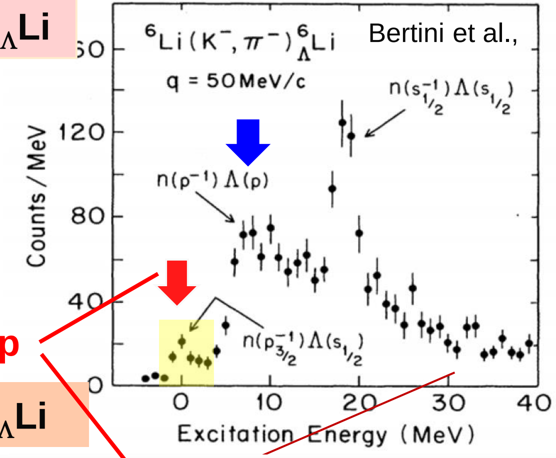
Experimentally easier, but theoretically difficult.

Production of $^{5}_{\Lambda}$He and $^{13}_{\Lambda}$C

M. May et al., PRL 47 (1981) 1106

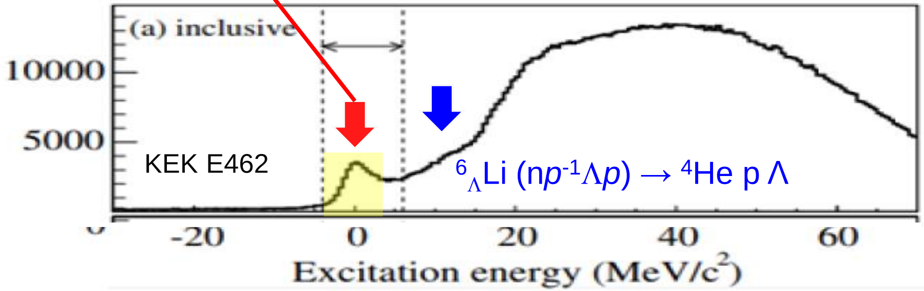
Production of both is well studied via (K^-, π^-) and (π^+,K^+).

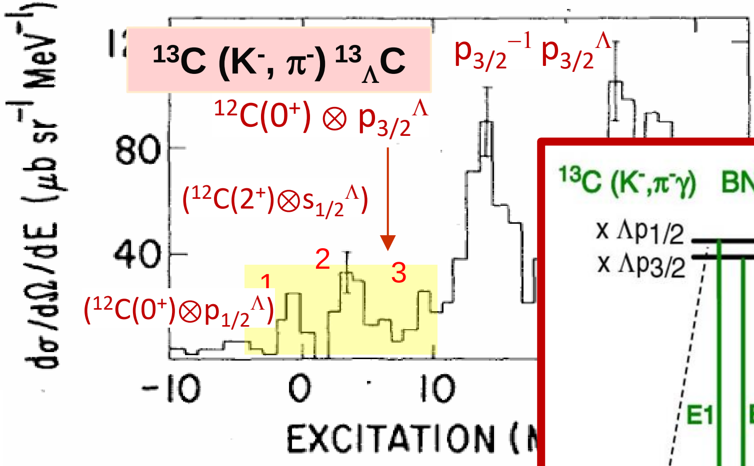
^{6}Li (K^-, π^-) $^{6}_{\Lambda}$Li

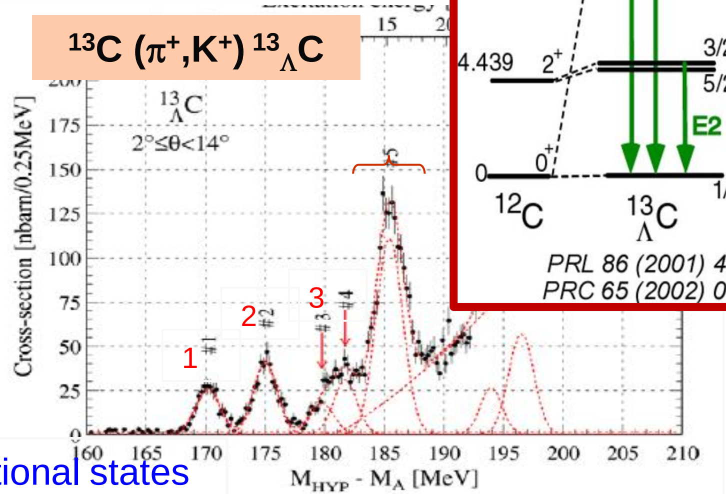


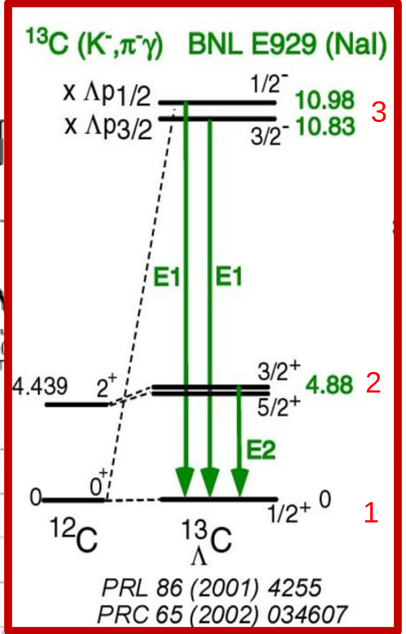
$^{6}_{\Lambda}$Li$_{g.s.}$ → $^{5}_{\Lambda}$He + p

^{6}Li (π^+,K^+) $^{6}_{\Lambda}$Li







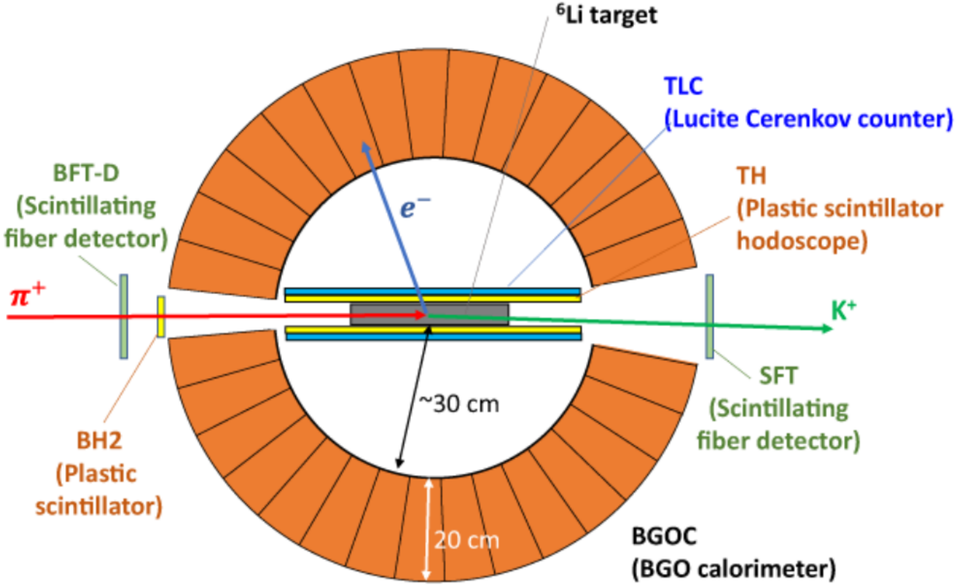


(K^-, π^-) : Not well separated from unbound n(p^{-1})Λ(p) substitutional states

(π^+,K^+) : Need an intense beam -> Detector rate high.

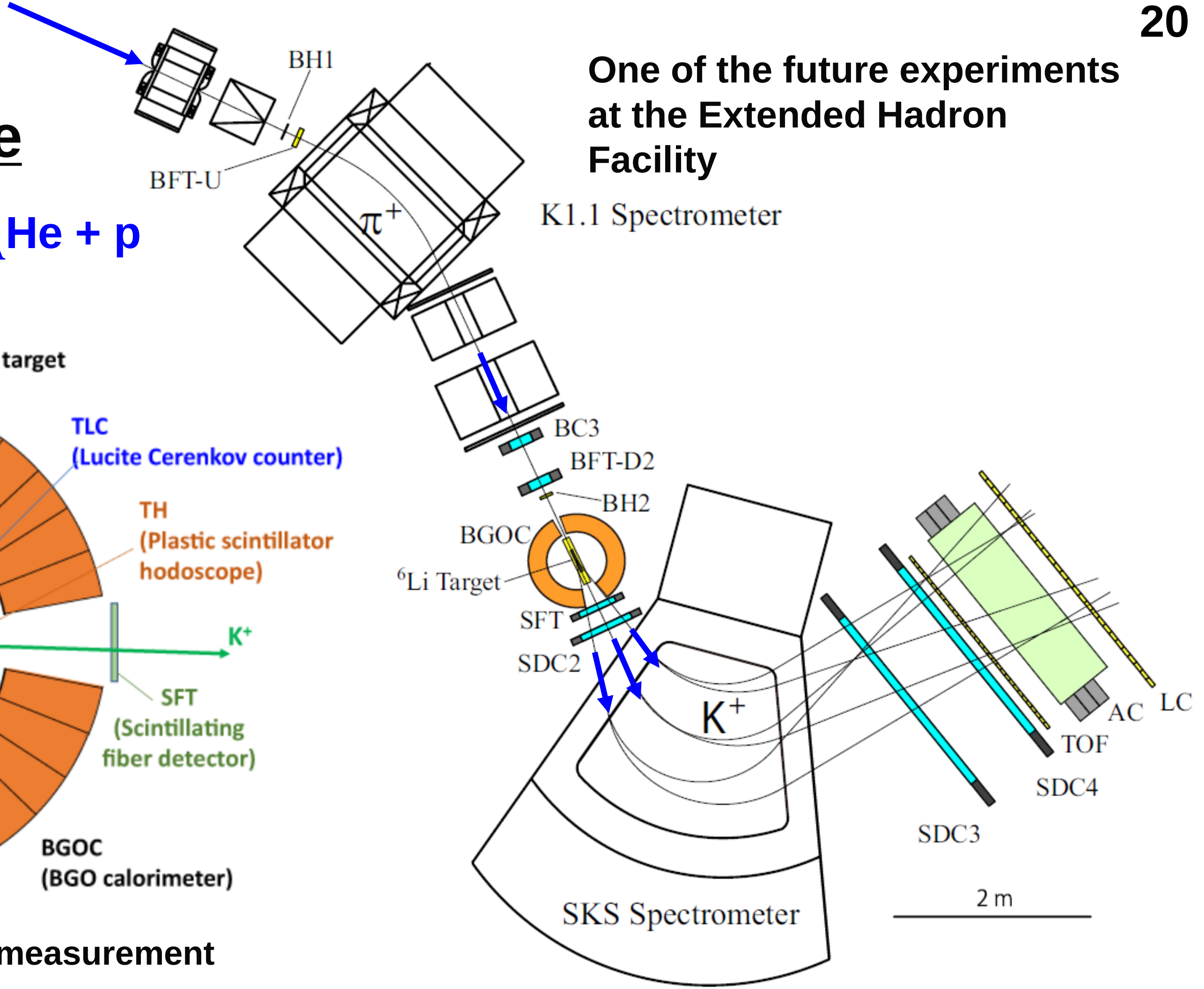
Planned setup at J-PARC K1.1 line

$^{6}Li(\pi^{+},K^{+})\,^{6}_{\Lambda}Li$, $^{6}_{\Lambda}Li \rightarrow \,^{5}_{\Lambda}He + p$



Setup around the target for BR measurement

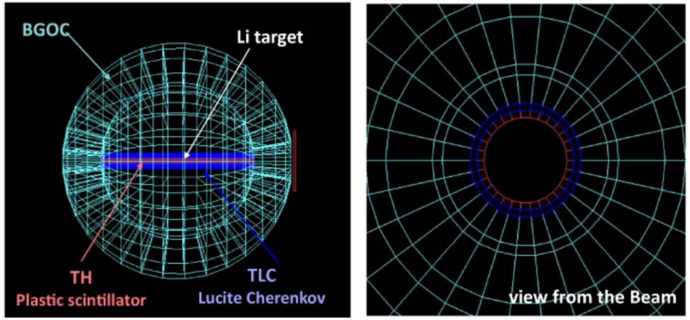
One of the future experiments at the Extended Hadron Facility



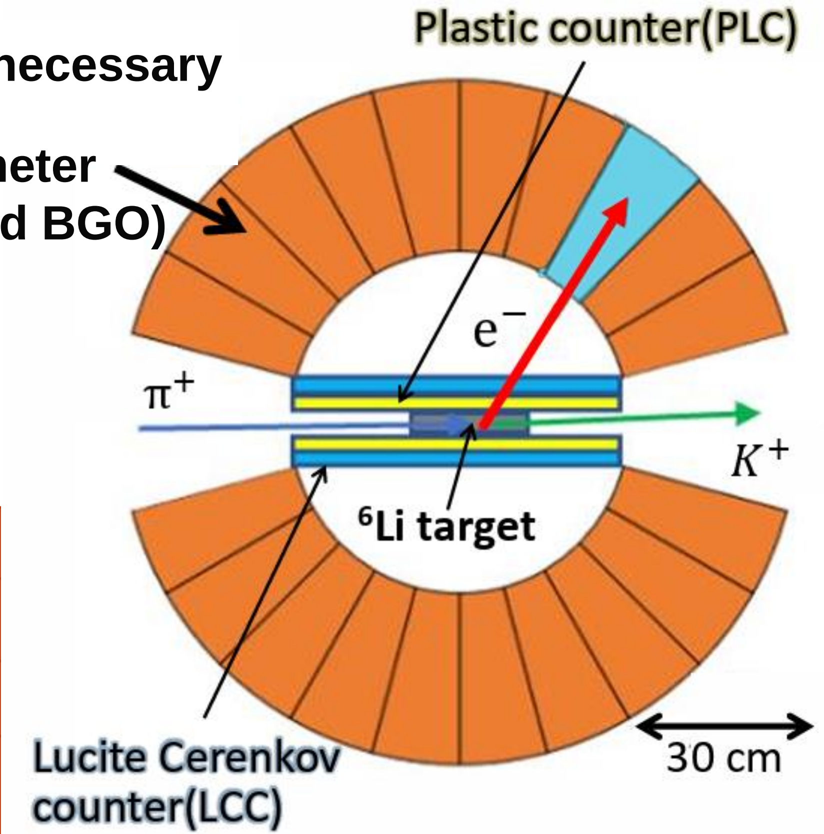
Setup design with GEANT4 simulation

by K. Kamada and M. Fujita

Challenge: Background reduction by 10^{-5} necessary



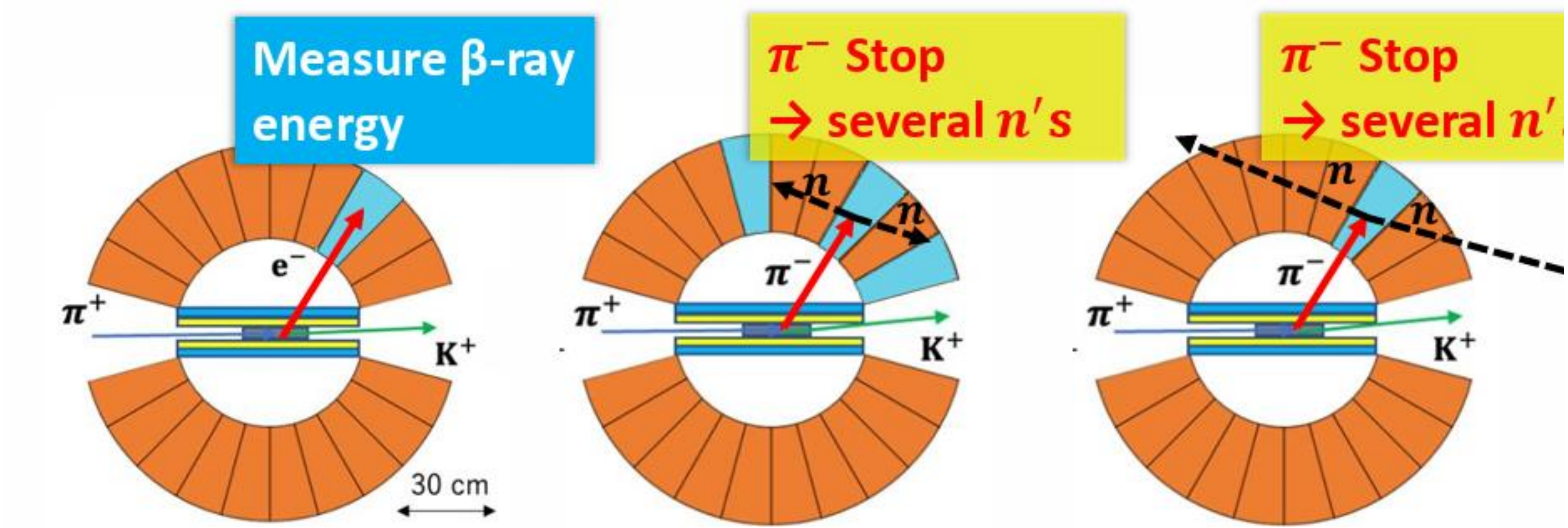
Calorimeter (segmented BGO)



Detector	Discriminate betweeni
PLC	e- / π-, p / n, γ (by ΔE)
LCC	e- (β~1) / π-(β~0.6), p((β~0.4) / n, γ
BGOC	Measure e- energy e- / π- (# of hit clusters)

[2] K. Kamada, Master's thesis (2021)

Beta-decay ID via clustering of calorimeter hits



1 cluster	Multi-clusters	1 cluster
Signal (β-decay e⁻)	Background (π⁻) ~ 93 % rejected	Background (π⁻) ~ 7 % not rejected

π^- absorption in BGO + neutron efficiency in BGO not well reproduced in GEANT4 (by C. Seong) → **We will measure them.**

Expected beta-ray spectrum

Background/ Signal

$\approx$ BR(π^0 bg)/ 0.68 BR(β)

= 0.35×10^{-4} / (0.68 x 8.3×10^{-4})

= 0.06

If background level can be experimentally estimated within 30% accuracy,
the systematic error in BR(β) will be < 2%

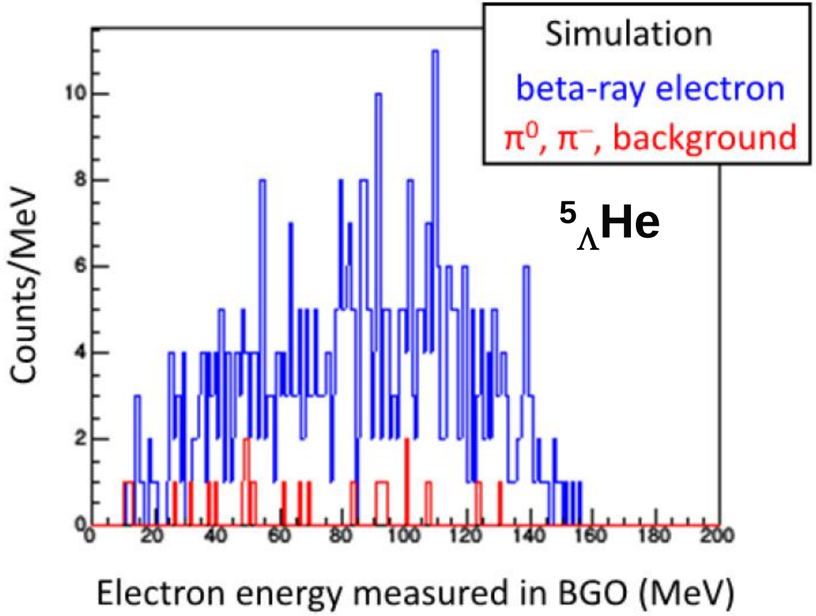


Figure 11: Simulated spectrum of the beta-ray electron energy (blue) and the contaminated background events (red) after all the background rejection analysis. The number of the background events is 4% of that of the beta-ray electron.

H.Tamura et al., J-PARC Letter-Of-Intent

Yield and statistical error for BR

1400 hours (2 months) beam time each w/100 kW proton intensity is assumed.

$^{5}_{\Lambda}$He via (π^+, K^+) @ K1.1+SKS

^{6}Li (π^+, K^+) $^{5}_{\Lambda}$He+p	PS-E462	Expected (in LOI)
# of pi+ beam (Any beamline)	2.5x10^{12}	24x10^{12} (20M/spill x1400h)
Target: ^{6}Li metal	3.7g/cm^2	14g/cm^2 (30 cm)
$\Delta\Omega_{eff}$ (SKS) x Eff.	↓	
$^{5}_{\Lambda}$He counts	45653	1.6x10^6
BR(beta) x Pauli		8x10^{-4} x 0.6
Eff (e-)		0.7
Beta-ray counts		550

$\sqrt{N_e}/N_e$ = 4.3%

$^{13}_{\Lambda}$C via (K^-, π^-) @K1.8 + S-2S

^{13}C (K^-, π^-) $^{13}_{\Lambda}$C	Expected
# of K- beam 1.5 GeV/c @K1.8	1.5x10^{12} (1.25 M/spill x1400h)
Target: ^{13}C scintillator	20 g/cm^2 (20 cm)
$\Delta\Omega_{eff}$ (S-2S) x Eff.	37 msr x ~0.7
$d\sigma/d\Omega$: $^{13}_{\Lambda}$C(0^+,2^+) @2^o-12^o 100+200 μb/sr x1/3	2.9x10^6
BR(beta) x Pauli	8x10^{-4} x ~ 0.3
Eff (e-)	0.7
Beta-ray counts	602

$\sqrt{N_e}/N_e$ = 4.1%

Theoretical calculations for $^{5}_{\Lambda}$He and $^{13}_{\Lambda}$C?

- **Nuclear effects of the daughter proton**
  ----Precise estimate w/ Pauli effect + ^{5}Li/ ^{13}N structure
- **Hadronic effects**
  ----Meson exchange current should be estimated.
- **Estimate "quark effects" from the effective density which a daughter proton feels**

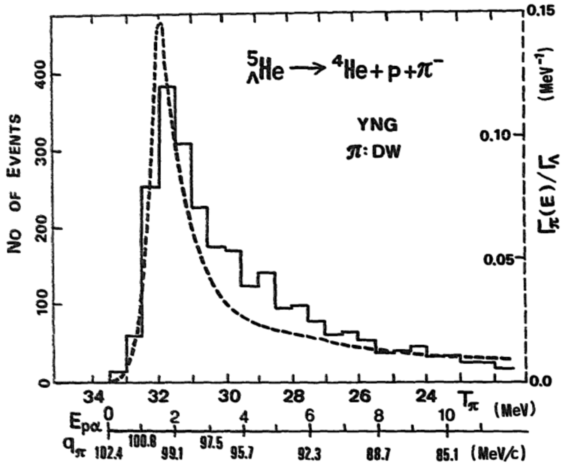


Fig. 4. The theoretical π⁻ decay spectrum $\Gamma_{\pi^-}(^{5}_{\Lambda}\mathrm{He})/\Gamma_\Lambda$ with YNG drawn as a function of the pα relative energy $E_{p\alpha}$ is compared with the observed π⁻ decay spectrum taken in the emulsion experiment [18,33]. The calculated π⁻ decay rate is compared with the experimental values [12,20] in table 1 and fig. 5.

T. Motoba et al., NPA 534 (1991) 597.

A good example:
Precise few-body calculation with N^{3}LO chiral perturbation theory for ^{6}He→ ^{6}Li beta decay

S.Vaintraub, N. Barnea, D. Gazit, PRC 79 (2009) 065501

Exp/Theory = 0.91 -> 0.975

- *Triton beta-decay rate is used to determine the LEC relevant to MEC.*
- *Very small dependence on the cutoff parameter.*
- *Nuclear many-body calculation using Hyperspherical-Harmonics expansion.*

A similar calculation is possible for $^{5}_{\Lambda}$He, but LEC for Λ should be determined.

Summary and prospect

- Electro-weak properties of hyperons in hypernuclei are good probes to investigate possible modification of baryons in nuclear matter.
- Magnetic moment (g-factor) of Λ in nuclei could be a probe for baryon modification.
  - We will measure the g_Λ in a nucleus in 5% accuracy via a B(M1) value of ${}^{7}_{\Lambda}$Li($3/2^+ \rightarrow 1/2^+$) transition (J-PARC E63).
- Λ's beta decay rate could be significantly changed due to baryon modification.
  - Measurement with ~ 5% statistical accuracy is possible for ${}^{5}_{\Lambda}$He and ${}^{13}_{\Lambda}$C.
  - GEANT4 simulation shows that huge background can be sufficiently suppressed and detailed desing of the experiment is going on.

To theorists:

- Please estimate precisely (1)Pauli effect and nuclear many-body effects, and (2)hadronic effects (MEC) in hypernuclear beta decay for ${}^{5}_{\Lambda}$He and ${}^{13}_{\Lambda}$C
- Other model calculations for medium effect in Λ's magnetic moment and beta-decay