Possible measurement of the lifetime of Hydrogen hyperisotopes at J-PARC and JLab

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Outline

- starting point
- present experimental knowledge
- how to measure $\tau({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H)$
  - at J-PARC
  - at JLab
- evaluation: rates, beam times, statistics, …. apparatuses (feasibility, requirements)

- **starting point**

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Status and perspectives of experimental studies on hypernuclear weak decays

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Summary. — From the first beginning the weak decay of Λ-hypernuclei has been considered a very interesting physics case, since its study could shed light on several topics in nuclear and particle physics, among which the $\Lambda N \to NN$ four-baryon weak interaction not otherwise accessible. However, only in the last decade a substantial series of reliable experimental data samples has been produced thanks to the synergic effort of dedicated facilities at some laboratories in the world. The existing pattern of data on lifetimes, partial decay widths for mesonic and non-mesonic decay (both one- and two-nucleon induced) and energy spectra and correlations of the emitted particles is reviewed and compared with existing theoretical predictions. Updated tables and plots summarizing the existing experimental information are presented. For each item a brief account of possible new experimental efforts, approved, planned or futuristic is given. From these analyses the full pattern of partial decay widths for ${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He, ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C is discussed. Rare decay channels and polarization studies are also briefly analyzed.

PACS 21.80.+a – 25.80.Pw.

- **present experimental knowledge**

	B_Λ (MeV)	τ (ps)
Λ	--	263.2±2.0 CPC 38(9) (2104) 090001
${}^3_\Lambda$H	0.13±0.05±0.04 Juric NPB 52 (1973) 1	216^{+19}_{-16} RNC
${}^4_\Lambda$H	2.08±0.08 Juric NPB 52 (1973) 1 2.04±0.04±0.04 Davis, NPA 754 (2005) 1 2.12±0.01±0.09 Esser PRL 114 (2015) 232501	192^{+20}_{-18} RNC
${}^4_\Lambda$He	2.39±0.03±0.04 Davis, NPA 754 (2005) 1 $\Delta B(1^+ \rightarrow 0^+)$ = 1.406±0.002± 0.003 (Yamamoto arXiv:a508.00376)	250±18 RNC
${}^5_\Lambda$He	3.12±0.02 Davis, NPA 754 (2005) 1	273±10 RNC

CSB

CSB ?

puzzling situation:
A=1, 3, 4, 5 lifetime
A=4 I_3=-1/2 vs I_3=1/2 **B_Λ** && **lifetime**

$^{3}_{\Lambda}H$

- ions & HI: precise, not completely consistent
- new precise dedicated counter experiments to find out eventual systematic effects due to measurement method

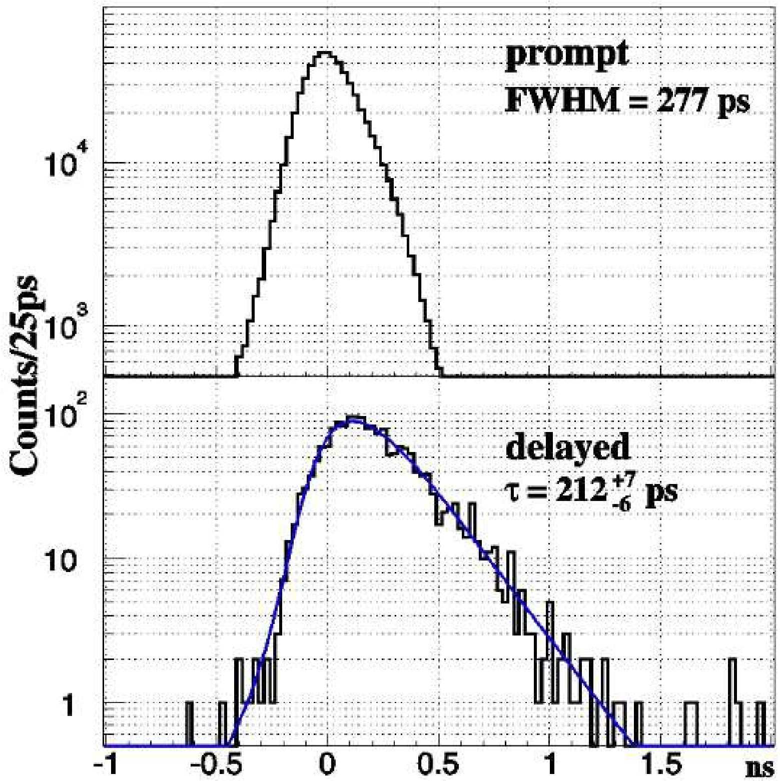
$^{4}_{\Lambda}H$

- new precise dedicated counter experiments
  → resolution below 10% (3-5%)
- UR-HI: statistics, schedule …?

• how to measure $\tau({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H)$

- counter experiments, MM spectra
- direct time delayed spectra technique (t_{decay} - t_{react})

- production reaction detection to identify the hypernucleus (MM) and measure t_{react} (HI/Ions) → trigger, apparatus (ε, $\Delta\Omega$)
- coincidence detection of MWD products (2b&3b) (t_{decay})
  → coincidence apparatus (ε', $\Delta\Omega'$)
- good MM spectroscopy resolution
- start and stop time counters with very good time resolution
- energy measurement for decay charged particles (π, p)
- background reactions ($\Lambda_{q.f.}$ production and decay, …) rejection
- prompt reaction for system time response function (σ~50 ps)



(π+, pp)

(π+, K+ p)

H.Bhang et al., Jou. Kor. Phys. Soc., 59 (2011) 1461, ^{12}C target

• how to measure $\tau(^{3}_{\Lambda}H, ^{4}_{\Lambda}H)$ at J-PARC

- π, K beams → $^{3}_{\Lambda}$**H**, $^{4}_{\Lambda}$**H** produced through associated production reaction:

  π^- (1.05 GeV/c) + ^{3,4}He → $^{3,4}_{\Lambda}$H (~400 MeV/c) + K^0(~700 MeV/c) forw. dir.

- E22 Proposal: ΛN weak interaction in A=4 Λ-hypernuclei ($\boldsymbol{\Gamma_n}$, $\boldsymbol{\Gamma_p}$, α^{NM}_{p}, ΔI=1/2)
K1.8 beamline, 1.1 GeV/c, **^{4}He (π^+, K^+) $^{4}_{\Lambda}$He**, beam & SKS spectrometer & decay arm (E15 CDC without magnet)

- Day-2 experiment to study NMWD of $^{4}_{\Lambda}$H
  production reaction **^{4}He (π^-, K^0) $^{4}_{\Lambda}$H** isospin simmetric
  K^0 from K_s decay ($\pi^+\pi^-$: 68.95%) → small detection efficiency → HIHR (?)

Parameters		Values	Parameter in Eqs.(5)
π^+ beam momentum		1.1 GeV/c	
π^+ beam intensity		$\boxed{1 \times 10^9\ /\mathrm{spill}}$	N_{Beam}
PS acceleration cycle		3.4 sec/spill	T_{Cycle}
^{4}He target thickness		1 g/cm^2	N_{Target}
Reaction cross section		$\boxed{10\ \mu\mathrm{b/sr}}$	$d\sigma/d\Omega$
Spectrometer solid angle	DWIA, Harada	0.02 sr	Ω_{SP}
Spectrometer efficiency	priv. comm.	0.03	ε_{SP}
Analysis efficiency		0.5	ε_{Anal}

E22 proposal

$$Yield\ ({}^{4}_{\Lambda}\mathrm{H}) = N_{Beam} \times \frac{N_{Target}}{4} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{SP} \times \varepsilon_{SP} \times \varepsilon_{Anal} \times \frac{Time}{T_{Cycle}}$$

$\boxed{\sim 11.4\mathrm{k}\ {}^{4}_{\Lambda}\mathrm{H/day.}}$

π^-_{react} + ^{3,4}He → $^{3,4}{}_{\Lambda}$H + K^0

$^{3,4}{}_{\Lambda}$H → ^{4}He + π^-_{decay} / d+p+π^-_{decay}

lifetime measurement: $t_{decay} - t_{react}$ = T1 – T0 = $t_{\pi-(react)} + \tau + t_{\pi-(decay)}$

prompt reaction: T1 – T0 = $t_{decay} - t_{react} = t_{\pi-(react)} + t_{\pi-(decay)}$

Yield($^4{}_{\Lambda}$H→ ^{4}He + π^-) = Yield($^4{}_{\Lambda}$H) * BR * Ω_π * ε_π * $\varepsilon_{analysis}$

= Yield($^4{}_{\Lambda}$H) * 0.49 * 0.5 * 1 * 0.8 ~ Yield($^4{}_{\Lambda}$H) * **0.2**

Tamura PRC 40 (1989) R479

~ 2 10^3/day 10^9 π^-/spill → 1-2 beam days (full HIHR) → 2-4 10^3 entries

~ 2 10^2/day 10^8 π^-/spill → 5-10 beam days (10% HIHR) → 1-2 10^3 entries

~ 2 10^1/day 10^7 π^-/spill → 10-20 beam days (present beam) 2-4 10^2 entries

$Yield(^3_\Lambda H) = Yield(^4_\Lambda H) * 4/3 * [d\sigma/d\Omega]_3/[d\sigma/d\Omega]_4$

$= Yield(^4_\Lambda H) * 1$ → $11.4\ 10^3$/day $10^9\ \pi^-$/spill
→ $11.4\ 10^2$/day $10^8\ \pi^-$/spill
→ $11.4\ 10^1$/day $10^7\ \pi^-$/spill

$= Yield(^4_\Lambda H) * 0.1$ → $11.4\ 10^2$/day $10^9\ \pi^-$/spill
→ $11.4\ 10^1$/day $10^8\ \pi^-$/spill
→ 11.4 /day $10^7\ \pi^-$/spill

$Yield(^3_\Lambda H \to d + p + \pi^-) = Yield(^3_\Lambda H) * BR * \Omega_\pi * \varepsilon_\pi * \varepsilon_{analysis}$

$\sim Yield(^3_\Lambda H) * \mathbf{0.4} * 0.5 * 1 * \mathbf{0.4} \sim Yield(^3_\Lambda H) * \mathbf{0.08}$

Kamada PRC 57 (1998) 1595 && Λ BR

~ $1.0\ 10^3$/day $10^9\ \pi^-$/spill && **1** → 1-2 days → 1-2 10^3 entries
~ $1.0\ 10^2$/day $10^8\ \pi^-$/spill && **1** → 5-10 days → 0.5-1 10^3 entries
~ $1.0\ 10^1$/day $10^7\ \pi^-$/spill && **1** → 10-20 days → 1-2 10^2 entries

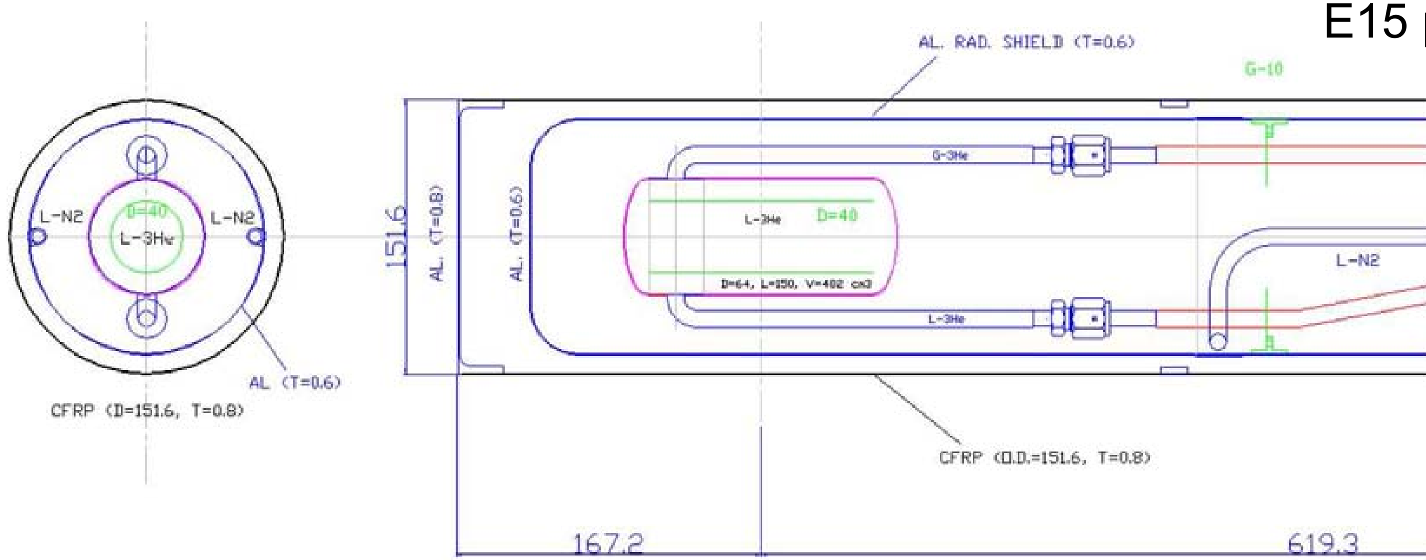
~ $1.0\ 10^2$/day $10^9\ \pi^-$/spill && **0.1** → 5-10 days → 0.5-1 10^3 entries
~ $1.0\ 10^1$/day $10^8\ \pi^-$/spill && **0.1** → 10-20 days → 1-2 10^2 entries

Apparatus hints/ideas

(high K1.8/HIHR momentum and MM resolution performances)

- LHe target, E15 He target cell, very thin material layers
  (threshold on π^- momentum ~ 70 MeV/c)
  inserted inside the inner CDC wall

E15 proposal



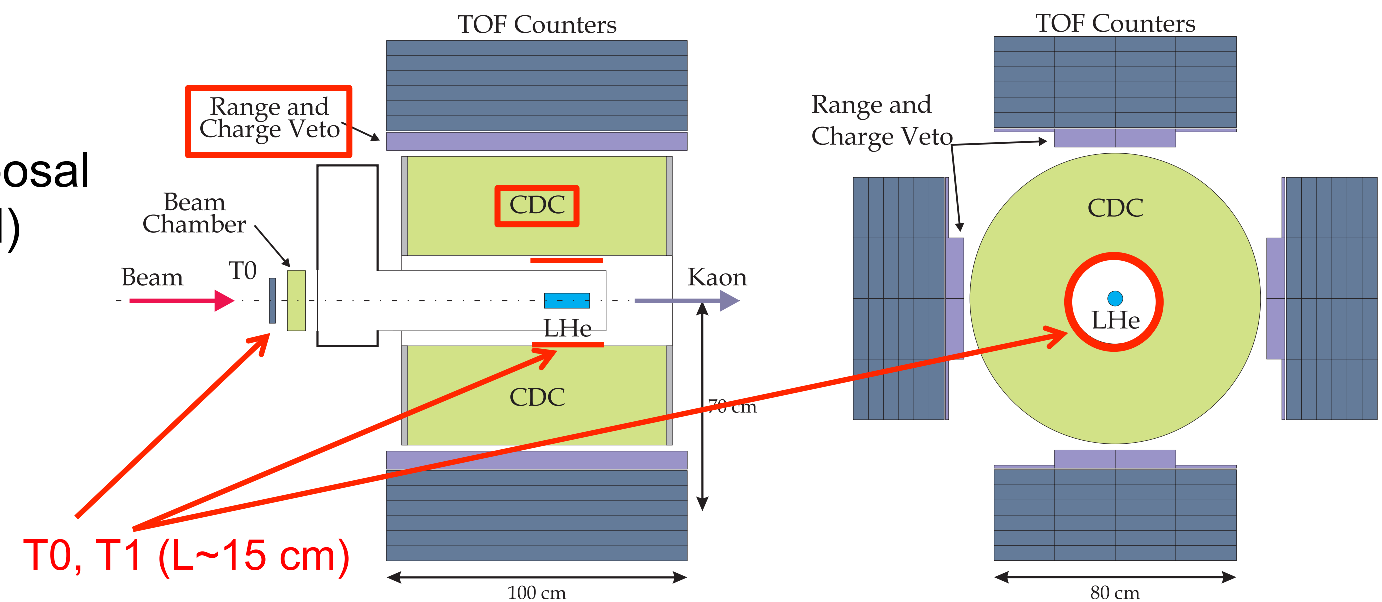
"free space" between LHe target outer wall and CDC inner wall ~ 0.4 cm radius

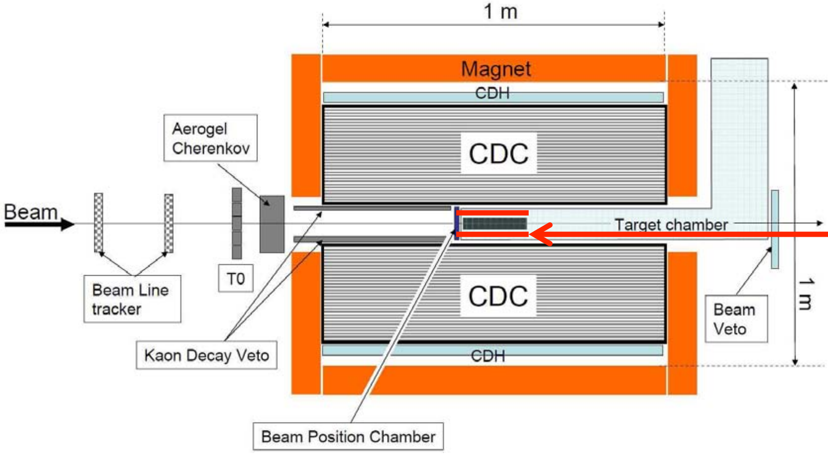
- time counters: start (T0), small segmented scintillator system ($10^7/cm^2\,s$ vs π^-/spill)
  stop (T1), scintillator barrel (12-15 slabs), 3 mm thick, 15 cm length,
  ~80-100 ps σ res., located between LHe target and CDC (r~7.8 cm)

- CDC used by E22 to reject n background due to MWD π^- absorption at rest
  → track straight charged decay particles → vertex and PId
  → use as tracker if magnet is present (E15) → vertex, π^- momentum and PId

- range counter: π^- energy measurement and PId (dE/dx vs E, R, hit position)
  (10 layers, 5.5 cm tot)
  → energy resolution < 4-5 MeV FWHM
  → PId contamination < 1%

E22 proposal (modified)





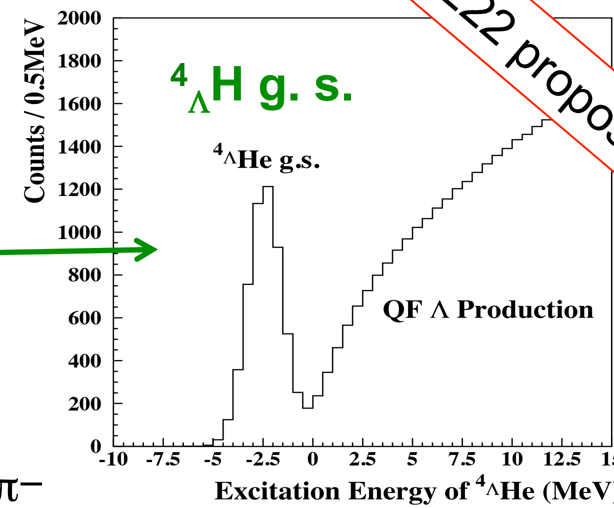
E15 proposal (modified)

T1 (L~15 cm)

- $^{3,4}{}_{\Lambda}$H not stopped before decay (~400 MeV/c, R~$\beta c\tau$, ≥ 50% (?) decay in flight in the target) → γ ~ 1.005, 0.5% max. syst.

- prompt reaction: (π^-, π^+ π^-_{prompt}), time thresholds/windows
  - π^- from production reaction: π^- + ^{3,4}He → $^{3,4}{}_{\Lambda}$H + K^0, K^0_S→π^+ π^-
  π^+: 2°-14°, p_π>650 MeV/c → π^-: 40°-100°, p_π<100 MeV/c, τ well known
  - π^-_{prompt} from (π^-, π^+ π^-) inelastic scattering

E22 proposal



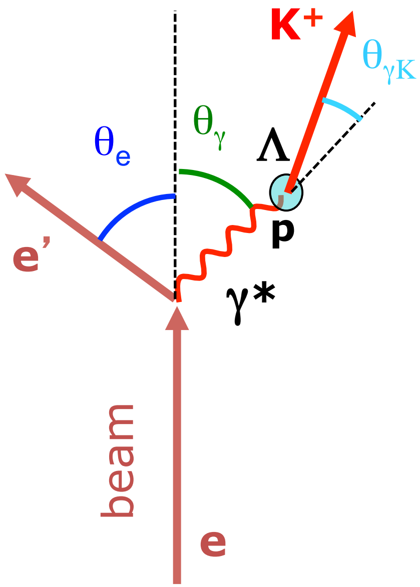
- background: $\Lambda_{q.f.}$
  - "absent" for $^4{}_{\Lambda}$H (B_Λ ~ 2 MeV, MM resolution!
  p_π ≈ 133 MeV/c)
  - $^3{}_{\Lambda}$H (B_Λ ~ 0.13 MeV) → 3b MWD: $^3{}_{\Lambda}$H → d + p + π^-
  lower π^- momentum (70-100 MeV/c): range counters → magnetic analysis

• how to measure $\tau({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H)$ at JLab

- e beams → produce ${}^{3}_{\Lambda}$**H**, ${}^{4}_{\Lambda}$**H** through electroproduction reaction:

$$e + {}^{3,4}He \rightarrow e' + {}^{3,4}_{\Lambda}H + K^{+}$$

HRS (e') HKS (K^+)



adapted from
F. Cusanno - HYPX

$E_\gamma = E(e) - E(e')$

$Q^2 = E_\gamma^2 - p_\gamma^2$

$p_\gamma = p(K^+) + p(\Lambda)$

$p(\Lambda) \sim 0.35$ GeV/c

$d\sigma/d\Omega \propto 1/Q^2 \rightarrow$ low Q^2

$d\sigma/d\Omega \rightarrow$ small θ_e

$p(\Lambda)$ small $\rightarrow \theta_{\gamma K} \sim 0^o$

high $p(K^+)$ for surv. prob.

$$MM^2 = (q^\mu + P_{\text{miss tot}} - p^\mu_K)^2$$

$\sigma_{MM} \sim$ 500-600 keV FWHM

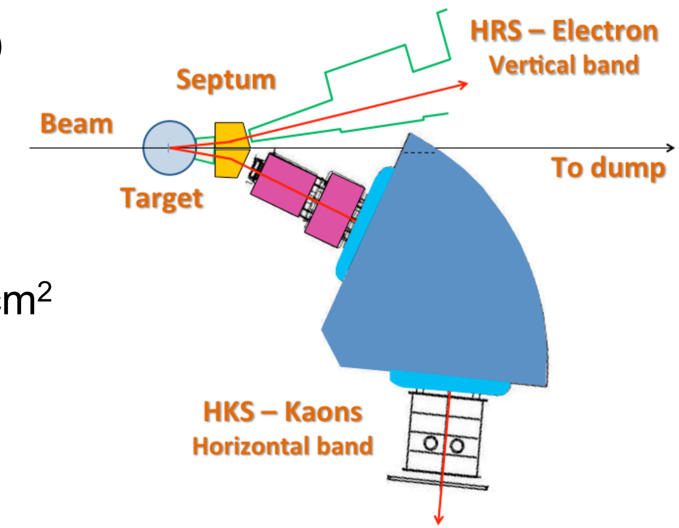
MM calibration: $p(e, e' K+)\Lambda$

- Proposal JLab Hypernuclear Collaboration (JLab PAC43)

- ΛN interaction & charge-zero exotic hyp. (nΛ, nnΛ)
- CSB A=4
- B_Λ for heavier hypernuclei (A=40-50, 208)

cryogenic gaseous ^{3,4}He target: thickness ~ 58 mg/cm^2
(200 psi, 20 cm length→
ρ ~ 0.0029 g/cm^3 ~ 20 * ρ_{gas})

Proposal JLab



Beam energy (12 GeV mode, 2-passes, injector energy included)	$\boxed{4.5238\text{ GeV}}$	
E' (HRS) central angle (horizontal and vertical bites)	$\boxed{7°}$ (±1.5° and ±2.5°)	+7°
E' (HRS) central momentum (percentage bite)	$\boxed{3.0296\text{ GeV/c}}$ (±4.0%)	
Virtual photon central angle ($\phi=\pi$)	$\boxed{14°}$	+12°
Virtual photon energy range	1.37 – 1.62 GeV	
Virtual photon momentum range	1.42 – 1.70 GeV/c	
Average Q^2	$\boxed{-0.21\ (\text{GeV/c})^2}$	
K^+ (HKS) central angle (horizontal and vertical bites)	14° (±4.5° and ±2.5°)	
K^+ (HKS) central momentum (percentage bite)	$\boxed{1.2\text{ GeV/c}}$ (±12.5%)	

new septum magnets

Hall A & C results

Target and objective hypernucleus	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected Yield (/hour)	Num. of events	Req. beamtime (hours)	B.G. Rate (/MeV/h)	S/N (±1σ)	Comments
^{3}He ($^3_\Lambda$H)	20	58	5	1.3	100	80	0.08	18	Gas, Reference
^{4}He ($^4_\Lambda$H)	20	58	20	3.8	1000	266	0.07	57	Gas

Yield($^4_\Lambda$H, $^3_\Lambda$H) production

very thin target → negligible energy loss, good momentum resolution → good S/N

Yield($^4_\Lambda$H→ ^{4}He + π^-) = Yield($^4_\Lambda$H) * BR * Ω_π * ε_π * $\varepsilon_{\text{analysis}}$

= Yield($^4_\Lambda$H) * 0.49 * 0.5 * 1 * 0.8 ~ 18/day

500-1000 entries: 30-60 days

Yield($^3_\Lambda$H→ ^{3}He + π^-) = Yield($^3_\Lambda$H) * BR * Ω_π * ε_π * $\varepsilon_{\text{analysis}}$

= Yield($^3_\Lambda$H) * 0.4 * 0.5 * 1 * **0.4** ~ 2.5/day

100-500 entries: 40-200 days

more dense target: → ρ_{dense}

Dohrmann, PRL 93, 242501
high density cryogenic targets ^{3}He: 0.310 g/cm^2 → ρ_{dense} ~0.0775 g/cm^3 , ^{4}He: 0.546 g/cm^2 → ρ_{dense} ~0.1365 g/cm^3

$\text{Yield}({}^4_\Lambda\text{H}, {}^3_\Lambda\text{H})_{dense} = \text{Yield}({}^4_\Lambda\text{H}, {}^3_\Lambda\text{H}) * \rho_{dense} / \rho$

${}^3_\Lambda$H: 1.3/hour → ~ 35/hour ~ 800/day

${}^4_\Lambda$H: 1.3/hour → ~ 179/hour ~ 4300/day

$\text{Yield}({}^4_\Lambda\text{H}, {}^3_\Lambda\text{H decay})_{dense}$:

${}^3_\Lambda$H: ~ 60/day 500-1000 entries: 8-15 days

${}^4_\Lambda$H: ~ 800/day 1000-2000 entries: 2-3 days

Drawbacks:
- worse momentum resolution (e', K+, π-), worse spectroscopy S/N
- higher energy loss → higher momentum threshold on MWD π-

Apparatus hints/ideas

- cryogenic gaseous He target: **higher density needed**
  - common (gas/liquid/solid) target chamber, external diameter 60-90 cm …??
  - define dimensions, smaller diameter or T1 inside the chamber

- T0: probably not a direct measurement (I=20 μA), t_{react} calculated from time signals on the K+ trajectory or from beam clock signal (DC?)

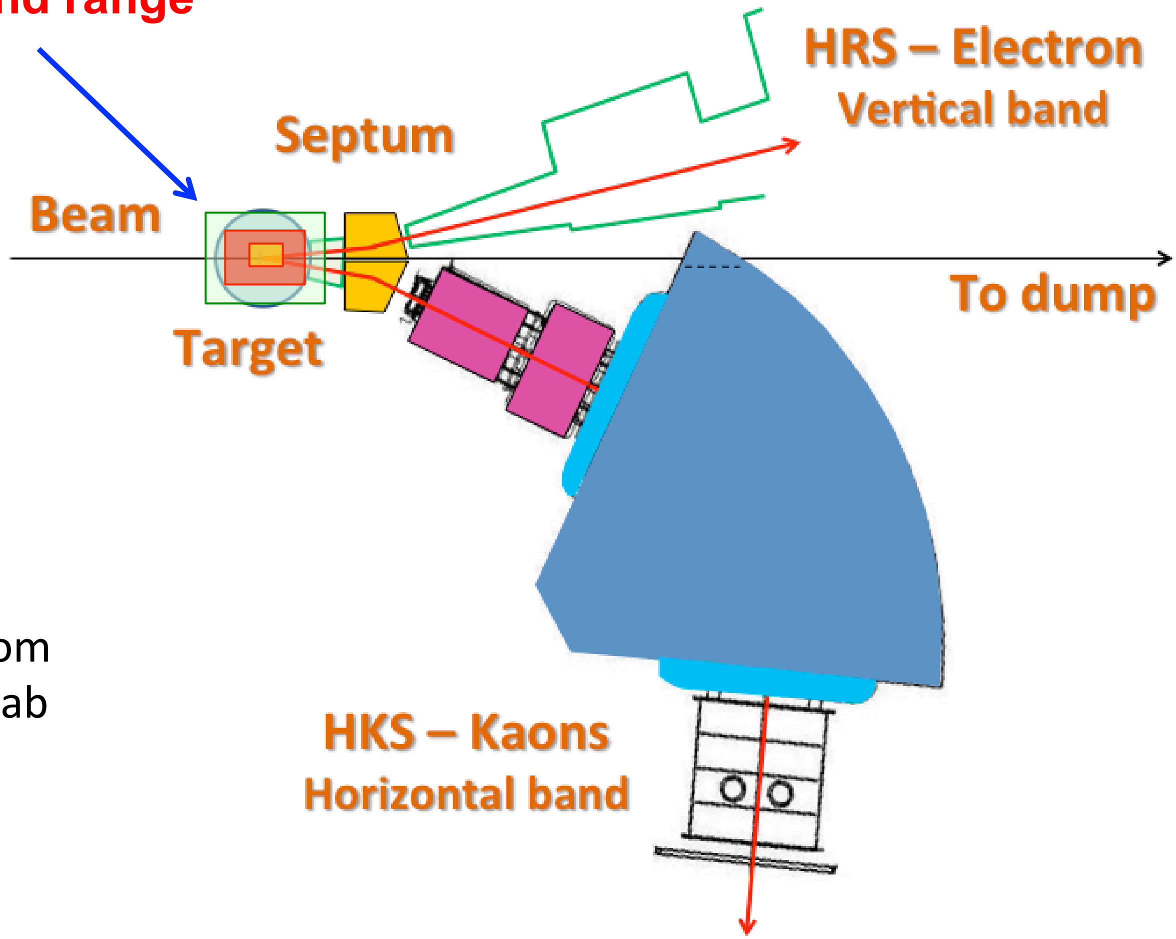
- T1: scintillator barrel (12-15 slabs?), 20 cm length, 4-5 mm thick, radius …

- hollow cylindrical drift chamber (inner radius depending on target dimensions, thickness ~ 30 cm)
  → track straight charged decay particles, vertex
  → use as tracker if a magnet can be added (difficult, background): vertex, π^- momentum and PId

too high background??

- range counter: π^- energy measurement and PId (dE/dx vs E, R, hit position) w/out magnet (and drift chamber?)
  (8-10 layers, 5-10 cm tot, to be studied!)
  → energy resolution < 4-5 MeV FWHM
  → PId contamination < 1%: e (β~1), π (~100 MeV/c), p (≤400 MeV/c)

T1
drift (?) and range
magnet?



adapted from
Proposal JLab

- total material thickness:

  - low density target: He completely negligible, only apparatus materials
  - high density target: similar to LHe in J-PARC

  in general, presumably comparable to the J-PARC situation
  → momentum cut on MWD π- ~ 70 MeV/c

- **$^{3,4}{}_{\Lambda}$H not stopped in He before decay** (~ 350 MeV/c, γ ~ 1.004, 0.4% syst.)
  - low density target: R>>$\beta c\tau$→ mainly decay in flight, outside the target

  - high density target (~ LHe): R~$\beta c\tau$, ≥ 50% decay in flight, inside the target

- prompt reaction: (e, e' K+(e+) π^-) inelastic scattering

- background:
  $\Lambda_{\text{q.f.}}$
  - "absent" for $^{4}{}_{\Lambda}$H (B_Λ ~ 2 MeV, MM resolution~ 600 keV)
  - $^{3}{}_{\Lambda}$H (B_Λ ~ 0.13 MeV) → 3b MWD,
    lower π^- momentum (70-100 MeV/c): range counters (→ magnetic analysis ..)

  accidental (e' K+) reduced by large opening angles of HRS and HKS

to be carefully evaluated !!

J-PARC

✓ **YES**

- present beam for $^{4}_{\Lambda}H$
- present beam/HIHR for $^{3}_{\Lambda}H$ vs $d\sigma/d\Omega$
- careful study of T1 insertion
- prompt reaction (K^0_s lifetime)
- parasitic measurement possible

JLab

✓ YES $^{4}_{\Lambda}H$, $^{3}_{\Lambda}H$

- dense target (rate, decay point)
- T0 not directly measured

✓ HOWEVER

- no tracking for MWD products
- range counter critical (Pid, E)
- prompt reaction
- background study

✓ NO

- parasitic measurement

MAMI …?

THANK YOU !!!

Kamada PRC 57 (1998) 1595 && Λ BR

$^{3}_{\Lambda}H \rightarrow d+p+\pi^-$ and $d+n+\pi^0$: $\Gamma/\Gamma_{\Lambda} = 0.619$

$\Gamma_{tot}/\Gamma_{\Lambda} = 1.03$

$\Lambda \rightarrow p + \pi^-$ BR: 0.639

$\rightarrow n + \pi^0$ BR: 0.358

$^{3}_{\Lambda}H \rightarrow d+p+\pi^-$ BR: 0.619 * 0.639 ~ 0.4

- **detailed situation analysis**

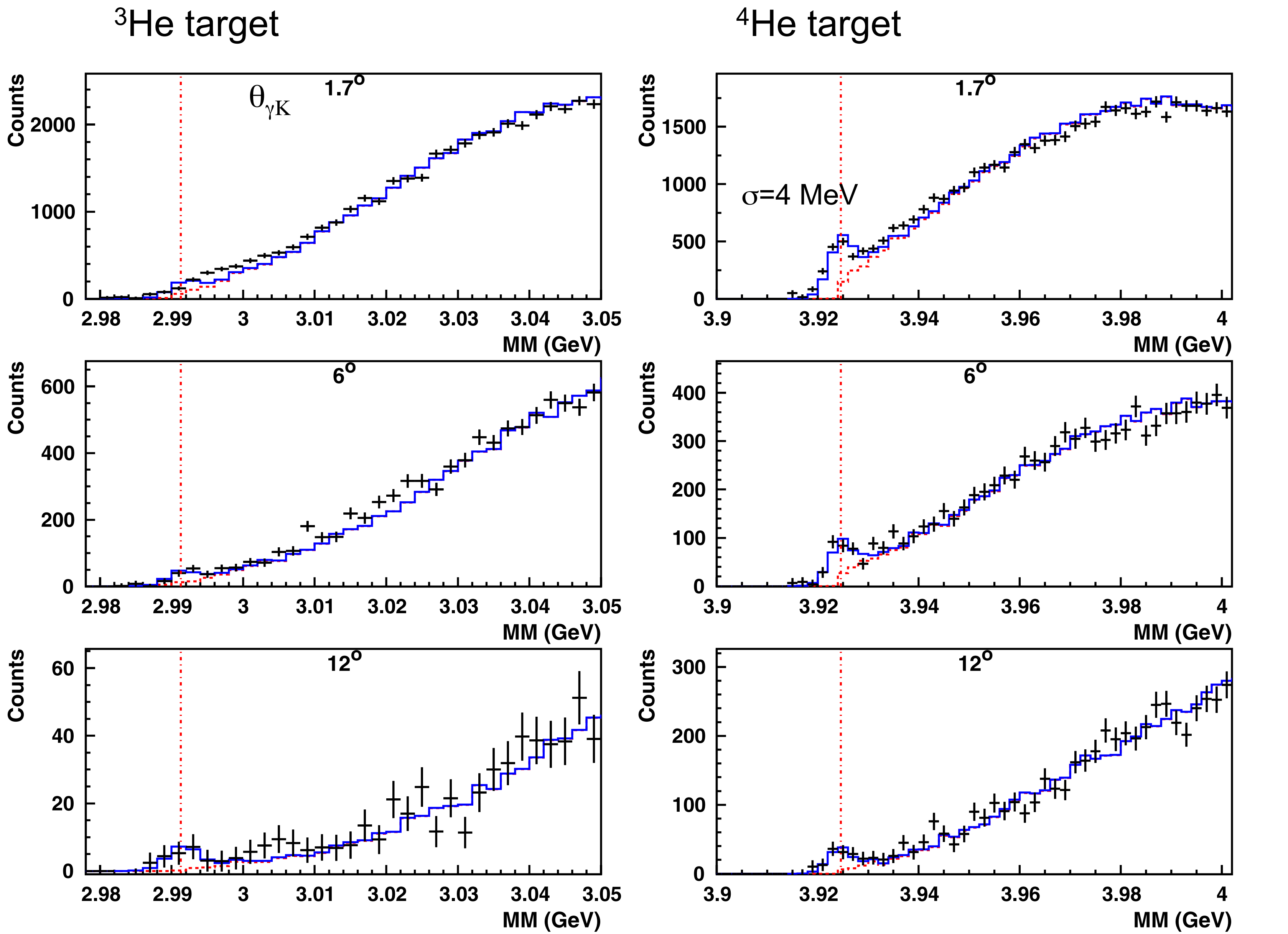
$^{3}_{\Lambda}H$ lifetime measurements

year	ref.	method	lab./react	τ (ps)	events
1963	Block, St. Cergue p.63	He BC	K^-, LBL Bevatron	105^{+20}_{-18}	29f + 7r
1964	Prem, PR 136 B1803	emuls.	K^-, BNL AGS	90^{+220}_{-40}	3f+1r
1965	Kang, PR 139 B401	emuls.	K^-, BNL AGS	340^{+820}_{-140}	5f+18r
1968	Keyes, PRL 20 819	He BC	K^-, ANL ZGS	232^{+45}_{-34}	3f+1r
1968	Phillips PRL 20 1383	emuls.	K^-, BNL AGS	274^{+110}_{-72}	21f+32r
1969	Phillips PR 180 1307	emuls.	K^-, BNL AGS	285^{+114}_{-75}	3f+1r
1970	Bohm, NPB 16 46	emuls.	K^-, CERN PS	128^{+35}_{-26}	120f+34r
1970	Keyes, PRD 1 66	He BC	K^-, ANL ZGS	264^{+84}_{-52}	27f
1973	Keyes, NPB 67 269	He BC	K^-, ANL ZGS	246^{+62}_{-41}	40f
1992 (A)	Avramenko, NPA 547 95c	ions	He, Li on C, Dubna	240^{+170}_{-100}	few events
2010	STAR, Science 328, 58	HI	Au, BNL RHIC	$182^{+89}_{-45} \pm 27$	
2013 (B)	STAR, NPA 904, 551c	HI	Au, BNL RHIC	$123^{+26}_{-22} \pm 10$	> stat. ?
2013	HypHI, NPA 913, 170	Ions	Li on C, GSI SIS	$183^{+42}_{-32} \pm 37$	
2014	Rappold et al., PLB 728, 543	analysis	no (A) and (B)	$\boxed{216^{+19}_{-16}}$	
2015	ALICE, arXiv:1506.08453	HI	Pb CERN LHC	$181^{+54}_{-38} \pm 33$	

${}^{4}_{\Lambda}H$ lifetime measurements

year	ref.	method	lab./react	τ (ps)	events
1962	Crayton, HEP CERN, p. 460	emuls.	K^-, LBL Bevatron	$< 120^{+70}_{-30}$	52f
1964	Prem, PR 136 B1803	emuls.	K^-, BNL AGS	180^{+250}_{-70}	3f + 4r
1965	Kang, PR 139 B401	emuls.	K^-, BNL AGS	240^{+600}_{-100}	5f + 40r
1969	Phillips PR 180 1307	emuls.	K^-, BNL AGS	268^{+166}_{-107}	10f + 5r
1991 (C)	Szymanski PRC 43 849	counter	K^- on ^{6}Li, BNL AGS	160 ± 20	
1992 ('89)	Avramenko, NPA 547 95c	ions	He, Li on C, Dubna	220^{+50}_{-40}	22
1992	Outa, NPA 547 109c	counter	K^-_{stop} on ^{4}He, KEK PS		
1995	Outa, NPA 585 109c	counter	K^-_{stop} on ^{4}He, KEK PS	194^{+24}_{-26}	
1998	Outa, NPA 639 251c	counter	K^-_{stop} on ^{4}He, KEK PS		
2013	HypHI, NPA 913, 170	ions	Li on C, GSI SIS	$140^{+48}_{-33} \pm 35$	
2014	Rappold et al., PLB 728, 543	analysis	no (C)	$\boxed{192^{+20}_{-18}}$	

w.a. = 173 ± 14 ps with (C) (weighted average)
w.a. = 183 ± 18 ps w/out (C)



Dohrmann, PRL 93, 242501