Precise Measurement of the Lifetime of Hydrogen Hyperisotopes: $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$

Elena Botta

INFN - Sezione di Torino and
Torino University - Physics Department

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Outline

- the physics case

- measurements with the (π^-, K^0) reaction at J-PARC

- **detailed situation**

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

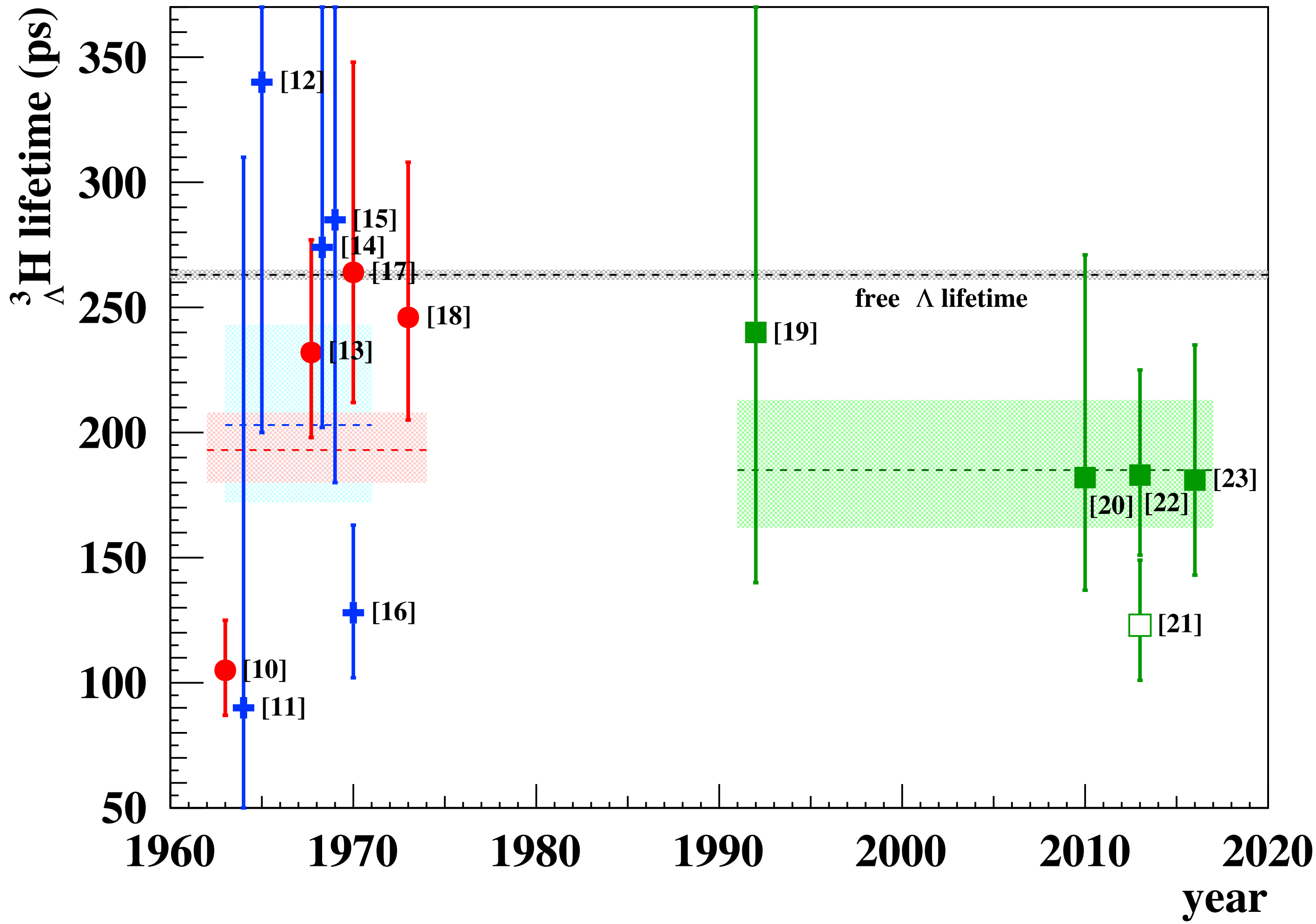
year	ref.	method	lab./react	τ (ps)
1963	Block, St. Cergue p.63 **[10]**	He BC	K^-, LBL Bevatron	105^{+20}_{-18}
1964	Prem, PR 136 B1803 **[11]**	emuls.	K^-, BNL AGS	90^{+220}_{-40}
1965	Kang, PR 139 B401 **[12]**	emuls.	K^-, BNL AGS	340^{+820}_{-140}
1968	Keyes, PRL 20 819 **[13]**	He BC	K^-, ANL ZGS	232^{+45}_{-34}
1968	Phillips PRL 20 1383 **[14]**	emuls.	K^-, BNL AGS	274^{+110}_{-72}
1969	Phillips PR 180 1307 **[15]**	emuls.	K^-, BNL AGS	285^{+114}_{-75}
1970	Bohm, NPB 16 46 **[16]**	emuls.	K^-, CERN PS	128^{+35}_{-26}
1970	Keyes, PRD 1 66 **[17]**	He BC	K^-, ANL ZGS	264^{+84}_{-52}
1973	Keyes, NPB 67 269 **[18]**	He BC	K^-, ANL ZGS	246^{+62}_{-41}
1992 (A)	Avramenko, NPA 547 95c **[19]**	ions	He, Li on C, Dubna	240^{+170}_{-100}
2010	STAR, Science 328, 58 **[20]**	HI	Au, BNL RHIC	$182^{+89}_{-45} \pm 27$
2013 (B)	STAR, NPA 904, 551c **[21]**	HI	Au, BNL RHIC	$123^{+26}_{-22} \pm 10$
2013	HypHI, NPA 913, 170 **[22]**	Ions	Li on C, GSI SIS	$183^{+42}_{-32} \pm 37$
2014	Rappold et al., PLB 728, 543	analysis	no (A) and (B)	216^{+19}_{-16}
2016	ALICE, PLB 754 360 **[23]**	HI	Pb CERN LHC	$181^{+54}_{-38} \pm 33$

counter experiments

- **detailed situation**

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

year	ref.	method	lab./react	τ (ps)	events
1963	Block, St. Cergue p.63 **[10]**	He BC	K^-, LBL Bevatron	105^{+20}_{-18}	29f + 7r (2b&3b)
1964	Prem, PR 136 B1803 **[11]**	emuls.	K^-, BNL AGS	90^{+220}_{-40}	3f+1r (2b)
1965	Kang, PR 139 B401 **[12]**	emuls.	K^-, BNL AGS	340^{+820}_{-140}	5f+18r (2b&3b)
1968	Keyes, PRL 20 819 **[13]**	He BC	K^-, ANL ZGS	232^{+45}_{-34}	35f+17r (2b&3b)
1968	Phillips PRL 20 1383 **[14]**	emuls.	K^-, BNL AGS	274^{+110}_{-72}	24f+99r (2b&3b)
1969	Phillips PR 180 1307 **[15]**	emuls.	K^-, BNL AGS	285^{+114}_{-75}	14f+89r (2B&3b)
1970	Bohm, NPB 16 46 **[16]**	emuls.	K^-, CERN PS	128^{+35}_{-26}	120r+34f (3b)
1970	Keyes, PRD 1 66 **[17]**	He BC	K^-, ANL ZGS	264^{+84}_{-52}	27f(170MeV/c 2b)
1973	Keyes, NPB 67 269 **[18]**	He BC	K^-, ANL ZGS	246^{+62}_{-41}	40f (2b&3b)
1992 (A)	Avramenko, NPA 547 95c **[19]**	ions	He, Li on C, Dubna	240^{+170}_{-100}	few events (2b)
2010	STAR, Science 328, 58 **[20]**	HI	Au, BNL RHIC	$182^{+89}_{-45} \pm 27$	(2b) ⟵
2013 (B)	STAR, NPA 904, 551c **[21]**	HI	Au, BNL RHIC	$123^{+26}_{-22} \pm 10$	(2b) > stat. ?
2013	HypHI, NPA 913, 170 **[22]**	Ions	Li on C, GSI SIS	$183^{+42}_{-32} \pm 37$	(2b) ⟵
2014	Rappold et al., PLB 728, 543	analysis	no (A) and (B)	216^{+19}_{-16}	
2016	ALICE, PLB 754 360 **[23]**	HI	Pb CERN LHC	$181^{+54}_{-38} \pm 33$	(2b) ⟵



M. Agnello et al., submitted to NPA

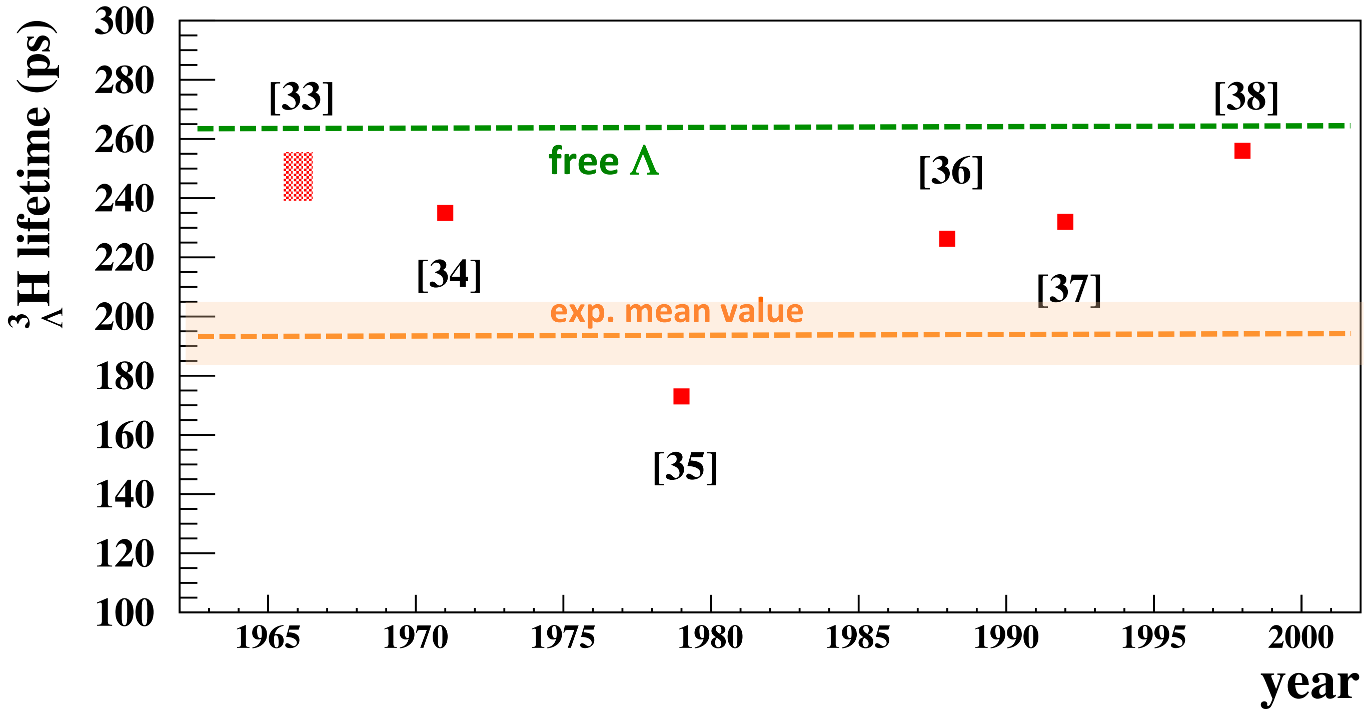
emulsion dataset: 203^{+40}_{-31} ps
He BC dataset: 193^{+15}_{-13} ps

195^{+14}_{-13} ps

counter experiments: 185^{+28}_{-23} ps
(163^{+18}_{-16} ps)

193^{+12}_{-11} ps
(185^{+11}_{-10} ps)

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



M. Agnello et al., submitted to NPA

[33] M. Rayet, R.H. Dalitz N.Cim A 46 (1966) 786
[34] M. Ram, W.Williams NP B 28 (1971) 566
[35] H. Mansour, K. Higgins N. Cim A 51 (1979) 180
[36] N. Kolesnikov, V. Kopylov, Sov. Phys. J 31 (1988) 210
[37] J.G. Congleton, J. Phys G 18 (1992) 339
[38] H. Kamada et al., PRC 57 (1998) 1595

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

year	ref.	method	lab./react	τ (ps)
1962	Crayton, HEP CERN, p. 460 [26]	emuls.	K^-, LBL Bevatron	118^{+65}_{-30}
1964	Prem, PR 136 B1803 [11]	emuls.	K^-, BNL AGS	180^{+250}_{-70}
1965	Kang, PR 139 B401 [12]	emuls.	K^-, BNL AGS	360^{+490}_{-130}
1969	Phillips PR 180 1307 [15]	emuls.	K^-, BNL AGS	268^{+166}_{-107}
1991 (C)	Szymanski PRC 43 849 [27]	counter	K^- on ^{6}Li, BNL AGS	160 ± 20
1992 ('89)	Avramenko, NPA 547 95c [19]	ions	He, Li on C, Dubna	220^{+50}_{-40}
1995	Outa, NPA 585 109c [28]	counter	K^-_{stop} on ^{4}He, KEK PS	194^{+24}_{-26}
2013	HypHI, NPA 913, 170 [22]	ions	Li on C, GSI SIS	140^{+48}_{-33} ±35
2014	Rappold et al., PLB 728, 543	analysis	no (C)	192^{+20}_{-18}

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

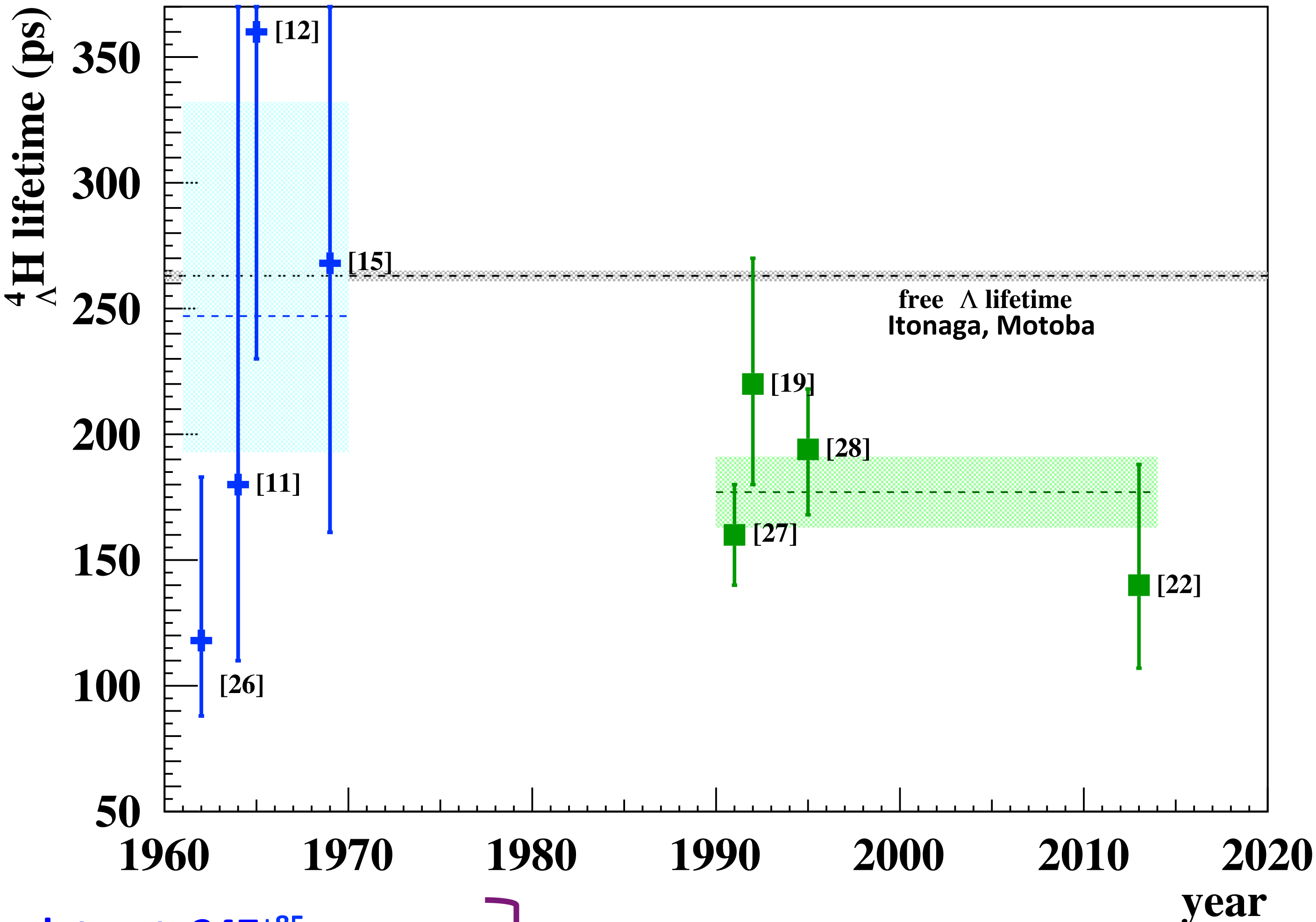
K. Itonaga, T. Motoba, PTPS 185 (2010) 252

(A=4-209) no 2N-induced NMWD

$\tau(^{4}_{\Lambda}\mathrm{H}) = 264.1$ ps

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

year	ref.	method	lab./react	τ (ps)	events
1962	Crayton, HEP CERN, p. 460 **[26]**	**emuls.**	K^-, LBL Bevatron	**118^{+65}_{-30}**	52f
1964	Prem, PR 136 B1803 **[11]**	**emuls.**	K^-, BNL AGS	**180^{+250}_{-70}**	3f + 4r
1965	Kang, PR 139 B401 **[12]**	**emuls.**	K^-, BNL AGS	**360^{+490}_{-130}**	5f + 40r
1969	Phillips PR 180 1307 **[15]**	**emuls.**	K^-, BNL AGS	**268^{+166}_{-107}**	10f + 5r
1991 (C)	Szymanski PRC 43 849 **[27]**	**counter**	K^- on ^{6}Li, BNL AGS	**160 ± 20**	
1992 ('89)	Avramenko, NPA 547 95c **[19]**	**ions**	He, Li on C, Dubna	**220^{+50}_{-40}**	22
1995	Outa, NPA 585 109c **[28]**	**counter**	K^-_{stop} on ^{4}He, KEK PS	**194^{+24}_{-26}**	
2013	HypHI, NPA 913, 170 **[22]**	**ions**	Li on C, GSI SIS	**140^{+48}_{-33} ±35**	
2014	Rappold et al., PLB 728, 543	analysis	no (C)	**192^{+20}_{-18}**	



M. Agnello et al., submitted to NPA

emulsion dataset: 247^{+85}_{-54} ps

counter experiments: 177^{+14}_{-14} ps

183^{+13}_{-13} ps

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

K. Itonaga, T. Motoba, PTPS 185 (2010) 252

(A=4-209) no 2N-induced NMWD

$\tau(^{4}_{\Lambda}H)$ = 264.1 ps

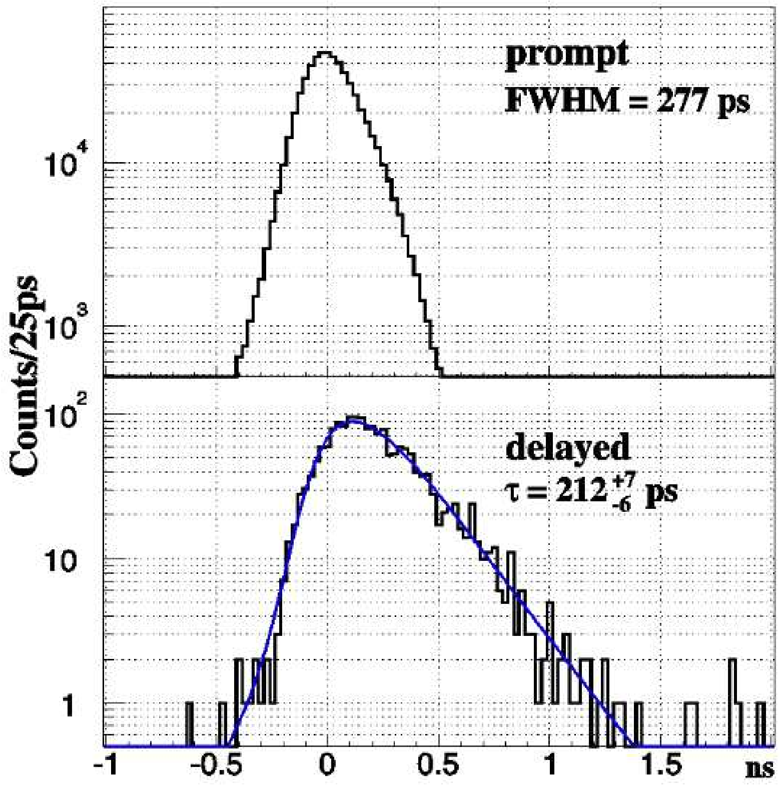
need for new precise measurements of $\tau(^{3}_{\Lambda}H)$ and $\tau(^{4}_{\Lambda}H)$

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

- counter experiments technique, MM spectra, no hyperfragment
- 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)

^{12}C target



(π+, pp)

(π+, K+ p)

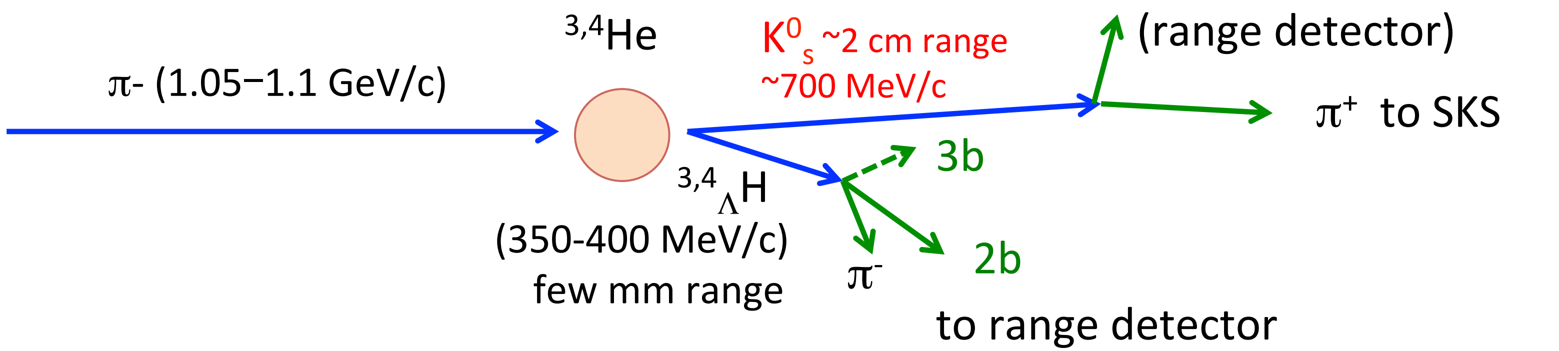
H.Bhang et al., Jou. Kor. Phys. Soc., 59 (2011) 1461,

$^{3,4}{}_{\Lambda}H$ production reactions on He targets

$K^{-} + {}^{3,4}He \rightarrow \pi^{0} + {}^{3.4}{}_{\Lambda}H$ strangeness exchange + charge exchange

$\pi^{-} + {}^{4,3}He \rightarrow K^{0} + {}^{3,4}{}_{\Lambda}H$ **associated production + charge exchange**

strongly asymmetric K^0 decay:



decay reactions:

$K^{0}_{s} \rightarrow \underline{\pi^{+}} + \underline{\pi^{-}}$ (π^{+}: >650 MeV/c, 2°-14° π^{-}: 10-120 MeV/c, 60°-100°)

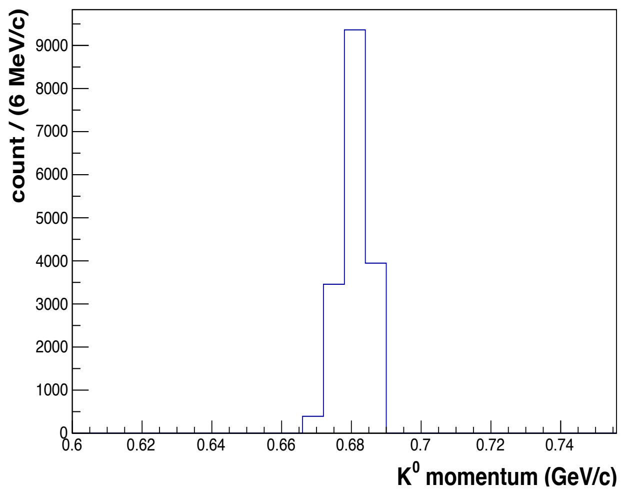
$^{3,4}{}_{\Lambda}H \rightarrow \underline{\pi^{-}} + X$ (2b & 3b) (0-133 MeV/c, 0°-180°) not always at rest

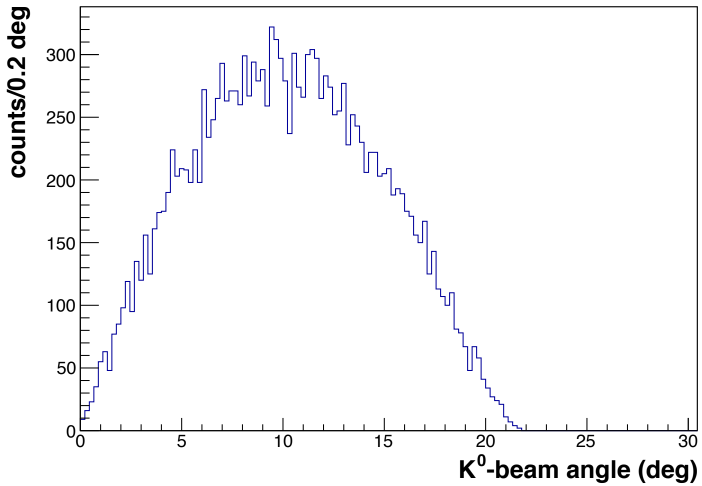
Phase space simulation: $^{4}_{\Lambda}H$

$\pi^- + {}^4He \rightarrow K^0 + {}^4_{\Lambda}H$; $K^0_s \rightarrow \pi^+ + \pi^-$

π^+: p>650 MeV/c, 2°-14° **SKS cut**

K^0 selection

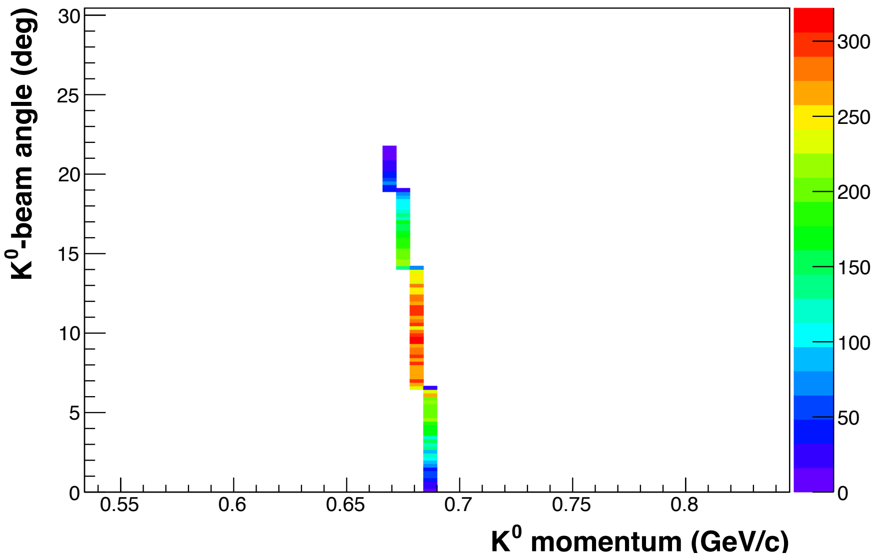




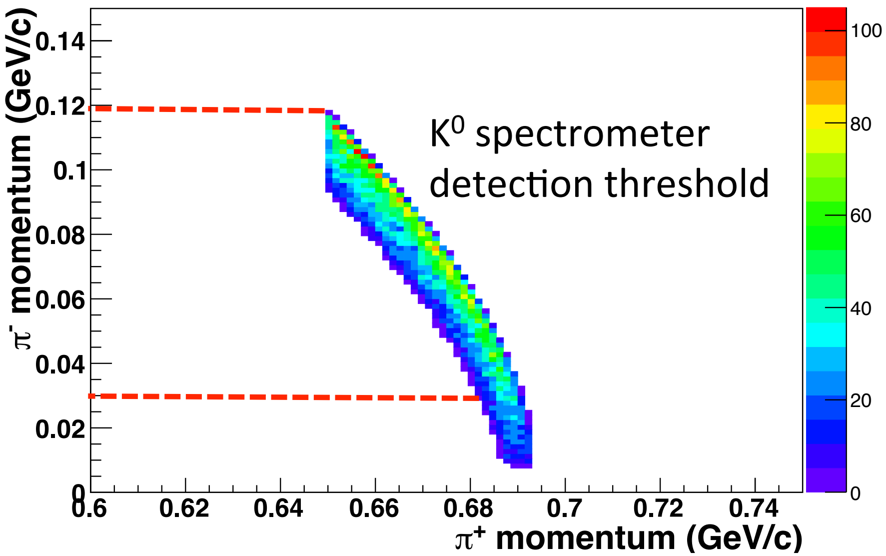
→ $d\sigma/d\Omega$

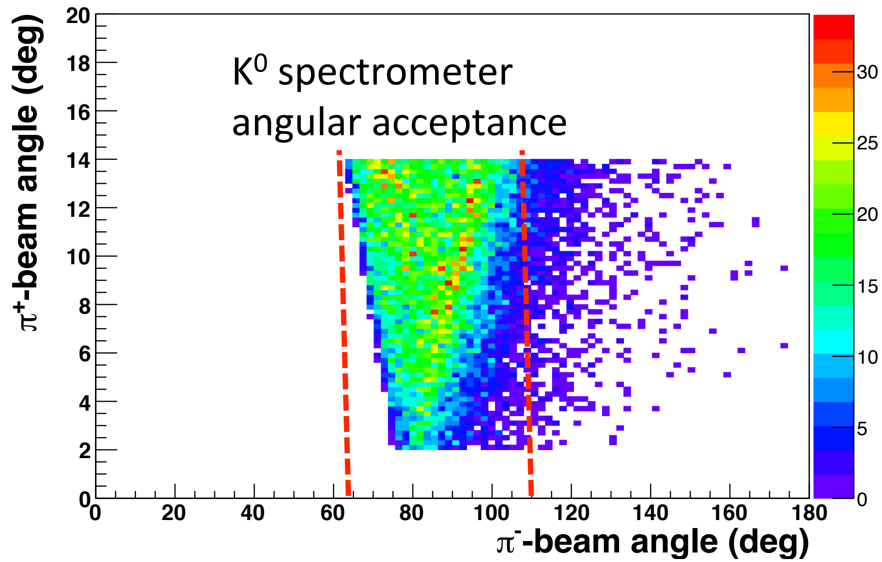
(π^-, K^0)

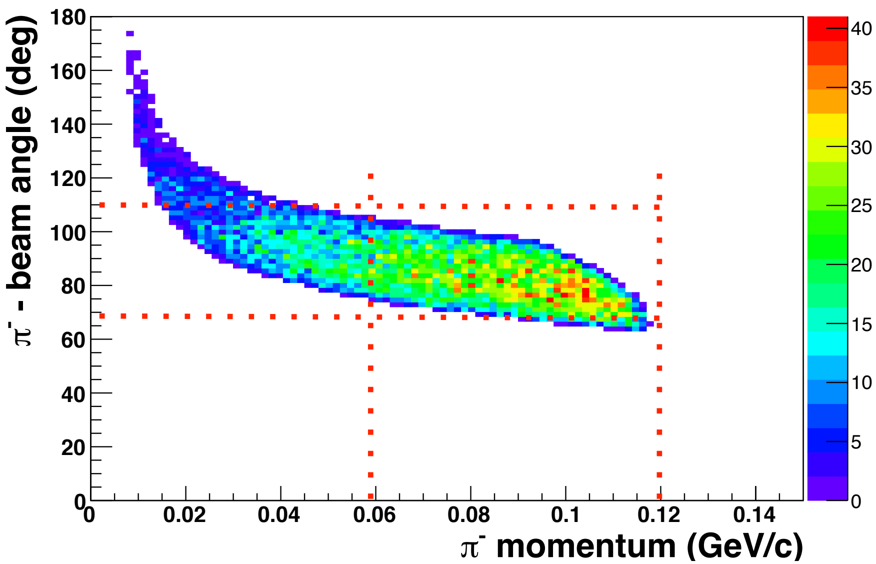
(π^+, K^+)



$K^0_s \rightarrow \pi^+ + \pi^-$ SKS cut







for $^3_\Lambda$H very similar distributions

$^3_\Lambda$H and $^4_\Lambda$H MWD π-:

- 2 π-/event (K^0_s and $^{3,4}_\Lambda$H decays)
- 2b&3b decays
- in flight/at rest decays
- almost isotropic emission
- momenta from threshold to ~ 2b decay momentum
- K^0_s identification by inv. mass

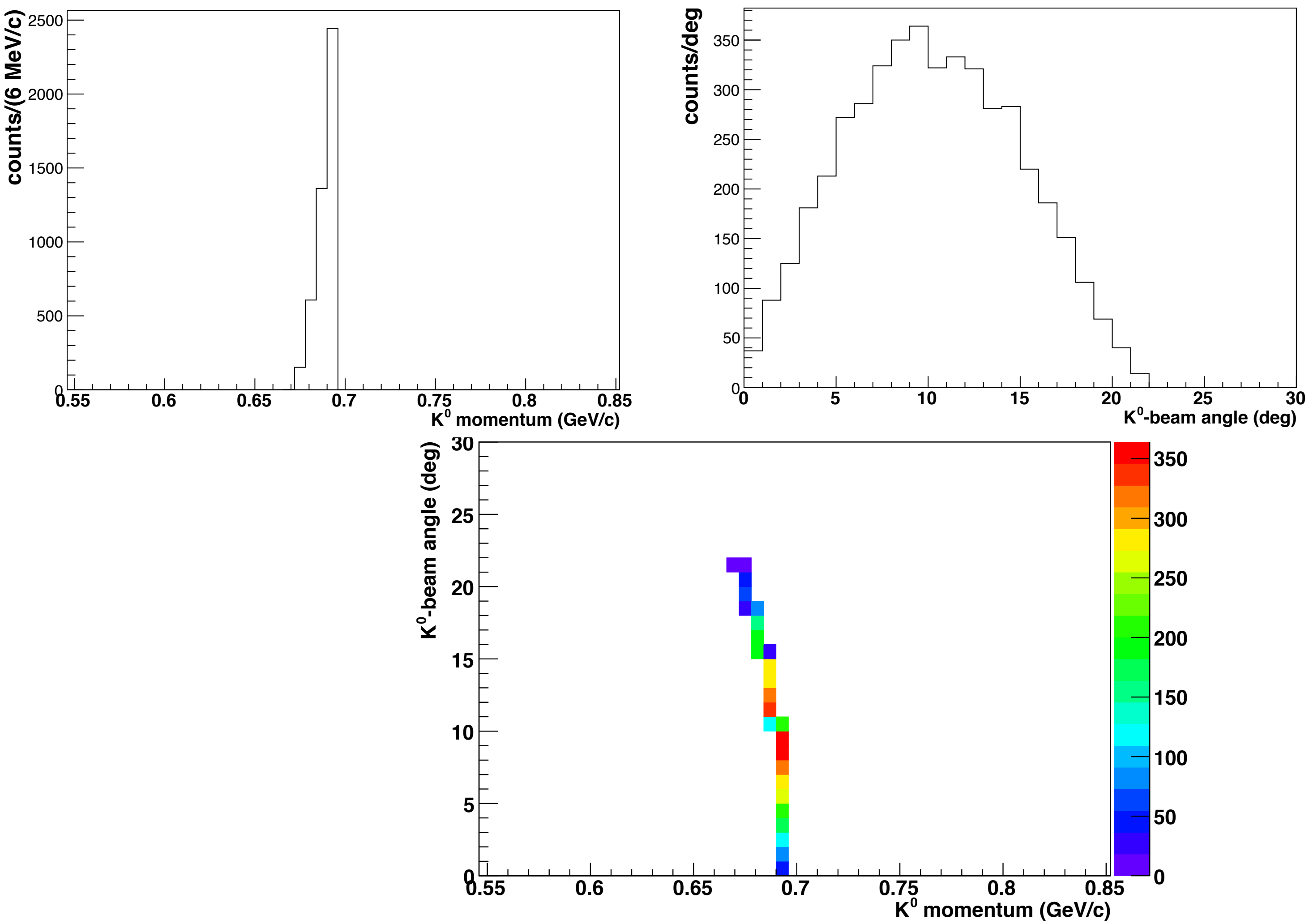
Phase space simulation: $^{3}_{\Lambda}H$

$\pi^- + {}^3He \rightarrow K^0 + {}^3_{\Lambda}H$; $K^0_s \rightarrow \pi^+ + \pi^-$

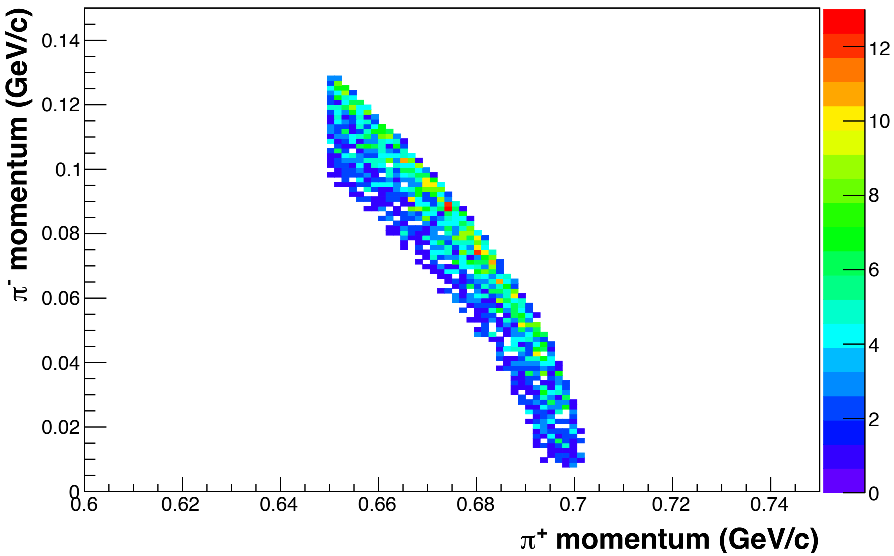
π^+: p>650 MeV/c, 2°-14°

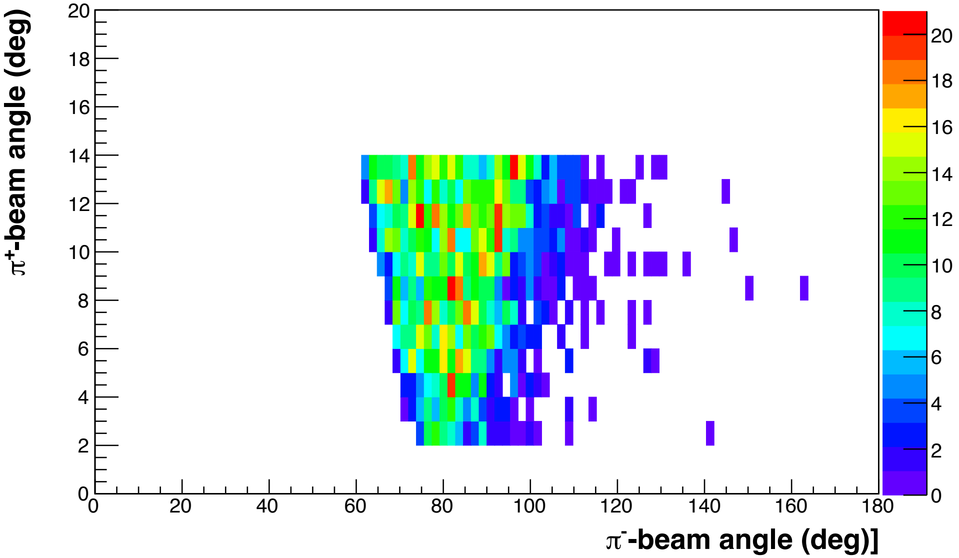
SKS cut

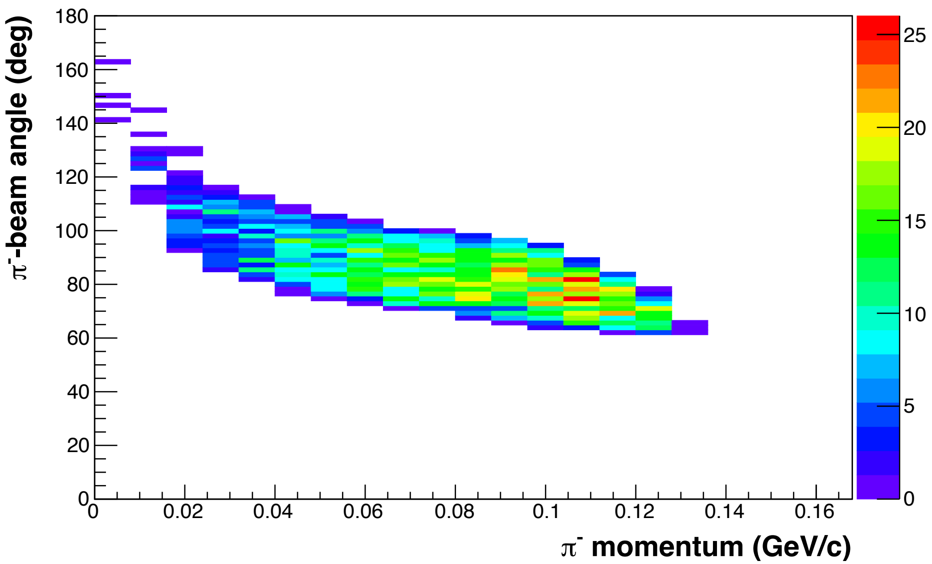
K^0 selection

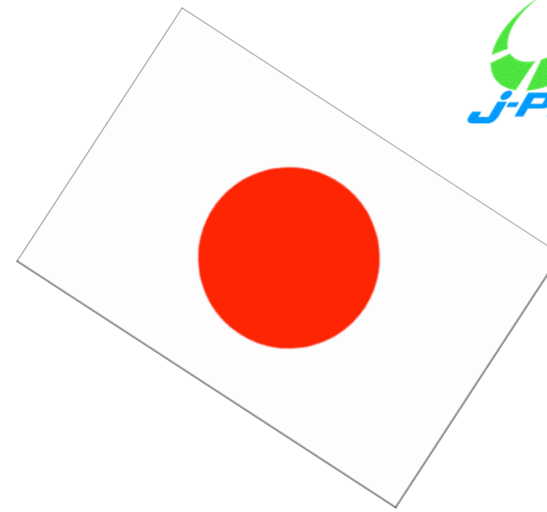


$K^0_s \rightarrow \pi^+ + \pi^-$ SKS cut









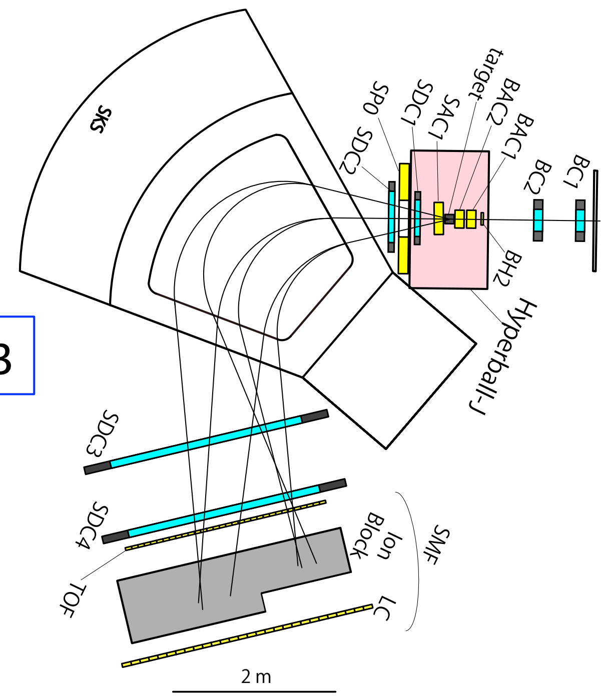
Letter of Intent
for precise measurement of the lifetime of Hydrogen Hyperisotopes $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H

Michelangelo Agnello[1,2], Elena Botta[2,3], Tullio Bressani[2], Stefania Bufalino[1,2], Alessandro Feliciello[2], Tomofumi Nagae[4], Toshiyuki Takahashi[5], Hirokazu Tamura[6]

[1] *Politecnico di Torino, Dipartimento di Scienze Applicate e Tecnologia, Corso Duca degli Abruzzi 24, Torino Italy*
[2] *INFN - Sezione di Torino, Via P. Giuria 1, Torino Italy*
[3] *Università di Torino, Dipartimento di Fisica , Via P. Giuria 1, Torino Italy*
[4] *Department of Physics, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto, Japan*
[5] *Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[6] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*

We are planning to propose an experiment to precisely measure the lifetimes of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H using the ^{3,4}He$(\pi^-, K^0)^{3,4}_{\Lambda}$H reaction at the K1.1 beamline by employing the SKS spectrometer and scintillation counters around the target.

K^0 spectrometer conceptual design



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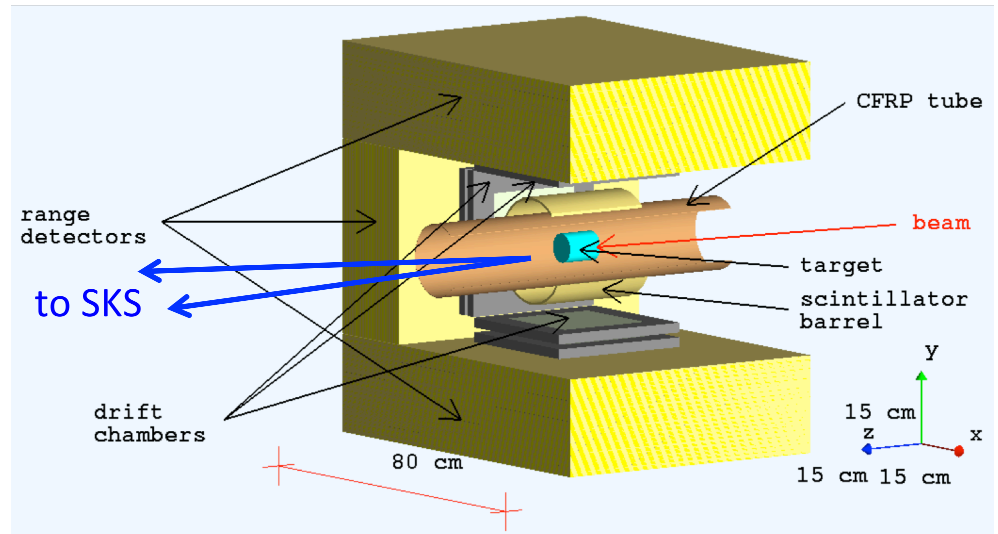


Range detector	impinging decay particle momentum → K^0_s momentum PId (π, K, p), $\Delta\Omega \sim 2\pi$, scintillator, ~ 10 cm total thickness (slabs: 1-3 mm), p_π>70-75 MeV/c, 4 modules
Drift chambers	impinging decay particle direction (2 3-d points, ~3 cm spacing) 250-300 μm resolution (σ), $\Delta\Omega \sim 2\pi$
Scintillator barrel	decay time measurement (formation time from beam scintillator) PId 4-5 mm thickness, 12 slabs, $\Delta\Omega \sim 2\pi$
Target	LHe, ~7.5 cm length

MM($^{3,4}{}_{\Lambda}$H) resolution with (π-, K^0) reaction

MM($^{3,4}{}_{\Lambda}$H): ~**3** MeV FWHM

B_{Λ}($^{4}{}_{\Lambda}$H) = 2.04 MeV, B_{Λ} ($^{3}{}_{\Lambda}$H) = 0.13 MeV

p(π- beam): ~ 0.1% @ 1.05 GeV/c → ~1 MeV/c FWHM

K1.1 @ Extension QQDQQ

p(K^0): contributions from p(π^+ SKS), p(π^- K^0 spectr.& DC)

π^+ (~700 MeV/c) SKS: ~ 0.1% FWHM → ~ 1 MeV/c

π^- (80-140 MeV/c) K^0 spectr. : ~ 3-3.5 MeV/c FWHM

θ(45°-100°) DC: <= 100 mrad FWHM

p(K^0): 3.5-4 MeV/c FWHM

→ MM($^{3,4}{}_{\Lambda}$H): ~**3.2** MeV FWHM

delayed time spectrum in coincidence with bound states

Expected events

Total number of π- on target: $N_\pi = 5 \bullet 10^{13}$

Yield($^4_\Lambda$H) = $N_\pi\, N_{target}/4\;\; N_A\; d\sigma/d\Omega\; \Delta\Omega\; \varepsilon_{sp}\; \varepsilon_{an}$ = 1.5 • 10^4

$N_{target} = 1\ g/cm^2$

$d\sigma/d\Omega(\pi^-, K^0) = d\sigma/d\Omega(\pi^+, K^+)\, F_{PS} = 10\ \mu b/sr(4^o) \bullet 0.05$

F_{PS} = (π- in 2°-14°, p>650 MeV/c, from K^0 in 2°-14°)/(K^0 in 2°-14°)

$\Delta\Omega = \Delta\Omega(SKS)\ \Delta\Omega(K^0\ spec.) = ½\ \Delta\Omega(SKS)$

$\varepsilon_{sp}\ \varepsilon_{an} = BR(K^0 \rightarrow K^0_s)\ BR(K^0_s \rightarrow \pi^+ \pi^-)\ \varepsilon_{det}\ \varepsilon_{an}$

Yield($^4_\Lambda$H π- MWD) = Yield($^4_\Lambda$H) BR $\Delta\Omega_\pi\ \ \varepsilon_\pi\ \ \varepsilon_{an}$

~ 2•10^3 2-b (BR=0.49 Tamura PRC 40 (1989) R479)

~ 5•10^2 3-b (BR=0.22)

$\varepsilon_\pi = \varepsilon_{det}$ •(MWD π- in K^0 spec. mom acceptance)/(MWD π-)

Yield($^3_\Lambda$H) ~ 1.5 • 10^4 = 1.0 • 10^4

$d\sigma/d\Omega(\pi^+, K^+)$ = 5 μb reasonable assumption

Yield($^3_\Lambda$H π- MWD) ~ 6 •10^2 2-b (BR=0.25 Bertrand NPB 16 (1970) 77)

~ 6 •10^2 3-b (BR=0.40)

Backgrounds in delayed time spectra

- Ambiguities due to 2 π- in K^0 spectrometer <= 1% (topological selections, inv. mass selections)

- Λ_{qf} production and decay:

$\pi^- + p \rightarrow K^0 + \Lambda$ $K^0_s \rightarrow \underline{\pi^+} + \underline{\pi^-}$ $\Lambda \rightarrow p + \underline{\pi^-}$ in flight

momentum distribution

assumption: Λ_{qf} production ~ 10* ${}^4_\Lambda H$ production peak in MM
unbound region up to 15 MeV (SKS acceptance)
Λ_{qf} MWD π^- : flat distribution up to ~ 160-170 MeV/c

${}^4_\Lambda H$ (B_Λ= 2.04 MeV) ≤10% contamination in the MM selection
2b decay: peak 132.9 MeV/c; contamination ≤ 1%
3b decay: continuum; contamination ≤ 20% → fit of delayed time spectrum with two exponentials (one with $\tau = \tau(\Lambda_{free})$)

${}^3_\Lambda H$ (B_Λ= 0.13 MeV) ~50% contamination in the MM selection
2b decay: peak ~114 MeV/c; contamination ~ 10%, fit with two exponentials
3b decay: continuum; contamination ~ 50% (signal~bckgd) → fit of delayed time spectrum with two exponentials

- complete comprehension of the lightest strange nuclear system elementary ΛN interaction
- simplest Λ nuclear system (I=0): $^{3}_{\Lambda}H$
- B_{Λ}: 0.13 ± 0.05 (± 0.05) MeV → $\tau(^{3}_{\Lambda}H) \sim \tau(\Lambda_{free})$
- B_{Λ} determination: emulsion experiment; $J^{P}=1/2^{+}$
- $\tau(^{3}_{\Lambda}H)$: not definite experimental determination
- decay widths, R_3: emulsions, no recent measurements

- B_{Λ}: - no γ-ray spectroscopy

  - (e, e' K^{+}) spectroscopy: Dohrman (2004), feasibility, 4 MeV FWHM; resolution improved to FWHM ~500 keV; new measurements @JLab?

  - (e, e' K^{+}) WD spectroscopy: MAMI ($\pm 0.01_{st} \pm 0.09_{sys}$), only $^{4}_{\Lambda}H$

  - HIc: GSI HypHI, WD spectroscopy, IM: σ~5 MeV/c^2

- $R_3 = \Gamma_{\pi-2b} \,/\, \Gamma_{\pi-tot}, \Gamma_{\pi 0}$ …. ?!

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

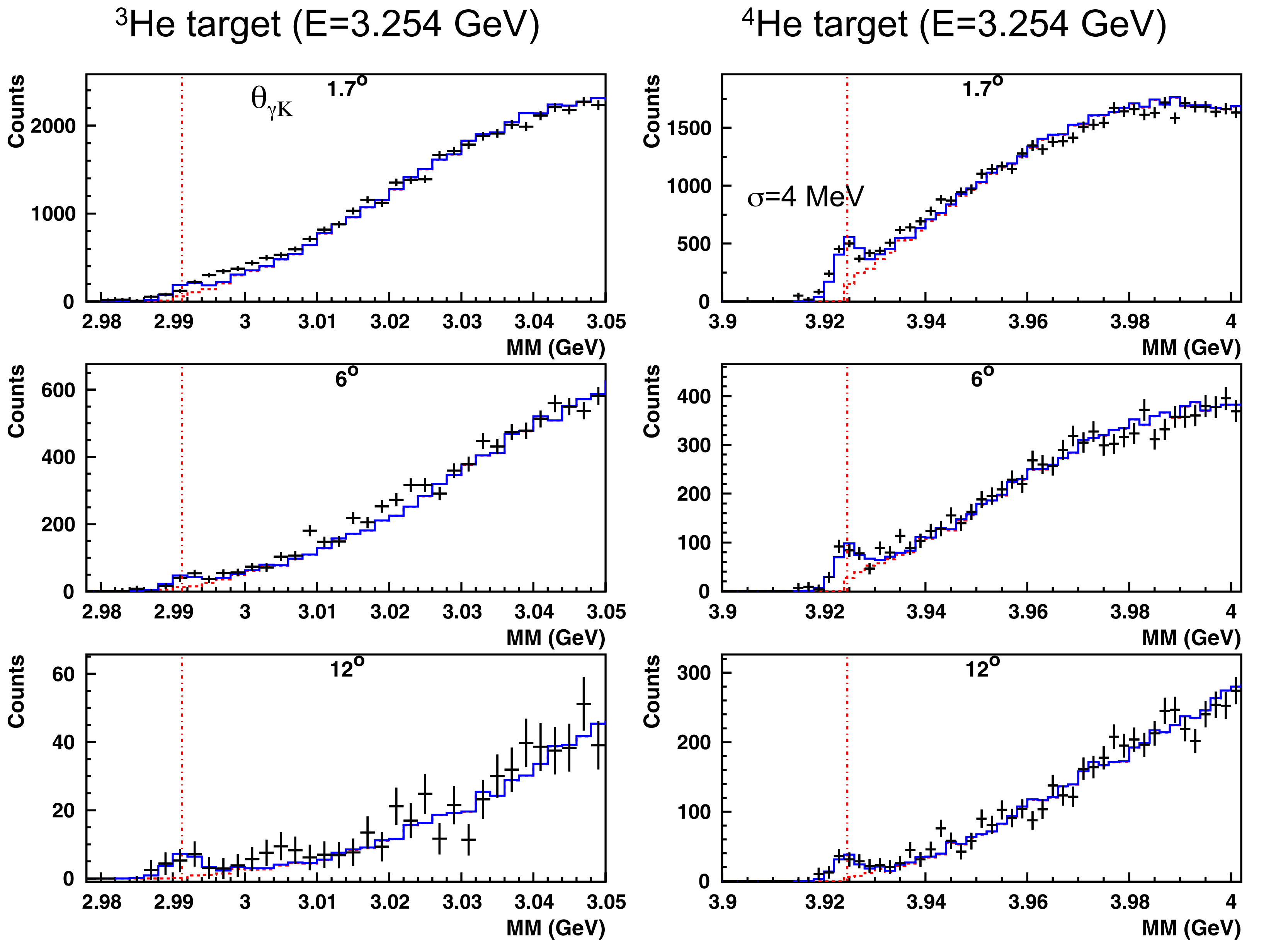
- **present experimental knowledge**

	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**



Dohrmann, PRL 93, 242501