Weak Decay of Hypernuclei (FINUDA, KEK) - Experiment

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Overview

- Introduction: Weak Decay (WD)
- Lifetime measurements
- Mesonic Weak Decay (MWD)
- Non-Mesonic Weak Decay (NMWD)
- Perspectives

Introduction

- "W"D - What it is not:

de-excitation through particle (hyperfragments production) and/or γ-ray emission (spectroscopy)

- WD - What it is:

$^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-$

$^{A}_{\Lambda}Z \rightarrow {}^{A}Z + \pi^0$

MWD

Γ_{π^-}, Γ_{π^0} } Γ_M ($\lesssim$100 MeV/c)

Pauli blocking

$^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$

$^{A}_{\Lambda}Z \rightarrow {}^{A-2}Z + n + n$

$^{A}_{\Lambda}Z \rightarrow {}^{A-3}(Z-X) + N + N + N$

X=0,1,2

NMWD

Γ_p, Γ_n, Γ_{2N} } Γ_{NM} (~420 MeV/c, ~340 MeV/c)

Introduction

• Hypernuclei discovered in 1953 (M.Danysz, J.Pniewski, *Philos. Mag.* **44** (1953) 348) in photographic emulsions, through the MWD.

• light hypernuclei/hyperfragments uniquely identified via their π^- MDW (kinematics of the decay reaction) with visualizing techniques (emulsions / bubble chambers exposed to energetic K^- beams)
• observation of charged decay modes.
• assignment of spin/parity of light hypernuclei ground state ($^3_\Lambda$H, $^4_\Lambda$H, $^4_\Lambda$He, $^8_\Lambda$Li, $^{11}_\Lambda$B and $^{12}_\Lambda$B) through properties of π^- MDW ($^7_\Lambda$Li).
• Λ-N spin dependent interaction ($J_{hyp\ g.s.} = J_{core} - 1/2$)

• limitations of visualizing techniques:
  • no timing information (τ) ;
  • no n, γ detection → only charged WD modes observed;
  • formed hypernuclei not counted → no BR determination

• WD studies at accelerators (BNL AGS, KEK PS) with counter experiments, from '80 on; (K^-, π^-) and (π^+, K^+), high intensity K^-/π^+ beams, coincidence measurements with large solid angle spectrometers.

Introduction

Physics motivations & open questions

- Experimental observables

  τ, $\Gamma_{\pi^-, \pi^0}/\Gamma_\Lambda$, (single) particle decay spectra, $\Gamma_{n, p, 2N}/\Gamma_\Lambda$, Γ_n/Γ_p

- MWD
  - J^π assignment: new indirect spectroscopic tool
  - ΛN interaction potential
  - π^--nucleus optical potential
- NMWD
  - 4-baryon strangeness-changing weak interaction
  - $\Delta I=1/2$ from *s*-shell ($^4_\Lambda H$) and heavy hypernuclei
  - Γ_n/Γ_p puzzle (solved ? … systematics)
  - Γ_{2N}, FSI contributions

KEK & LNF results

Lifetime measurements

- Measurement of the delay in the emission of the decay products from the ground state of a specific hypernucleus

- $\tau(\Gamma_{tot})$ is the observable that can be measured most accurately and can interpreted free from nuclear final state interaction.

- Starting point for obtaining various observables $\Gamma_{\pi-}$, $\Gamma_{\pi0}$, Γ_{n}, Γ_{p}, Γ_{2N}

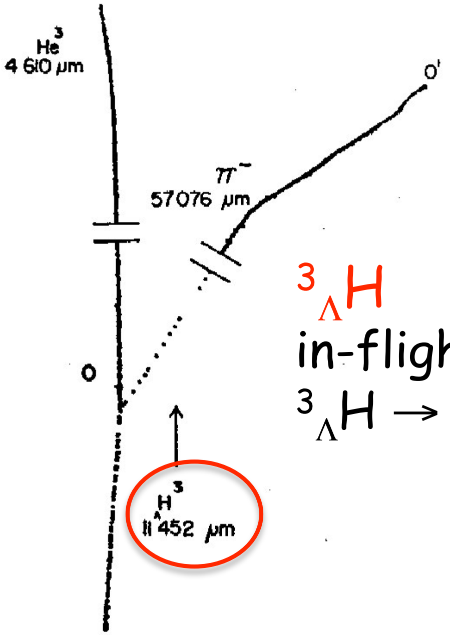
- Variation of τ vs A: qualitative understanding of the nuclear medium effects on the baryon-baryon interaction.

Lifetime measurements

Present knowledge: light hypernuclei

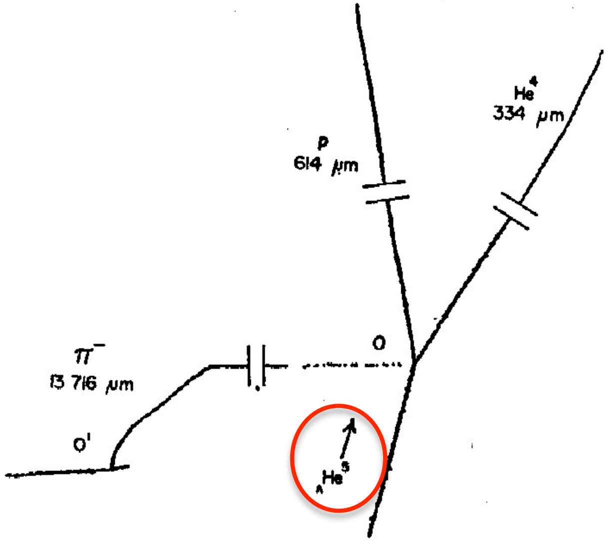
A	τ(ps)	Ref.	Expt.
$^{3}_{\Lambda}H$	90^{+220}_{-40} 285^{+127}_{-105} 128^{+35}_{-26} 264^{+84}_{-52} 246^{+62}_{-41}	Prem PR136(1964) B1803 Phillips PR180 (1969) 1307 Bohm NPB 16 (1970) 46 Keyes PRD 1 (1970) 66 Keyes NPB 67 (1973) 269	emulsion emulsion emulsion bubble chamber bubble chamber
$^{4}_{\Lambda}H$	180^{+250}_{-70} 360^{+490}_{-130} 268^{+166}_{-107} 194^{+24}_{-26}	Prem PR136(1964) B1803 Kang PR139 (1965) B401 Phillips PR180 (1969) 1307 Outa NPA 585 (1995) 109c Outa NPA 639 (1998) 251c	emulsion emulsion emulsion KEK (K^-_{stop}, π^-) KEK (K^-_{stop}, π^-)
$^{4}_{\Lambda}He$	228^{+233}_{-129} 245 ± 24 256 ± 27 245 ± 24	Phillips PR180 (1969) 1307 Zeps NPA 639 (1998) 261c Outa NPA 639 (1998) 251c Parker PRC 76 (2007) 035501	Emulsion BNL AGS (K^-, π^-) KEK (K^-_{stop}, π−) BNL AGS (K^-, π^-)
$^{5}_{\Lambda}He$	140^{+190}_{-50} 180^{+150}_{-60} 251^{+190}_{-73} 274^{+60}_{-50} 256 ± 21 278± 21	Prem PR136(1964) B1803 Kang PR139 (1965) B401 Phillips PR180 (1969) 1307 Bohm NPB23 (1970) 93 Szymanski PRC43 (1991) 849 Kameoka NPA 754 (2005) 173c	emulsion emulsion emulsion emulsion BNL AGS (K^-, π^-) KEK (π+, K+)

Lifetime measurements



$^{3}_{\Lambda}H$
in-flight decay
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

$^{5}_{\Lambda}He$
in-flight decay
$^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$

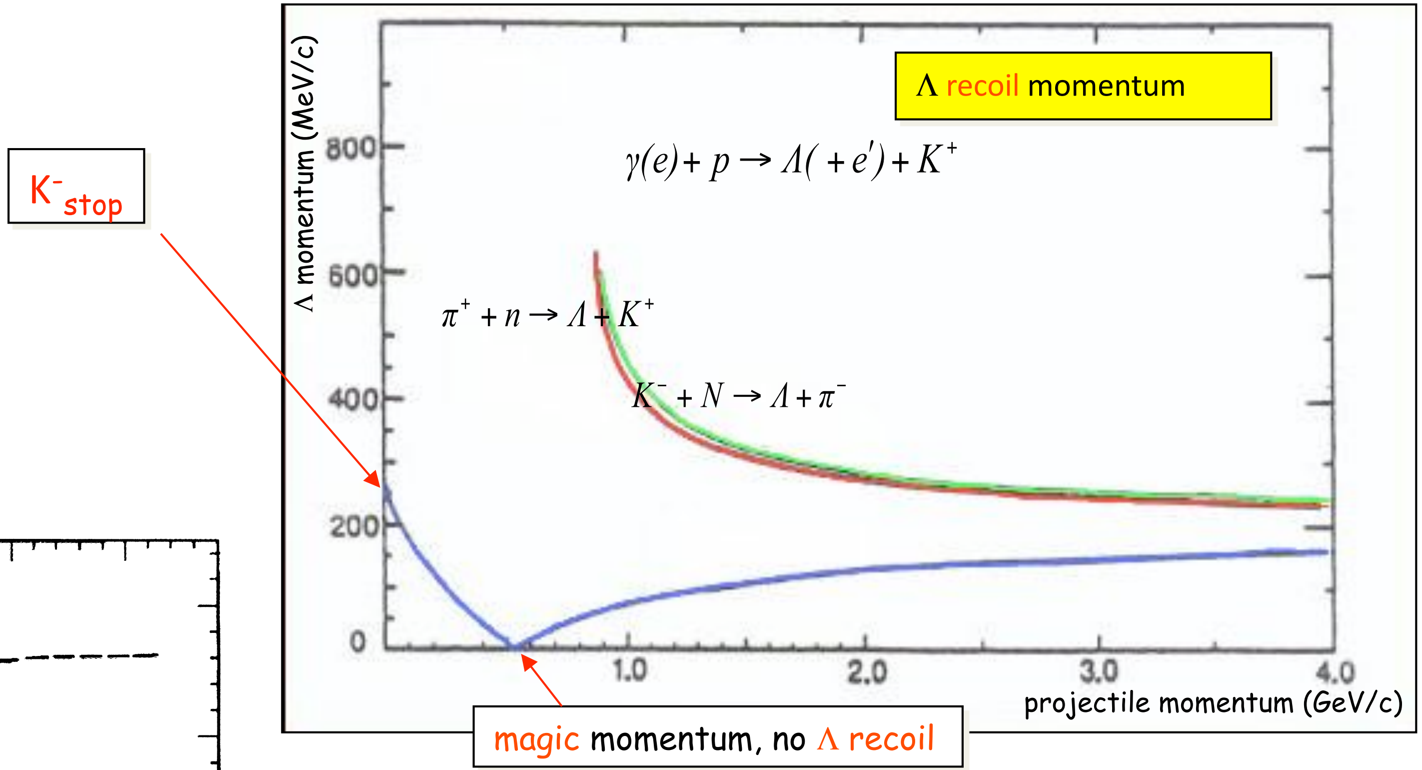


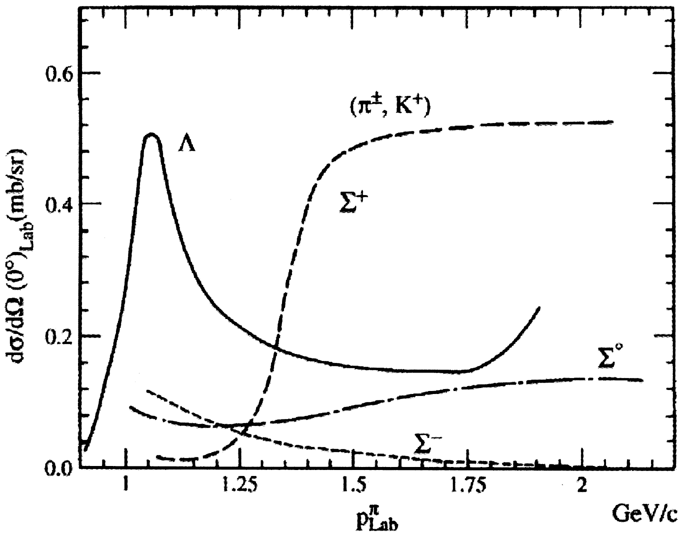
Present knowledge: medium-heavy hypernuclei

A	τ (ps)	Ref.	Expt.
${}^{9}_{\Lambda}\mathrm{Be}$	201 ± 30	Szymanski PRC43 (1991) 849	BNL AGS (K-, π-)
${}^{11}_{\Lambda}\mathrm{B}$	192 ± 22	Grace PRL 55 (1985) 1055 Szymanski PRC43 (1991) 849	BNL AGS (K-, π-) BNL AGS (K-, π-)
	211 ± 13	Park PRC 61 (2000) 054004	KEK (π+, K+)
${}^{12}_{\Lambda}\mathrm{C}$	211 ± 31	Grace PRL 55 (1985) 1055 Szymanski PRC43 (1991) 849	BNL AGS (K-, π-) BNL AGS (K-, π-)
	231 ± 15	Park PRC 61 (2000) 054004	KEK (π+, K+)
	212 ± 6	Kameoka NPA754 (2005) 173c	KEK (π+, K+)
${}^{16}_{\Lambda}\mathrm{Z}$	86^{+33}_{-26}	Nield PRC 13 (1976) 1263	LBL, ^{16}O beam, K+ tagging
${}^{27}_{\Lambda}\mathrm{Al}$	203 ± 10	Park PRC 61 (2000) 054004	KEK (π+, K+)
${}^{28}_{\Lambda}\mathrm{Si}$	206 ± 12	Park PRC 61 (2000) 054004	KEK (π+, K+)
${}_{\Lambda}\mathrm{Fe}$ (${}^{55}_{\Lambda}\mathrm{Mn}$, ${}^{55}_{\Lambda}\mathrm{Fe}$, ${}^{56}_{\Lambda}\mathrm{Fe}$)	215 ± 14	Park PRC 61 (2000) 054004	KEK (π+, K+)
$\bar{p}$ + ^{209}Bi	250^{+250}_{-100} 180 ±40±60	Bocquet PLB 192 (1987) 312 Armstrong PRC 47 (1993) 1957	CERN delayed fission CERN delayed fission
e + ^{209}Bi	2700 ± 500	Noga Yad. Fiz. 43 (1986) 1332	URSS delayed fission
$\bar{p}$ + ^{238}U	100^{+80}_{-40} 130 ±30±30	Bocquet PLB 192 (1987) 312 Armstrong PRC 47 (1993) 1957	CERN delayed fission CERN delayed fission
p + ^{238}U	240 ± 60	Ohm PRC 55 (1997) 3062	COSY delayed fission
p + ^{209}Bi	145 ±7±23	Kulessa NPA 639 (1998) 283c	COSY delayed fission
p + ^{238}U^{209}Bi^{197}Au	145 ± 11	Cassing EPJA 16 (2003) 549	COSY delayed fission

Counter experiments decay studies
→ coincidence measurement
ground state production & identification

high momentum transfer to Λ





(π^+, K^+) elementary reaction

(π^+, K^+) kinematics

$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$ in flight ($p_\pi = 1.06$ GeV/c)

$$[p^2_\pi + m^2_\pi]^{1/2} + m_A = [p^2_{hyp} + m^2_{hyp}]^{1/2} + [p^2_K + m^2_K]^{1/2}$$

$$\vec{p}_\pi = \vec{p}_{hyp} + \vec{p}_K$$

energy & momentum conservation

$$m_{hyp} = \{[[p^2_\pi + m^2_\pi]^{1/2} + m_A - [p^2_K + m^2_K]^{1/2}]^2 - [p^2_\pi + p^2_K - 2p_\pi p_K \cos\theta]\}^{1/2}$$

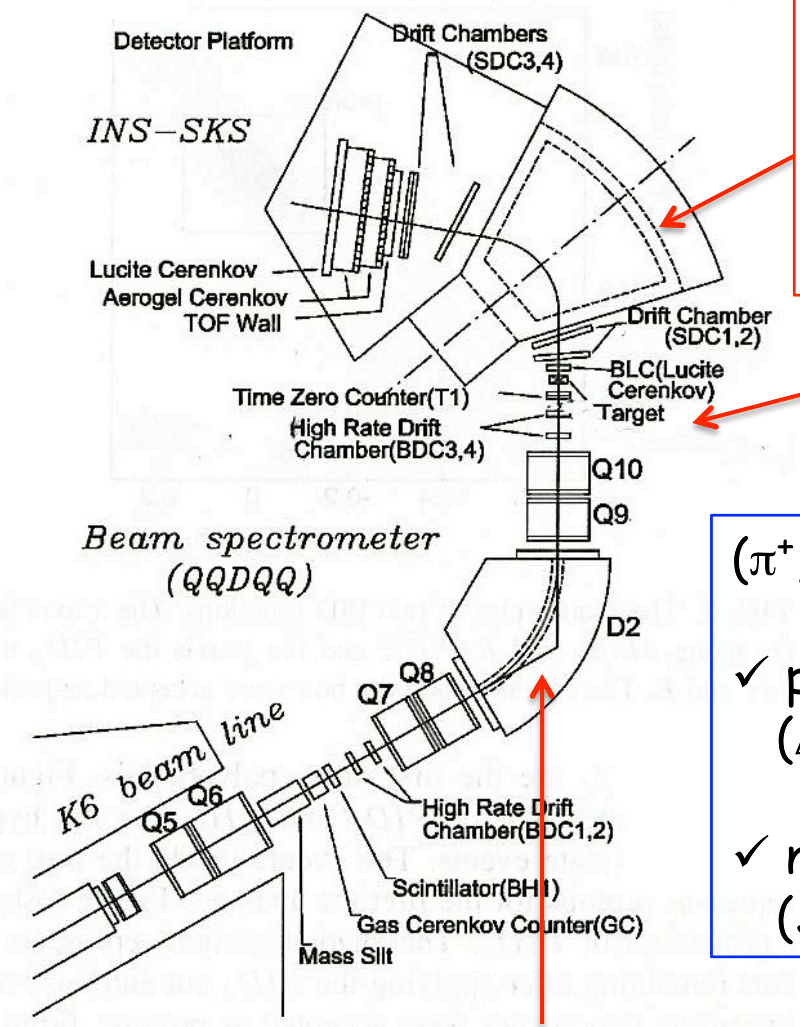
$$m_{hyp} = m_{A-1} + m_\Lambda - B_\Lambda \rightarrow B_\Lambda = m_{A-1} + m_\Lambda - m_{hyp}$$

$$m_{hyp} - m_A = m_\Lambda - B_\Lambda - m_n + B_n$$

Lifetime measurements @ KEK

E307 – $^{11}_{\Lambda}B$, $^{12}_{\Lambda}C$, $^{27}_{\Lambda}Al$, $^{28}_{\Lambda}Si$, $_{\Lambda}Fe$

H. Park et al., PRC 61 (2000) 054004



π^+ beam (p_π=1.06 GeV/c)

SKS:
- ✓ scattered K^+ to reconstruct the hypernuclear mass spectrum (+beam spectrometer)
- ✓ acceptance ~ 100 msr
- ✓ $\Delta p/p$ 0.1% FWHM @720 MeV/c

target region (decay products detection)

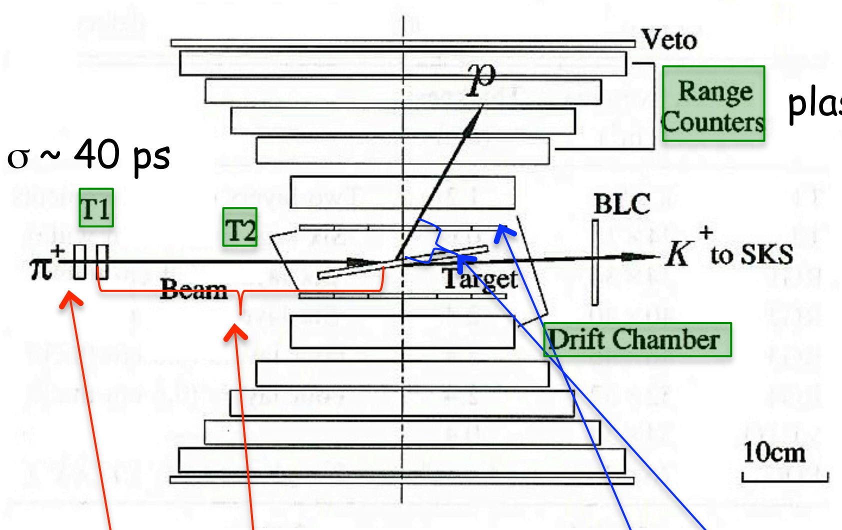
(π^+, K^+) reaction figures:

- ✓ populates deeply bound state (Δp~400 MeV/c)
- ✓ no background from beam particles decay (Szymanski *et al.* 1991)

Lifetime measurements @ KEK

Target region: Coincidence detector
Coincidence of K^+ from bound states tagged by SKS and charged decay particles
(p: 30-150 MeV, π-: 12-70 MeV; acceptance ~30%)

$\sigma \sim 40$ ps



plastic scintillator, 9.6 cm

target tilt angle: 10° vs beam direction

$t_p = t_1 + t_{fb}$

$t_d = t_2 - t_{fd}$

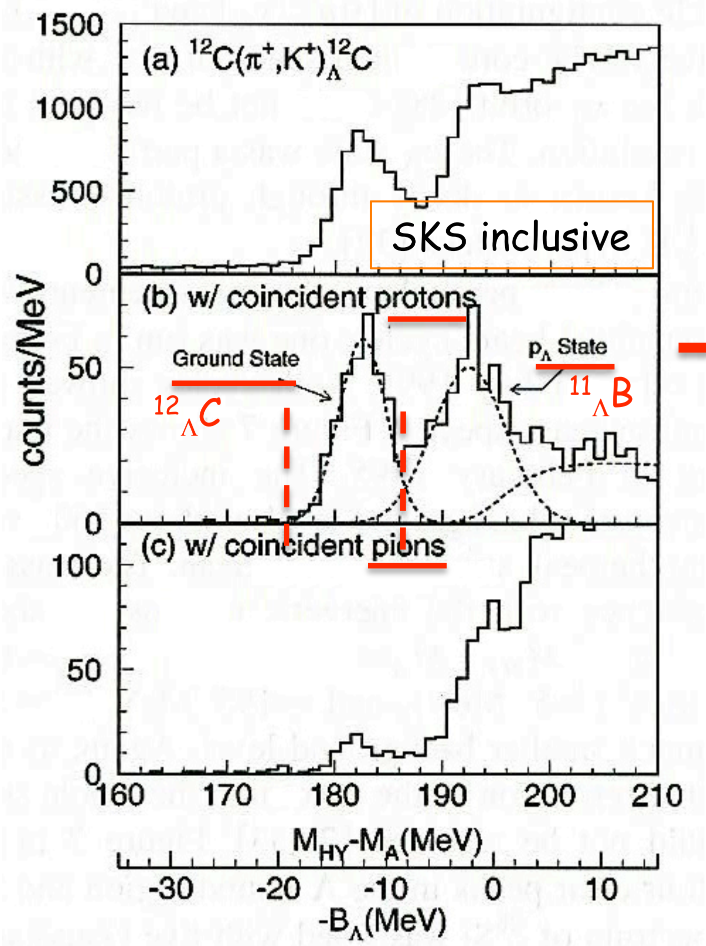
targets (natural isotopic composition)

^{12}C	6.45 $g/cm^2 \rightarrow$ 2.9 cm	
^{28}Si	10.35 $g/cm^2 \rightarrow$ 4.5 cm	
^{56}Fe	7.00 $g/cm^2 \rightarrow$ 0.9 cm	

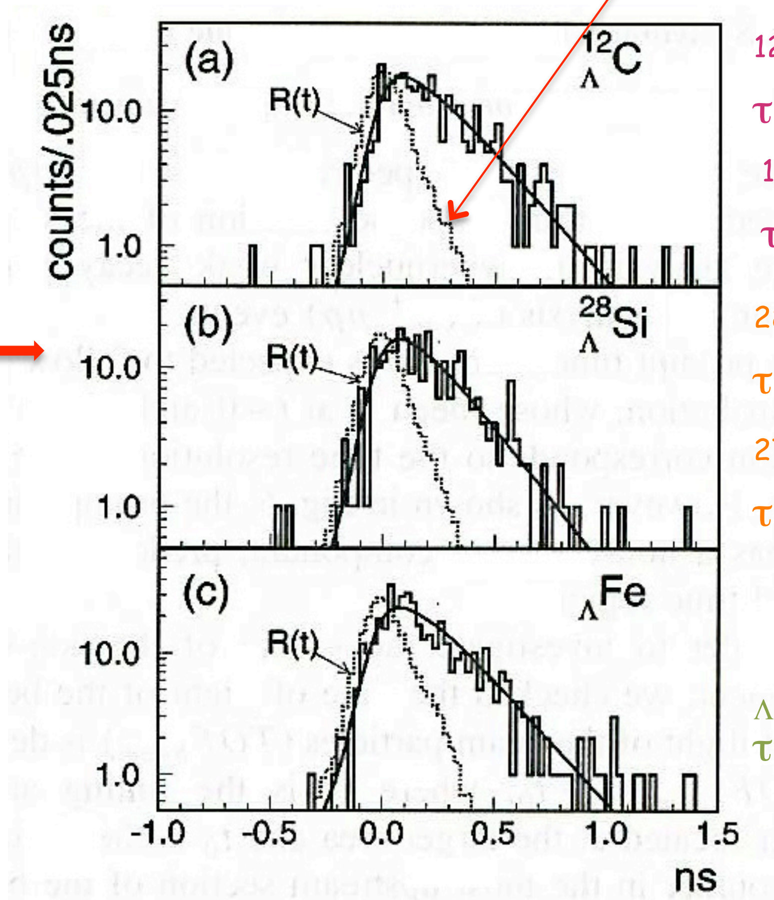
$$\Delta t = t_d - t_p$$

PID (p, π) from:
- dE/dx in T2
- RANGE
- ΔE in T2+RANGE

R(t): time response function from (π+, pp) events
strong interaction → prompt response



Δt →



$^{12}{}_{\Lambda}C$
τ = 231±15 ps

$^{11}{}_{\Lambda}B$
τ = 211±13 ps

$^{28}{}_{\Lambda}Si$
τ = 206±12 ps

$^{27}{}_{\Lambda}Al$
τ = 203±10 ps

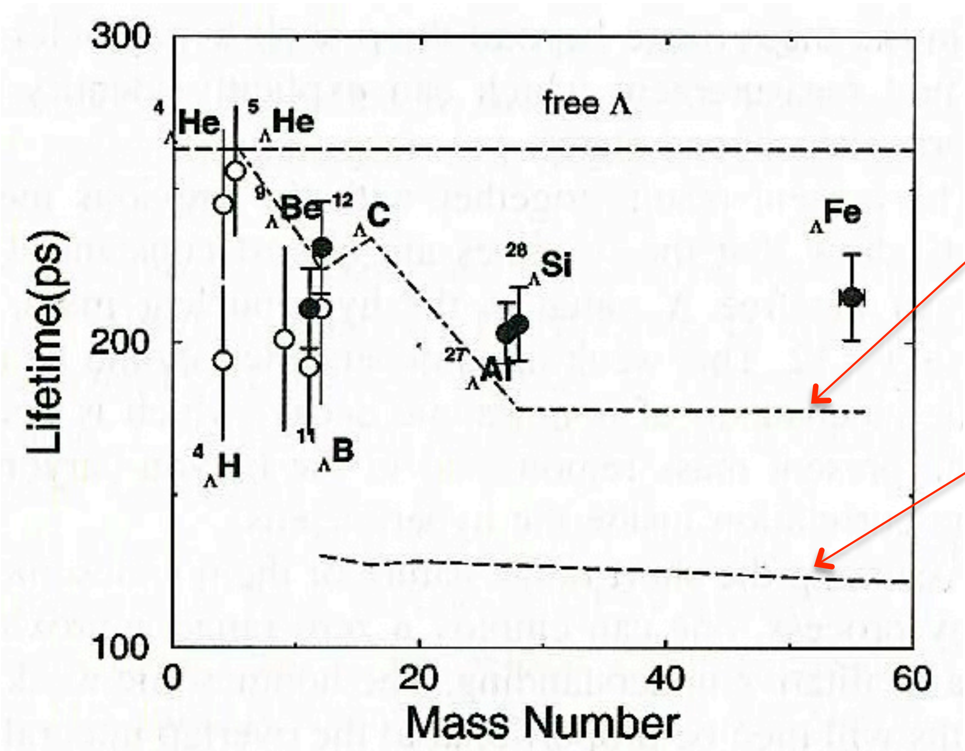
$_{\Lambda}Fe$
τ = 215±14 ps

$$P(t) = \frac{1}{\tau} e^{-t/\tau}$$

τ from a fit to the actual time distribution

$$S(t) = \int_0^{\infty} P(t')R(t-t')dt'$$

Lifetime measurements @ KEK



Itonaga, Ueda, Motoba
NPA 639 (1998) 329c
(OPE+$2\pi/\rho$+$2\pi/\sigma$ for NMWD,
s-and p-shell N)

Ramos, Oset, Salcedo
PRC 50 (1994) 2314
(Λ self energy for NMWD
+ OPE+2N; local density appr.,)

Both measurements and calculations show a saturation
(210 ps ~ 80% τ_Λ, from data)

Lifetime measurements @ COSY

COSY-13   p-Au, Bi, U collisions
W. Cassing et al., EPJ A16 (2003) 549

Heavy hypernuclei:

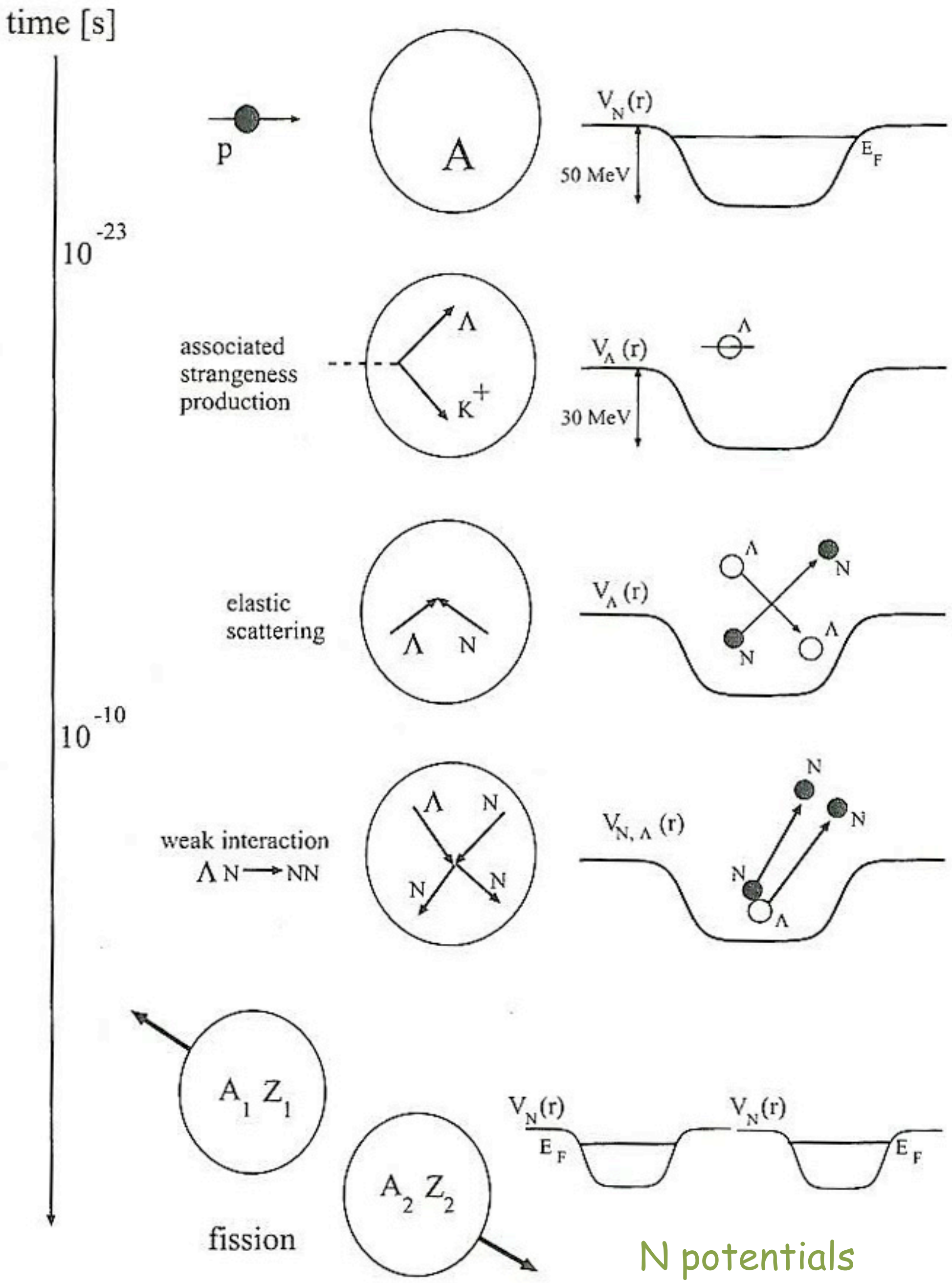
- no direct timing techniques for τ measurements

- large background of light particles → detection of heavy fragments from fission induced by Λ decay in heavy hypernuclei

Delayed fission due to the $\Lambda N \rightarrow NN$ decay

- p-A collisions ('80-'90: antiproton-nucleus collisions at CERN)
- measurement of background by varying the beam energy (1 GeV) concurrently with the effect (1.9 GeV)
- in p-A reactions a large momentum is transferred to the hypernucleus
  → surviving hypernuclei recoil fast (>750 MeV/c)
  → increase of sensitivity of the recoil shadow method

Formation and decay of Λ hypernuclei in p-A collisions



Initial configuration

Associated ΛK production in the target nucleus by pN inelastic scattering (10^{-23} s)
(threshold = 1.6 GeV)

Λ- hyperon capture in the residual nucleus via elastic ΛN scattering (10^{-23} s) (prompt fission)

$\Lambda N \to NN$ interaction on the timescale of 200 ps

Delayed fission of the hypercleus

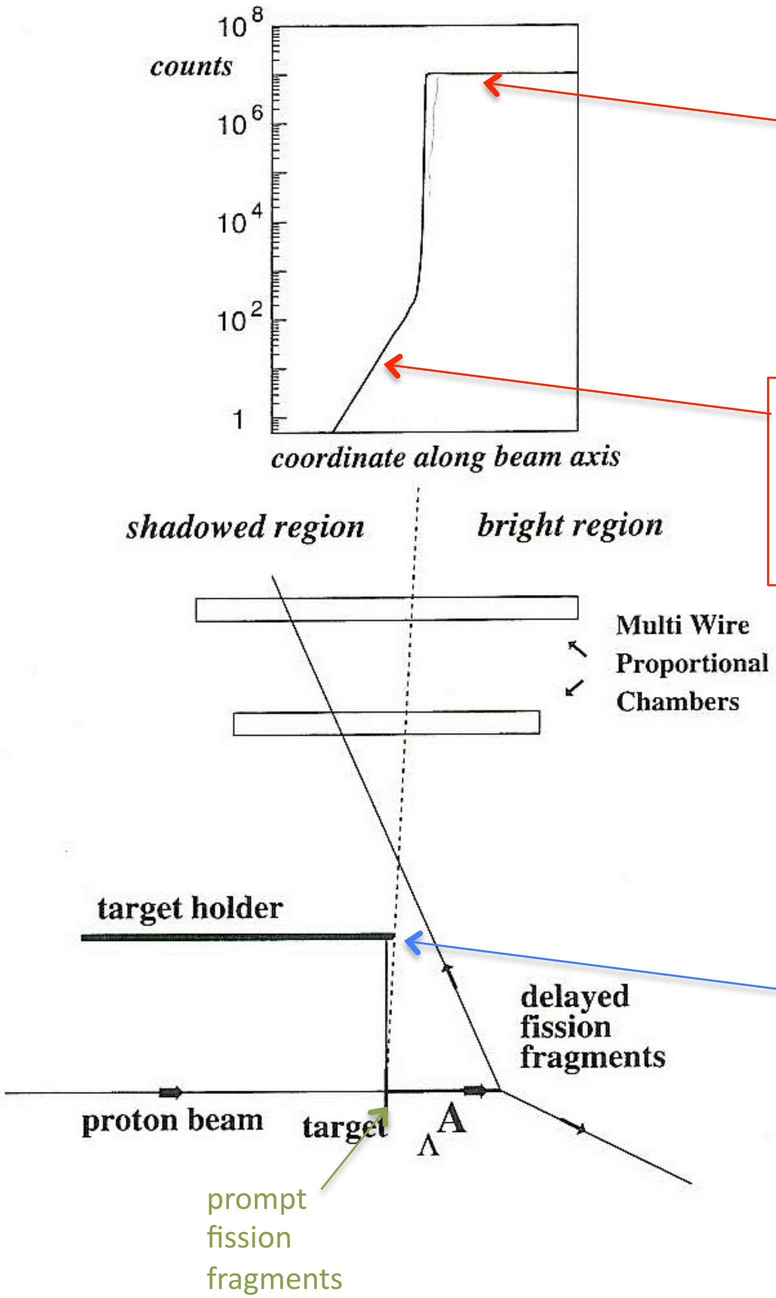
Lifetime measurements @ COSY

Hypernuclei which survive the prompt fission stage leave the target with a recoil velocity v_R and decay at some distance from the target proportional to τ and v_R.

Prompt and delayed fission can be separated by spatial distribution of the decay.

- $N_{prompt} \sim 10^5 N_{delayed}$
- high accuracy in the measurement of spatial distribution
- Recoil Shadow method: analysis of spatial distribution of delayed decays vs $\tau \cdot v_R$.

Recoil Shadow Method



Bright region:
constant yield for the prompt fission

Shadow region:
exponential fall-off for the delayed fission
(& prompt fission + scattering on the holder:
background from 1 GeV runs)

sensitive to fission fragments
not to light particles ($\varepsilon < 10^{-11}$)

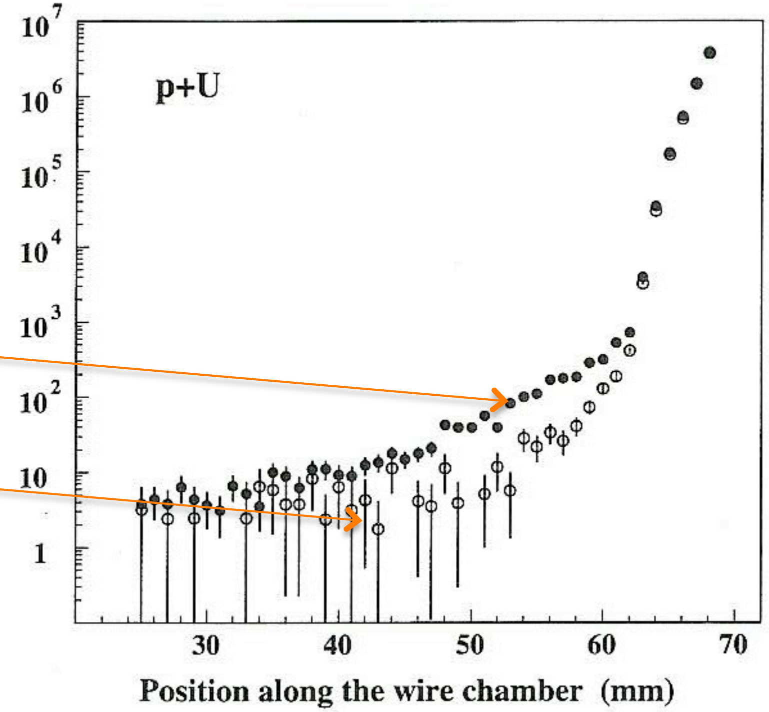
target holder partly screens MWPC:
prompt fission fragments cannot hit
the shadow part of MWPC

technique used also in antiproton-A
hypernuclei production experiments

Experimental distribution of hit position of the fission fragments onto MWPC

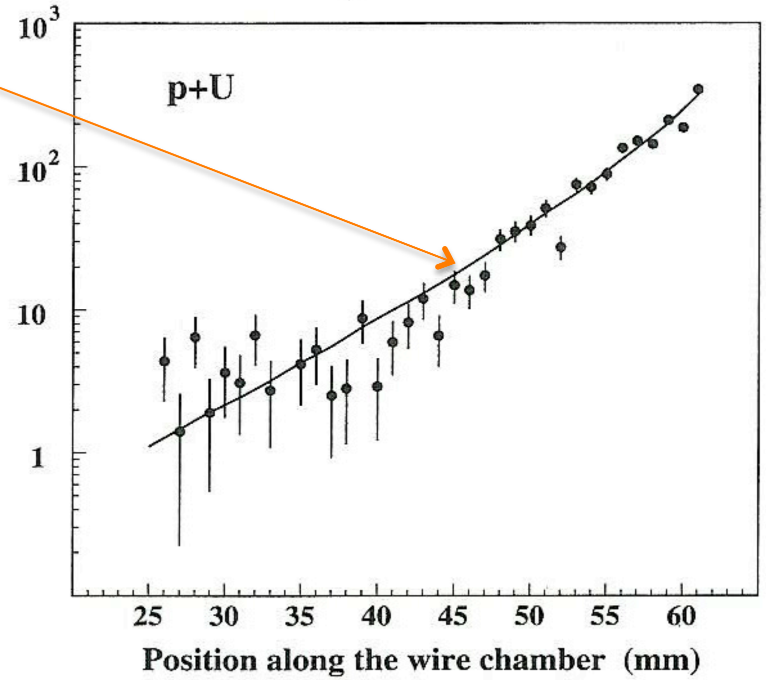
1.9 GeV: hypernuclear production

1.0 GeV: background estimation



Comparison with simulated distributions:

- hypernuclei velocity distribution from CBUU+HF
- τ free parameter of the fit procedure
- best lifetime τ_{best} by maximum-likelihood



Au	130±20 ps
Bi	161±16 ps
U	138±18 ps

τ_Λ=145±11 ps A~180-225

… new mechanisms to enhance the decay rate in the very heavy A region ?

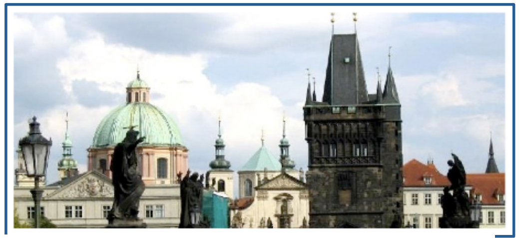
Mesonic Weak Decay Measurements

- s-shell: Λ-N potential central repulsion
- p-shell:
  - π distortion effect and MWD enhancement
  - π^--nucleus optical potential
  - J^π assignment: new indirect spectroscopic tool
- s-d shell …

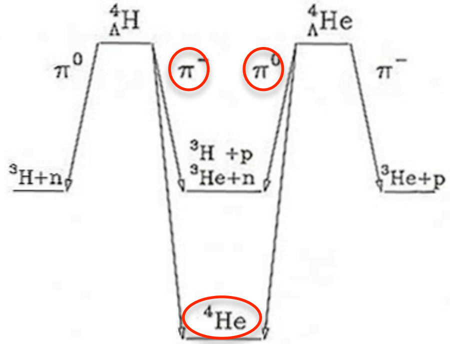
MWD: s-shell hypernuclei

- Λ-hypernuclei are the practical way to study ΛN interaction (τ_Λ=2.63 10^{-10} s)
- few-body theories are able to calculate up to 5-body systems from raw ΛN interaction → basic requirement: to reproduce s-shell hypernuclei B_Λ
- ΛN phenomenological potentials determined by fitting $B_\Lambda(^3_\Lambda H)$, $B_\Lambda(^4_\Lambda H)$ and $B_\Lambda(^4_\Lambda He)$ overestimate $B_\Lambda(^5_\Lambda He)$
- ΛN-ΣN coupling
- central repulsion in YN potential: long-range attraction of YN weaker than NN and counterbalanced by short-range → inner repulsion in Y-nucleus interaction
- strong effect in s-shell case (A=4,5): Λ pushed out from the core nucleus → overlap of w.f. reduced
- repulsive core exp. established for $^4_\Sigma He$: ΣN→ΛN conversion suppressed → narrow width
- experimental evidence for Λ-nucleus from mesonic decay observables: π-mesonic decay, Pauli suppressed, sensitive to the overlap of Λ and core w.f.: enhancement of MWD due to Pauli relaxation
- decay rate reflects Λ-nucleus potential shape → precise measurements of $\Gamma_{\pi-}$ and $\Gamma_{\pi 0}$

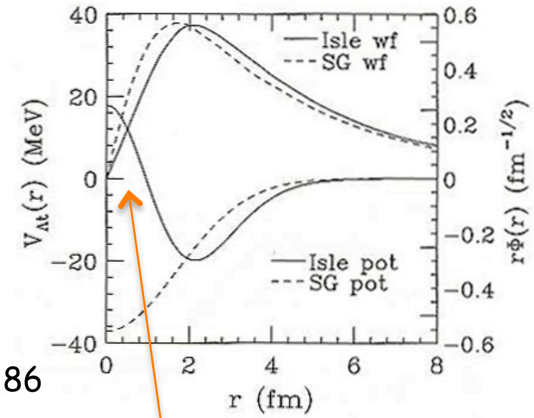
MWD: s-shell hypernuclei



Central repulsion: Γ_{2body}↓, Γ_{3body}↑,
Γ_{MWD}≈, $\Gamma_{2body}/\Gamma_{3body}$



Kumagai-Fuse, PLB 345 (1995) 386



central repulsion

$^4_\Lambda$H, $^4_\Lambda$He: KEK E167 (K^-_{stop}, π)
Outa NPA 639 (1998) 251c

$^5_\Lambda$He: KEK E462 - E508 (π^+, K^+)
Kameoka NPA 754 (2005) 173
Okada NPA 754 (2005) 178

$\Gamma_{tot} = \hbar/\tau$
$BR_{\pi-} = N_{\pi-} / \varepsilon_{\pi-} N_{hyp}$
$\Gamma_{\pi-} = BR_{\pi-} \Gamma_{tot}$
$BR_{\pi0} = N_{\pi0} / \varepsilon_{\pi0} N_{hyp}$
$\Gamma_{\pi0} = BR_{\pi0} \Gamma_{tot}$

$BR_{NM} = 1 - BR_{\pi-} - BR_{\pi0}$
$\Gamma_{NM} = \Gamma_{tot} - \Gamma_{\pi-} - \Gamma_{\pi0}$

KEK E167: $^4_\Lambda$H, $^4_\Lambda$He

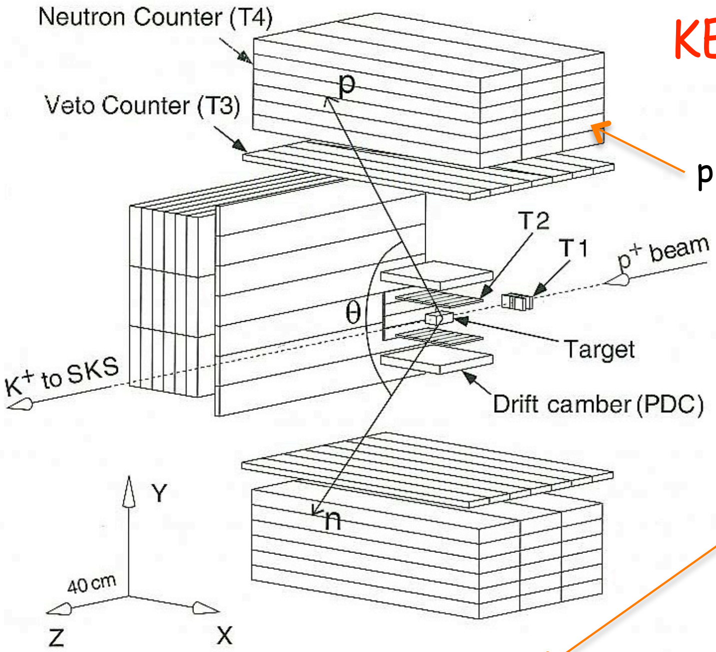
Decay widths of $^4_\Lambda$He

Decay	Results	Zeps [40]	SRG	Isle
$\Gamma_{total}/\Gamma_\Lambda$	$1.03^{+0.12}_{-0.10}$	1.07 ± 0.11		
$\Gamma_{\pi^0}/\Gamma_\Lambda$	0.53 ± 0.07	0.60 ± 0.08	0.49	0.51
$\Gamma_{\pi^-}/\Gamma_\Lambda$	0.33 ± 0.05	0.26 ± 0.03	0.25	0.31
$\Gamma_{\pi^0}/\Gamma_{\pi^-}$	1.59 ± 0.20	2.3 ± 0.4	2.02	1.59
Γ_p/Γ_Λ	0.16 ± 0.02	0.16 ± 0.02		
Γ_n/Γ_Λ	$0.01^{+0.04}_{-0.01}$	0.04 ± 0.02		
$\Gamma_{nm}/\Gamma_\Lambda$	0.17 ± 0.05	0.20 ± 0.03		
$\Gamma_{nm}/\Gamma_{\pi^-}$	0.51 ± 0.16	0.77 ± 0.15		
Γ_n/Γ_p	$0.06^{+0.28}_{-0.06}$	$0.25^{+0.05}_{-0.13}$		

Decay widths of $^4_\Lambda$H

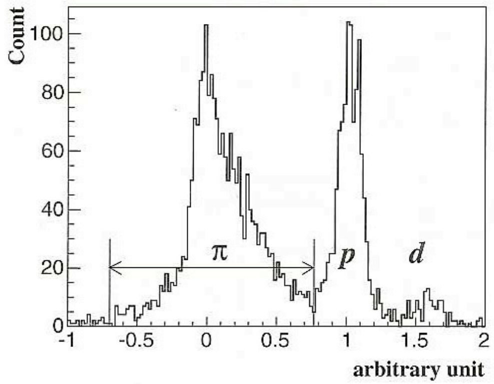
Decay	Results	SRG	Isle
$\Gamma_{total}/\Gamma_\Lambda$	$1.36^{+0.21}_{-0.15}$		
$\Gamma_{\pi^0}/\Gamma_\Lambda$		0.16	0.19
$\Gamma_{\pi^-}/\Gamma_\Lambda$	$1.00^{+0.18}_{-0.15}$[a]	0.93	0.88
$\Gamma_{\pi^- {}^4He}/\Gamma_\Lambda$	$0.69^{+0.12}_{-0.10}$[a]	0.71	0.61
$\Gamma_{\pi^- {}^4He}/\Gamma_{\pi^-}$	0.69 ± 0.02[a]	0.76	0.69
$\Gamma_{nm}/\Gamma_\Lambda$	0.17 ± 0.11[a]		

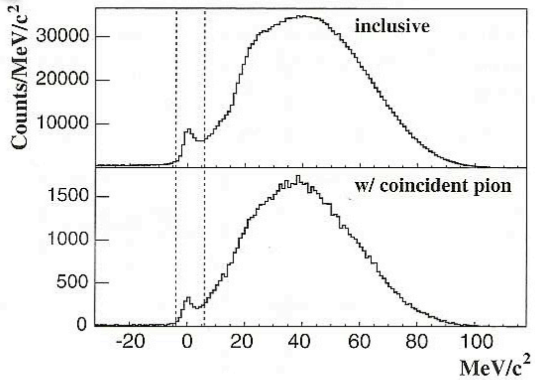
KEK E462 – E508 : $^{5}_{\Lambda}He$ (+ $^{12}_{\Lambda}C$: MWD & NMWD)

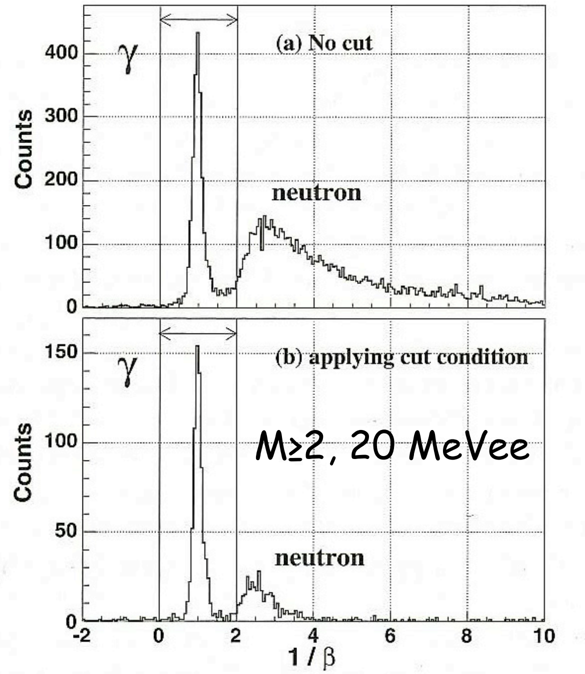


Charged particles (p,π):
dE/dx on T2, ΔE (T2, T3, T4)
TOF(T2-T3)

Neutral particles (n,γ):
TOF (T1-T4), T3 veto







$BR_{\pi-}$ = 0.359 ± 0.009 Kameoka
Isle potential: 0.354; SG: 0.271
$\Gamma_{\pi-} / \Gamma_\Lambda$ = 0.342 ± 0.016
$\Gamma_{tot} / \Gamma_\Lambda$ = 0.954 ± 0.039
$BR_{\pi 0}$ = 0.212 ± 0.008 Okada
$\Gamma_{\pi 0} / \Gamma_\Lambda$ = 0.201 ± 0.011
Isle potential: 0.215; SG: 0.177

MWD: p-shell hypernuclei

- MWD Pauli forbidden (p_N~100 MeV/c)
- theoretical calculations with pion distorted wave predict MWD to be less suppressed for p-shell (A~10)
- π feels attraction in nuclear medium due to the p-wave part of the optical potential → dispersion relation modified inside the nucleus → pion carries lower energy for fixed momentum q: $\omega(q) = (q^2+m_\pi^2)^{1/2}$ → Energy conservation increases the final nucleon chance to come out above the Fermi surface
- Enhancement of MWD:
  - Bando et al., Progr. Theor. Phys. Suppl. 72 (1984) 109
  - Oset et al., NPA 443 (1985) 704

Extensive calculations:

- Motoba et al., Progr. Theor. Phys. Suppl. 117 (1994) 477
- Gal Nucl. Phys. A 828 (2009) 72.

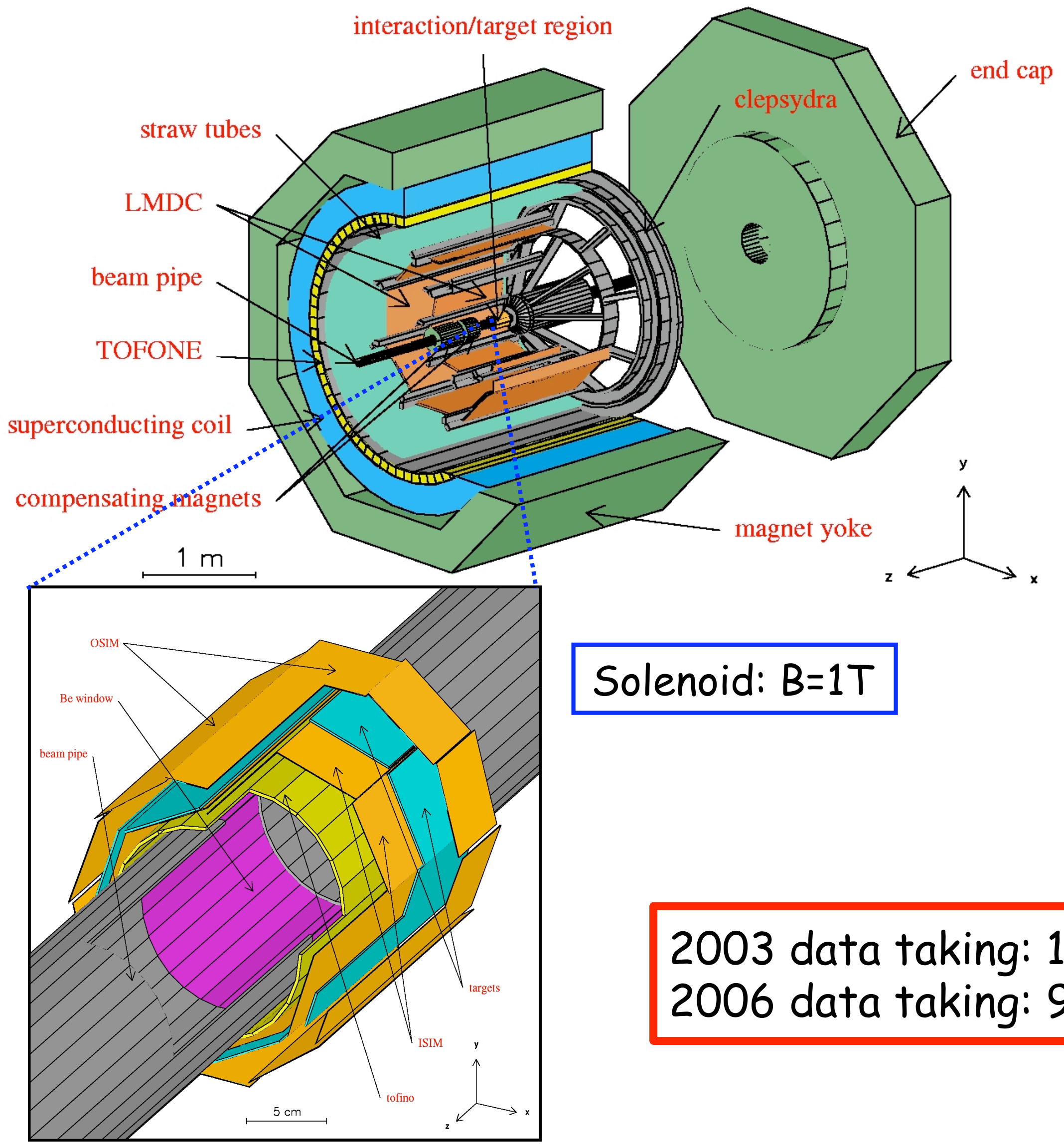
MWD: p-shell hypernuclei

Present knowledge

A	$\Gamma_\pi/\Gamma_\Lambda$	$\Gamma_{tot}/\Gamma_\Lambda$	References	Exp.
$^{5}_{\Lambda}He$	π^-: 0.44±0.11 [1] 0.340±0.016 [2] 0.332±0.069 [3] π^0: 0.14±0.19 [1] 0.201±0.011 [4]	1.03±0.08 [1] 0.947±0.038 [2]	[1] Szymanski PRC 43 (1991) 849 [2] Kameoka NPA 754 (2005) 173 [3] Agnello PLB 681 (2009) 139 [4] Okada NPA 754 (2005) 178 [5] Park PRC 61 (2000) 054004 [6] Montwill NPA 234 (1974) 413	BNL AGS KEK PS E462 LNF KEK PS E508 KEK PS E307 emulsion
$^{7}_{\Lambda}Li$	π^-: 0.353±0.059 [3]		[7] Noumi PRC 52 (1995) 2936	KEK PS E160
$^{9}_{\Lambda}Be$	π^-: 0.178±0.050 [3]	1.31±0.20 [1]	[8] Sato PRC 71 (2005) 025203	KEK PS E307
$^{11}_{\Lambda}B$	π^-: 0.22±0.05 [6] 0.23±0.06 [7] 0.212±0.036 [8] 0.249±0.051 [3] π^0: 0.192±0.056 [9]	1.37±0.16 [10] 1.25±0.08 [5]	[9] Sakaguchi PRC 43 (1991) 73 [10] Barnes PRL 55 (1985) 1055	KEK PS BNL AGS
$^{12}_{\Lambda}C$	π^-: $0.052^{+0.063}_{-0.035}$ [1] 0.14±0.07 [7] 0.113±0.014 [8] π^0: 0.217±0.073 [9]	1.25±0.18 [10] 1.14±0.08 [5] 1.24±0.04 [2]		
$^{15}_{\Lambda}N$	π^-: 0.108±0.038 [3]			
$^{27}_{\Lambda}Al$	π^-: 0.041±0.010 [8]	} s-d shell		
$^{28}_{\Lambda}Si$	π^-: 0.046±0.011 [8]			

FINUDA @ DAΦNE (LNF)

$$e^+ + e^- \rightarrow \phi(1020) \rightarrow K^+ + K^- \ (127\ \mathrm{MeV}/c)$$
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$



Solenoid: B=1T

Detector capabilities:

Selective trigger based on fast scintillation detectors (TOFINO, TOFONE)

Clean K^- vertex identification

(ISIM P.ID.+ *x,y,z* resolution + K^+ tagging)

π, K, p, d, … P.I.D. (OSIM&LMDs d*E*/d*x*, TOF)

High momentum resolution

(6‰ FWHM for π- @270 MeV/c for spectroscopy)

(1% FWHM for π- @270 MeV/c for decay study)

(6% FWHM for π- @110 MeV/c for decay study)

(2% FWHM for p @400 MeV/c for decay study)

(tracker resolution + He bag + thin targets)

Solid angle ~ 2π srad

2003 data taking: 190 pb^{-1} (2x^{6}Li, ^{7}Li, 3x^{12}C, ^{27}Al, ^{51}V)
2006 data taking: 966 pb^{-1} (2x^{6}Li, 2x^{7}Li, 2x^{9}Be, ^{13}C, D_2O)

(K^-_{stop}, π^-) kinematics

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

$$m_k + m_A = [p^2_{hyp} + m^2_{hyp}]^{1/2} + [p^2_\pi + m^2_\pi]^{1/2}$$
$$\vec{p}_\pi = - \vec{p}_{hyp}$$

energy & momentum conservation

$$m_{hyp} = \{[m_k + m_A - [p^2_\pi + m^2_\pi]^{1/2}]^2 - p^2_\pi\}^{1/2}$$
$$B_\Lambda = m_{A-1} + m_\Lambda - m_{hyp}$$

MWD & NMWD studies in FINUDA

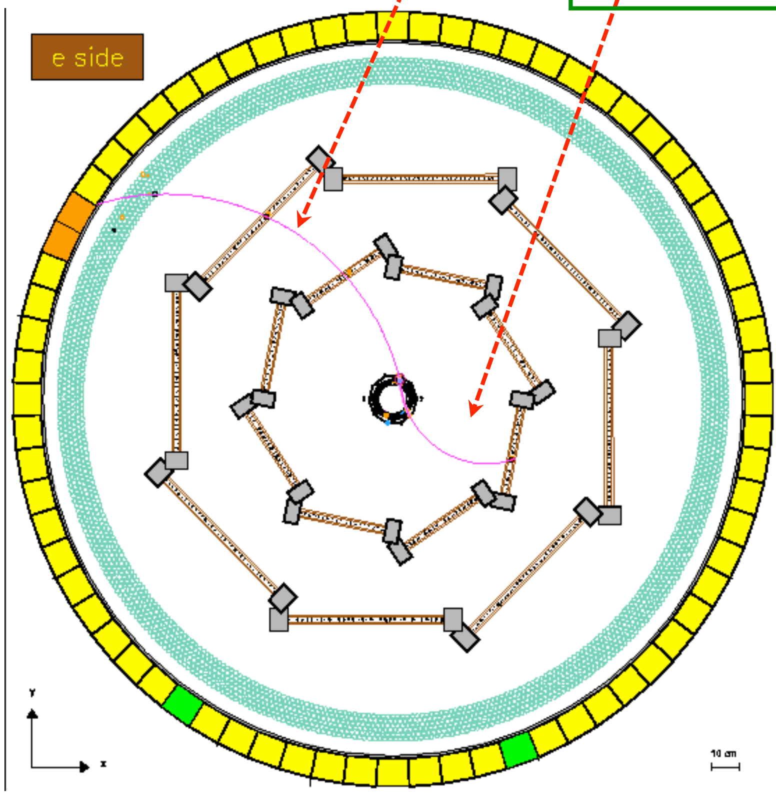
Coincidence measurement

charged Mesonic channel

$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$
$${}^A_\Lambda Z \rightarrow {}^A(Z+1) + \pi^-$$

S-EX
260-280 MeV/c

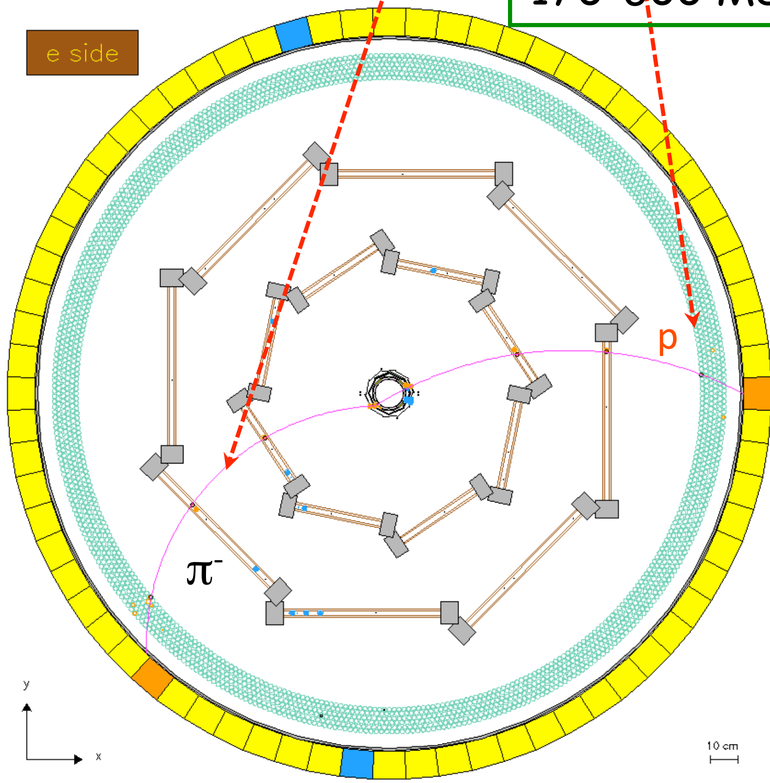
MWD
80-110 MeV/c



charged Non-Mesonic channel

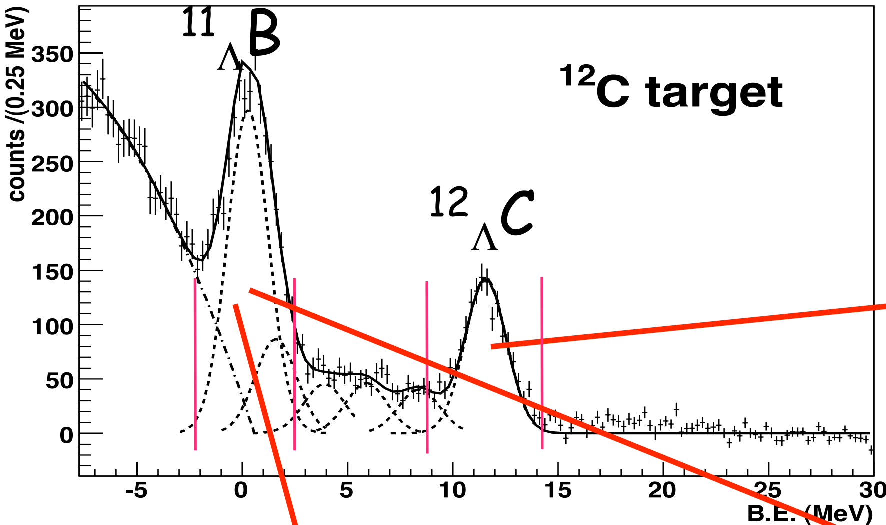
$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$
$${}^A_\Lambda Z \rightarrow {}^{A-2}(Z-1) + p + n$$

NMWD
170-600 MeV/c

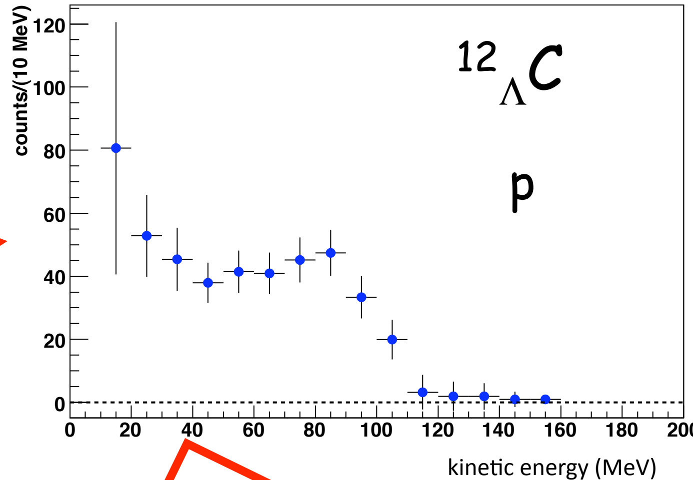


MWD & NMWD in FINUDA: strategy

Inclusive production π^- spectra
K^-np background corrected



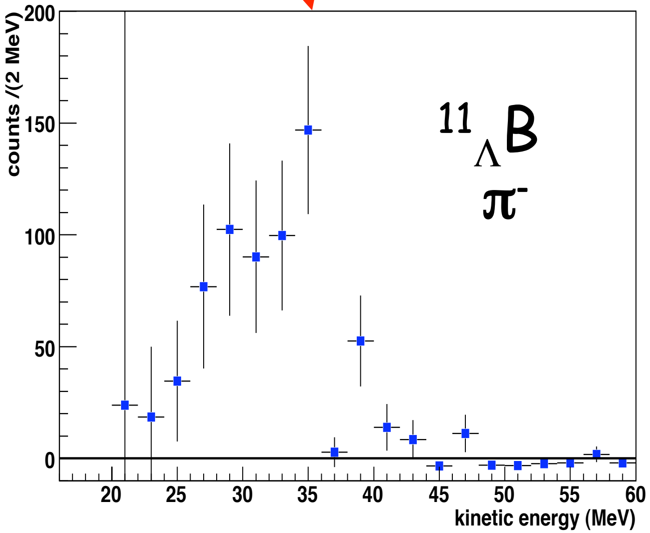
NMWD

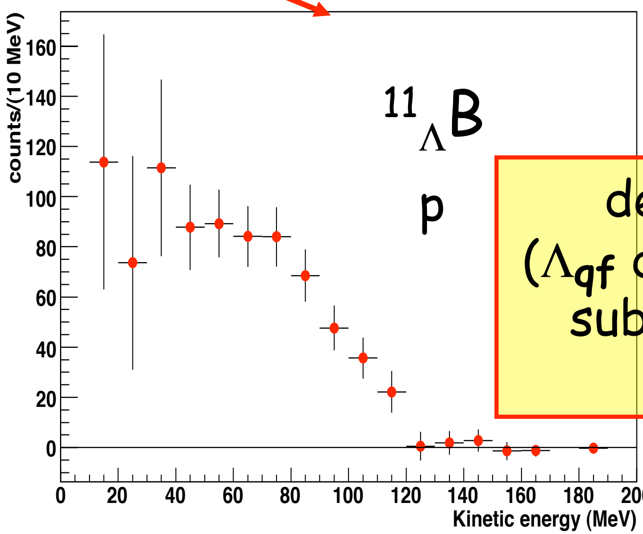


MWD

NMWD

magnetic analysis !!





decay π^- and p spectra
(Λ_{qf} decay)/K^-np background
subtracted & acceptance
corrected

MWD (spectra): theoretical calculations

- ✓ T. Motoba, K.Itonaga, H.Bando, Nucl. Phys. A 489 (1988) 683.
- ✓ T. Motoba, K.Itonaga, Progr. Theor. Phys. Suppl. 117 (1994) 477.

Decay rates calculations:

$\Gamma^{free}{}_{\pi\alpha} = c_a\ q_0/(1+w_p(q_0)/E_N(q_0))\ (s_p{}^2 + p_p{}^2\ q^2/q_0{}^2)$ $p_\pi{}^2 / s_\pi{}^2 \sim 1/9$ P-violation

$c/c_0 \sim 2 \quad \Delta I = 1/2$

$\Gamma^{(s)}{}_{\pi\alpha} = c_\alpha\ q/(1+\omega_\pi(q)/E_A(q))\ s_\pi{}^2\ \ P^{(s)}{}_{i\to f}$

$P^{(s)}{}_{i\to f}$: effective p number for the transition, (Λ, p) transition matrix element

- hypernuclear and nuclear wave functions: Cohen-Kurath /DDHF
- DW for π FSI: π-nuclear polarization effect enhances MWD
- Pauli suppression

Calculation of: $\Gamma^{(s,p)}{}_{\pi\alpha\ tot}/\Gamma_\Lambda$, $\Gamma^{(s)}{}_{\pi\alpha\ i}/\Gamma_\Lambda$

- 1p, 2s1d small contributions
- strong nuclear structure effects
- charge dependence
- excitation functions

✓ A. Gal. Nucl. Phys. A 828 (2009) 72.

Sum rule $(2J_i+1)$-averaged, J_f stripping sum rule

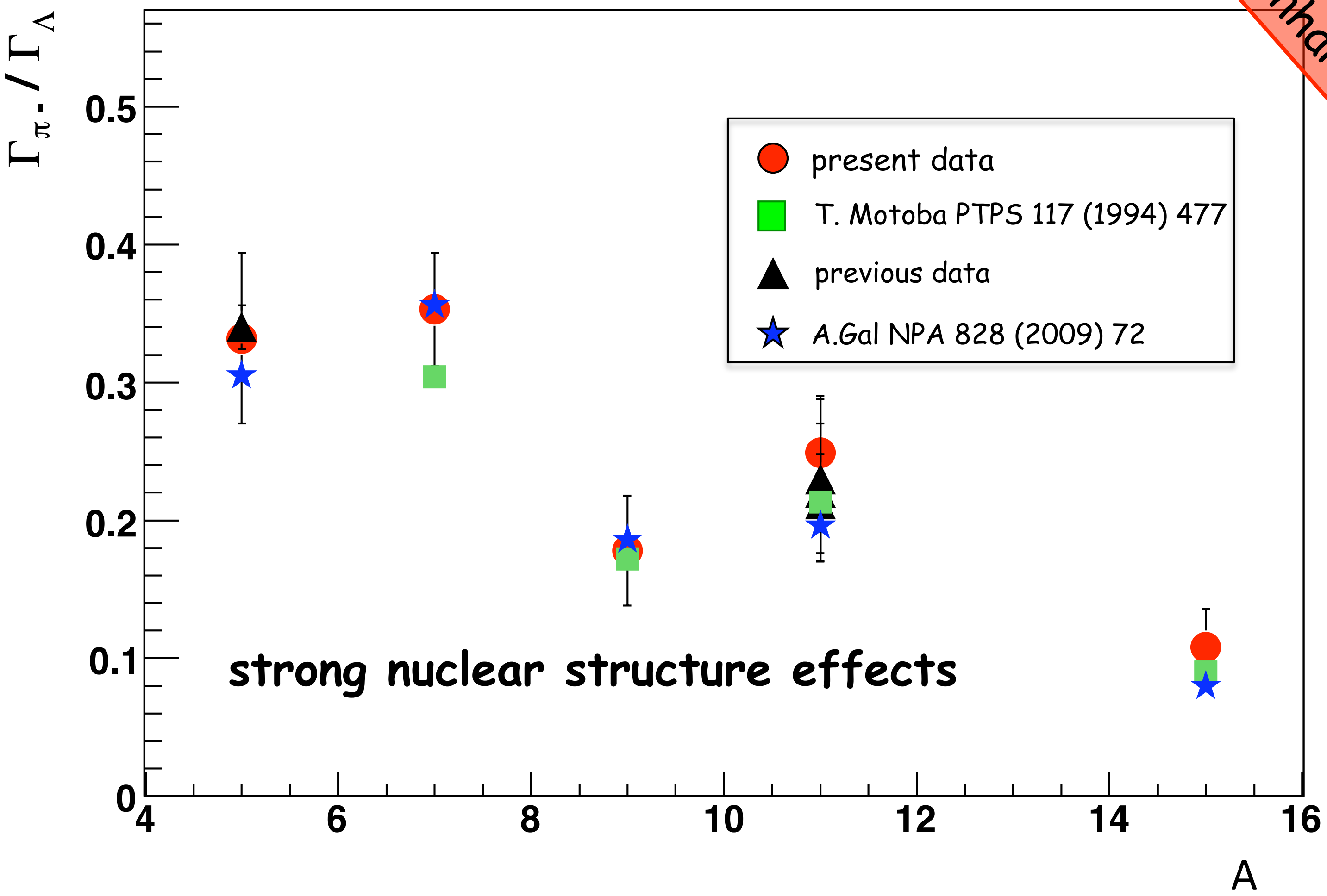
Mesonic decay ratio: $\Gamma_{\pi-} / \Gamma_\Lambda$

$$\Gamma_{\pi-} / \Gamma_\Lambda = \Gamma_{tot} / \Gamma_\Lambda \bullet BR_{\pi-}$$

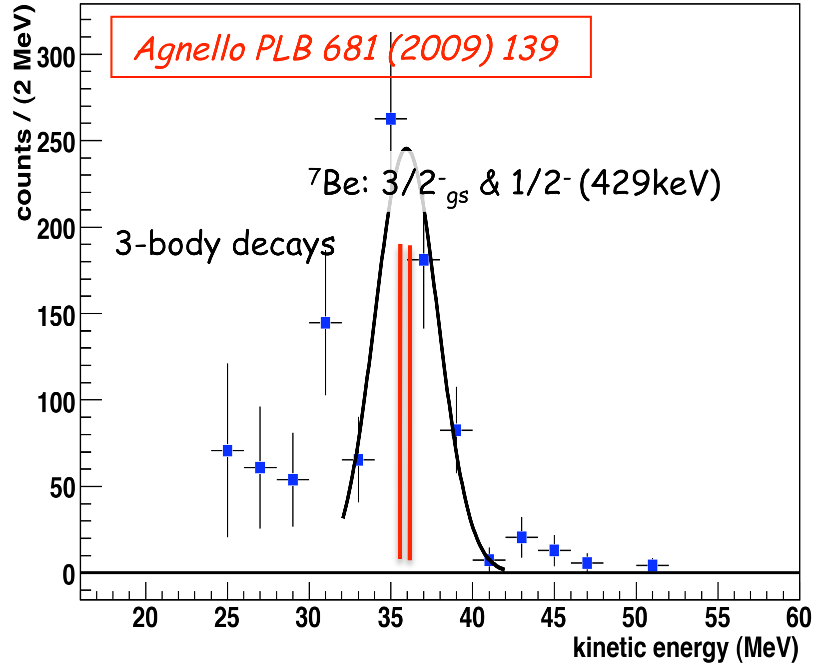
$$\Gamma_{tot} / \Gamma_\Lambda = (0.990 \pm 0.094) + (0.018 \pm 0.010) \bullet A$$

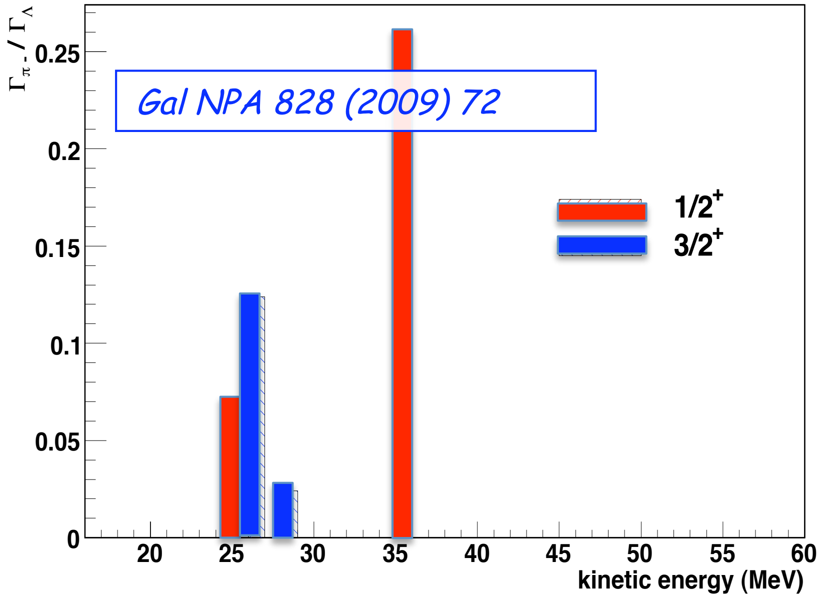
fit from measured values for A=4-12 hypernuclei

π distortion, MWD enhancement proved !

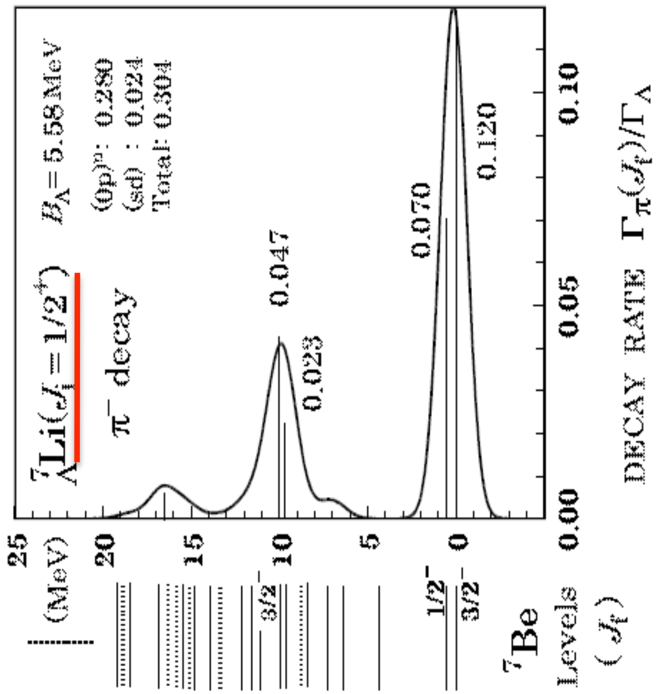


J^{π} assignment: $^{7}_{\Lambda}Li$ (new)



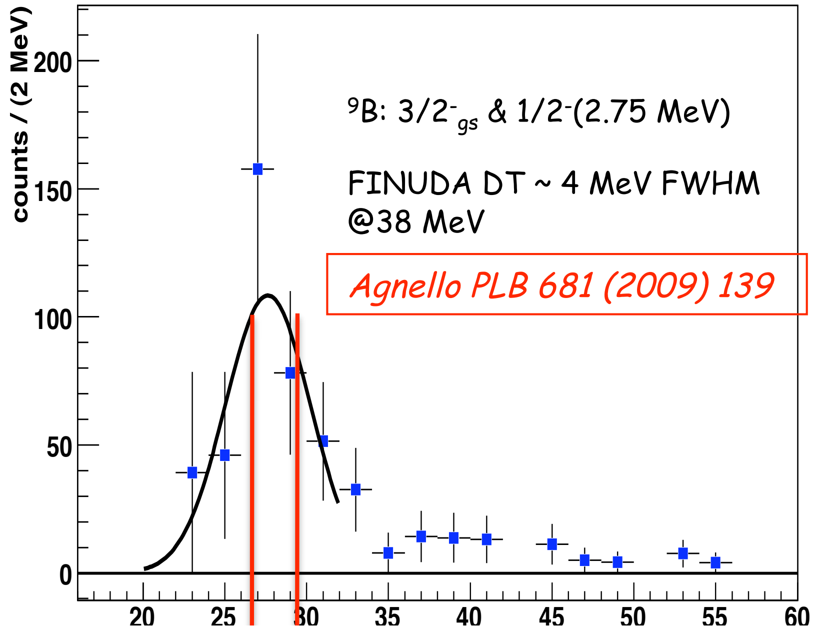


- Correspondence with the calculated strenght functions
  - ✓ T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.
  - ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.
- Formation of different excited states of the daughter nucleus
- Initial hypernucleus spin
  $J^{\pi}(^{7}_{\Lambda}\mathbf{Li}_{g.s.}) = 1/2^{+}$ (Sasao, PLB 579 (2004) 258.



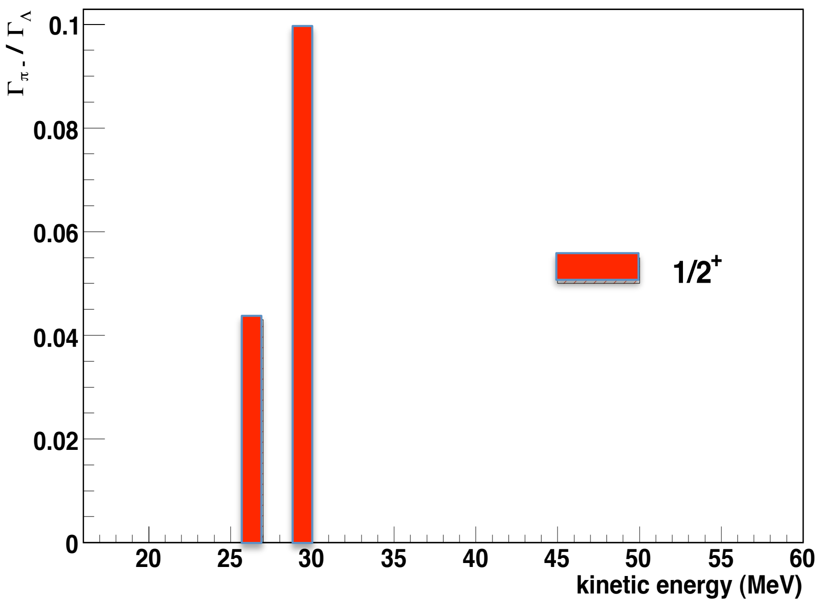
T. Motoba (Private Communication)

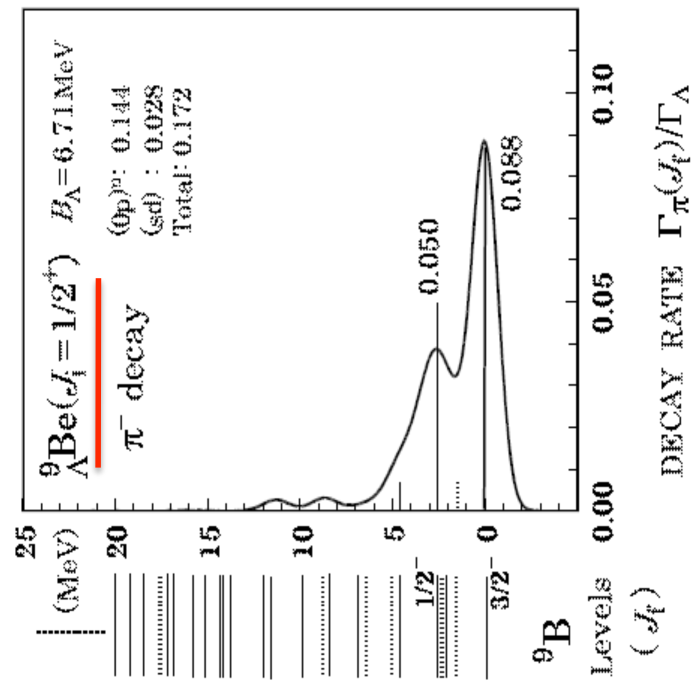
J^{π} assignment: $^{9}_{\Lambda}Be$



- Correspondence with the calculated strenght functions
  - ✓ T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.
  - ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

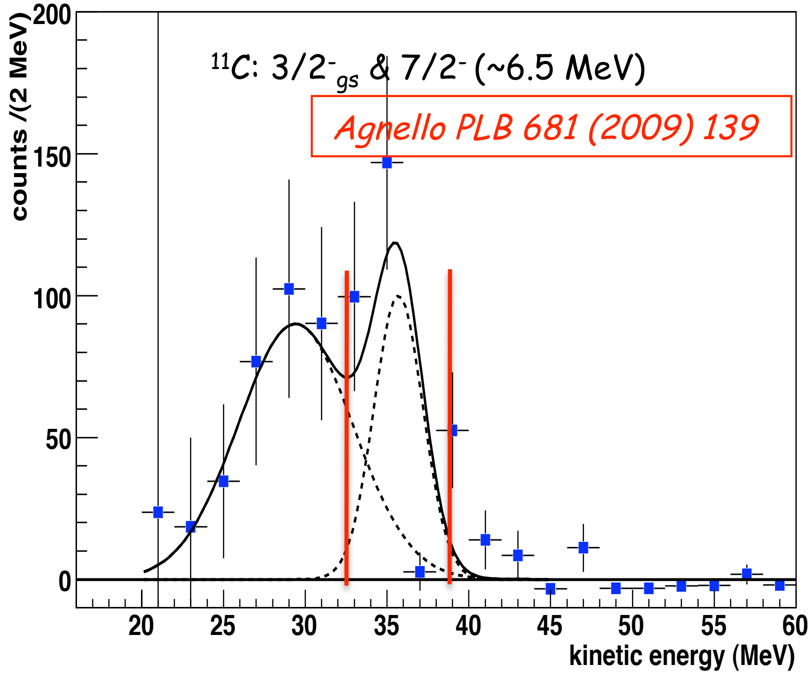
- Initial hypernucleus spin
  $J^{\pi}(^{9}_{\Lambda}Be_{g.s.}) = 1/2^{+}$
  O.Hashimoto NPA 639 (1998) 93c.



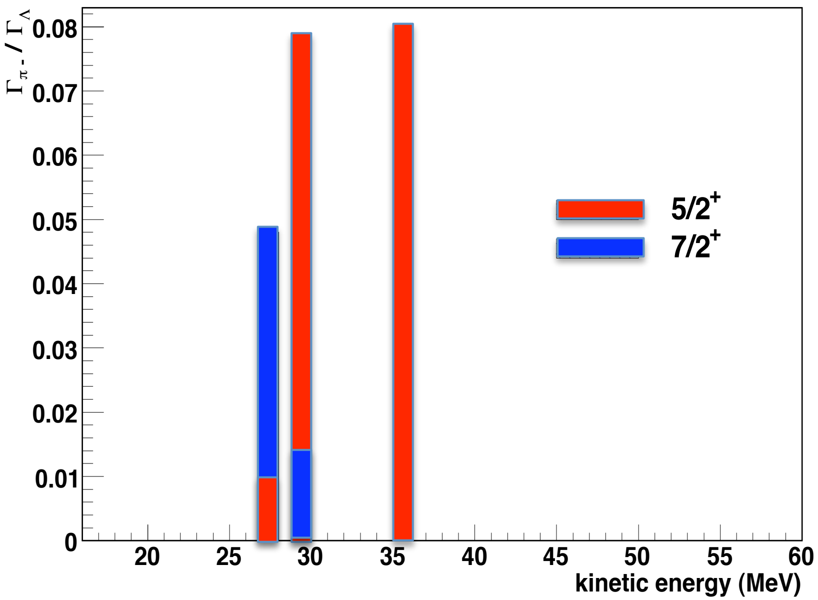


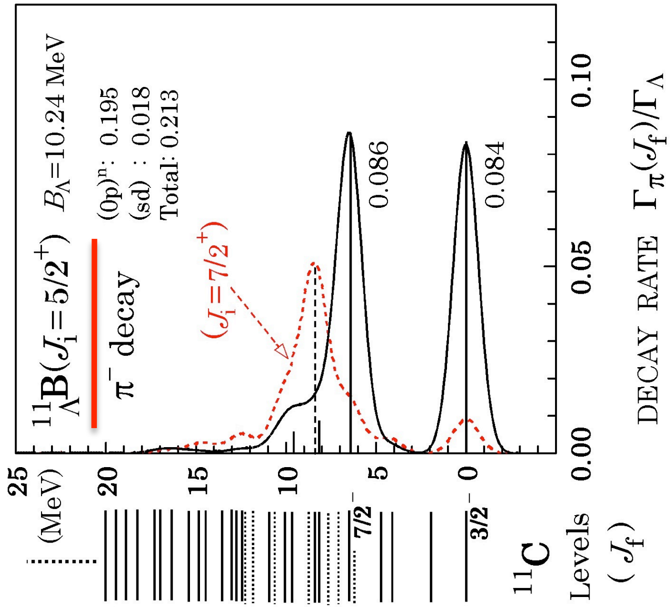
T. Motoba (Private Communication)

J^π assignment: $^{11}{}_\Lambda B$



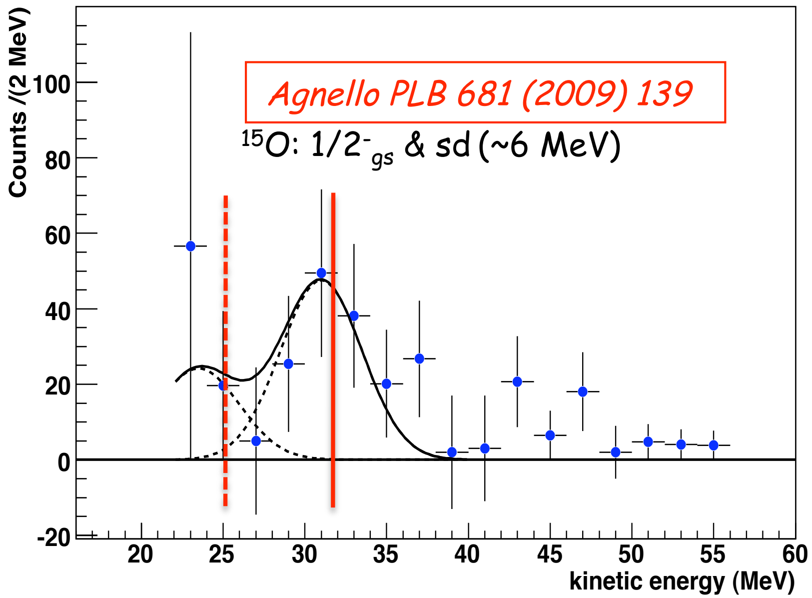
- Correspondence with the calculated strenght functions
  - ✓ H. Bando et al, Pers. Meson Science (1992) p.571
  - ✓ A. Gal, Nucl. Phys A 828 (2009) 72.
- Two contributions of the ^{11}C ground state $5/2^-$ and its $7/2^-$ excited state
- Initial hypernucleus spin
  $J^\pi(^{11}{}_\Lambda B_{g.s.}) = 5/2^+$: experimental confirmation (Sato et al., PRC 71 (2005) 025203) by different observable





Motoba (Private Communication)

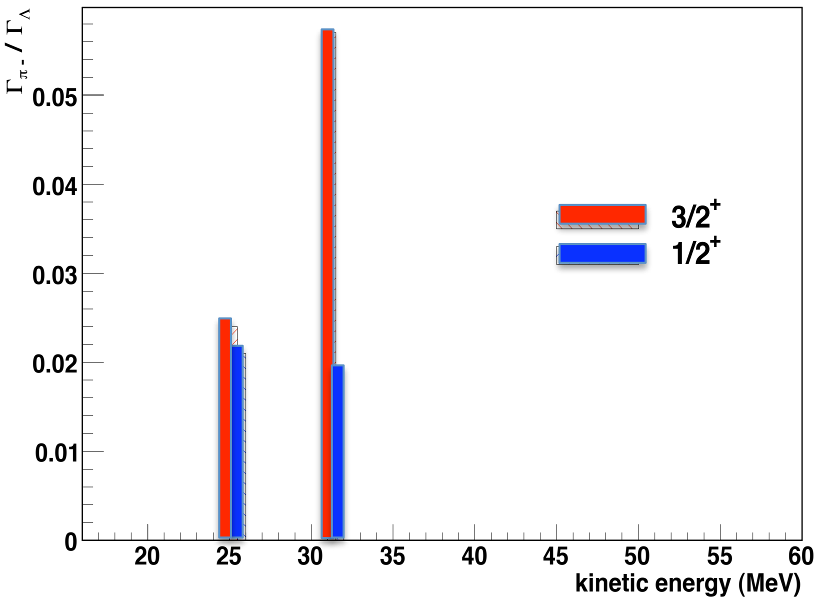
J^{π} assignment: $^{15}_{\Lambda}N$

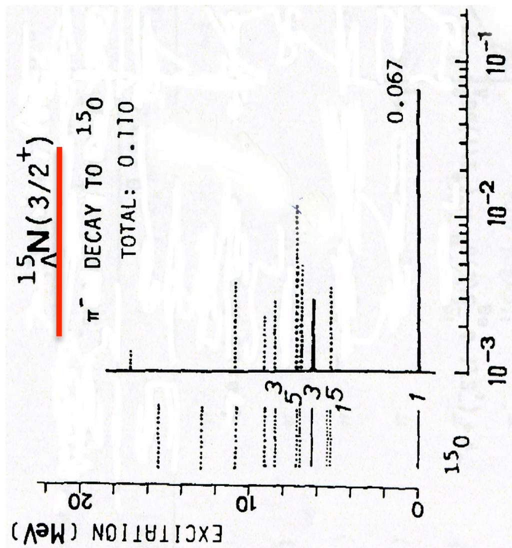


- Correspondence with the calculated strenght functions
- ✓ T. Motoba et al, Nucl. Phys. A 489 (1988) 683.
- ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

- $^{15}_{\Lambda}N_{g.s}$ spin not known. $J^{\pi}(^{15}_{\Lambda}N_{g.s.}) = 3/2^{+}$
D.J.Millener, A.Gal, C.B.Dover Phys. Rev. C 31 (1985) 499.
Spin ordering not obtained from γ-rays of $^{16}_{L}O$ M.Ukai et al. Phys. Rev.C 77 (2008) 054315.

- First experimental determination of $J^{\pi}(^{15}_{\Lambda}N_{g.s.}) = 3/2^{+}$ from decay rate value (and spectrum shape)





T. Motoba NPA 489 (1988) 683.

J^π assignment: $^4_\Lambda H$ (old)

R.H.Dalitz and L.Liu, PR 116 (1959) 1312

Properties of weak interaction:

- ✓ $\Delta I = 1/2$ empirical rule
- ✓ P-violation, s-wave 88%, spin-non-flip

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

$0^- + 0^+ \rightarrow 0^+ + 0^-$ strong

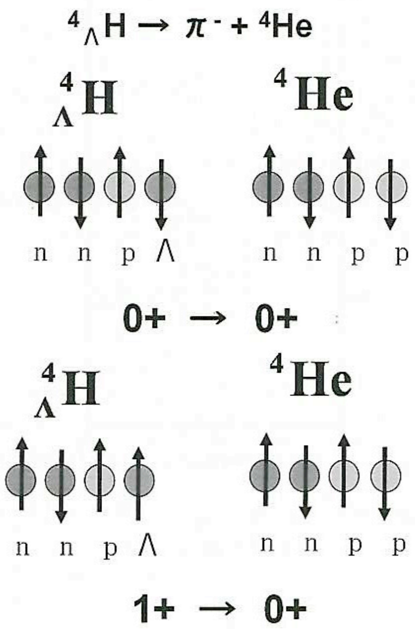
(K^- negative parity)

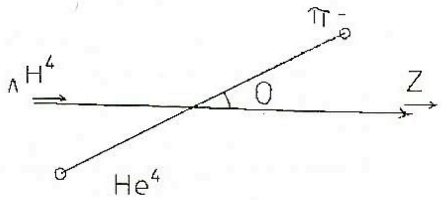
${}^4_\Lambda H \rightarrow {}^4He + \pi^-$ weak

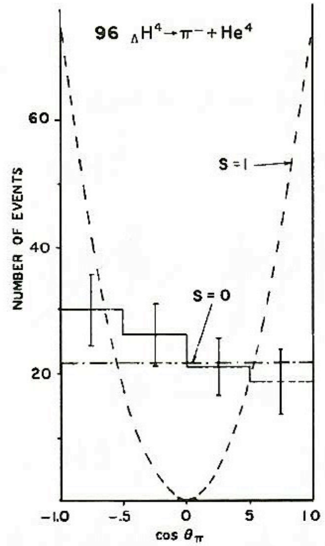
isotropic π^- emission (s-wave)

& P violation $\rightarrow J^\pi_i = 0^+$:

$0^+ \rightarrow 0^+ + 0^-$ s-wave







Non-Mesonic Weak Decay Measurements

- s-shell: $\Delta I = 1/2$ rule ($^{4}_{\Lambda}H$) see A. Ramos lecture
  heavy hypernuclei and $\Delta I = 1/2$ rule (in-medium $\Lambda N \rightarrow NN$)

- observables :
  - $\Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_{2N}$
  - Γ_n/Γ_p puzzle (solved ? … systematics)
  - Γ_{2N}, FSI contributions
  - p distribution asymmetry in NMWD of polarized hypernuclei see A. Ramos lecture

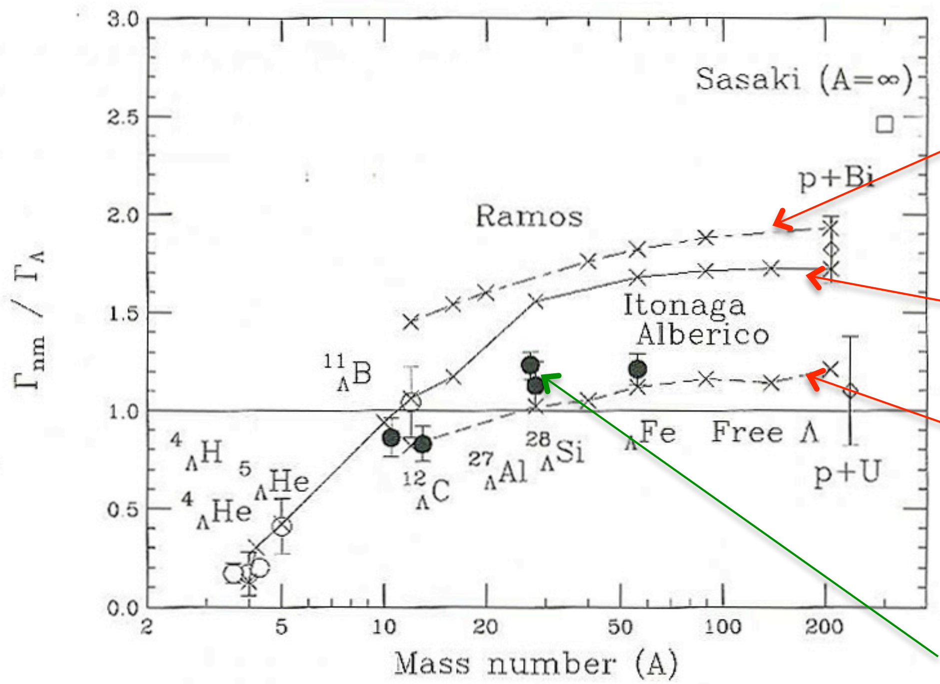
Counting experiments results

NMWD data

References	Exp.	Measurement
Szymanski PRC 43 (1991) 849	BNL AGS, LESB I (K^-,π^-) 800 MeV/c	p spectrum, Γ_p, Γ_n, Γ_{nm}, Γ_n/Γ_p for ${}^5_\Lambda$He, Γ_{nm}, Γ_n/Γ_p for ${}^{12}_\Lambda$C
Noumi PRC 52 (1995) 2936	KEK PS E160 (π^+, K^+) 1.05 GeV/c	p spectrum for ${}^{12}_\Lambda$C, Γ_p/Γ_Λ, $\Gamma_{nm}/\Gamma_\Lambda$, Γ_n/Γ_p for ${}^{11}_\Lambda$B and ${}^{12}_\Lambda$C
Hashimoto PLR 88 (2002) 045203	KEK PS E307 (π^+, K^+) 1.05 GeV/c	p spectrum and Γ_n/Γ_p for ${}^{12}_\Lambda$C and ${}^{28}_\Lambda$Si (theory)
H.J.Kim PRC 68 (2003) 065201	KEK PS E369 (π^+, K^+) 1.05 GeV/c	n spectrum for ${}^{12}_\Lambda$C and ${}^{89}_\Lambda$Y and Γ_n/Γ_p for ${}^{12}_\Lambda$C (theory)
Okada PLB 597 (2004) 249	KEK PS E462-E508 (π^+, K^+) 1.05 GeV/c	p, n spectra and Γ_n/Γ_p for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C (exp)
Sato PRC 71 (2005) 025203	KEK PS SKS E307 (π^+, K^+) 1.05 GeV/c	p spectrum and $\Gamma_{nm}/\Gamma_\Lambda$ for ${}^{11}_\Lambda$B, ${}^{12}_\Lambda$C, ${}^{27}_\Lambda$Al, ${}^{28}_\Lambda$Si, ${}_\Lambda$Fe (theory)
Kang PRL 96 (2006) 062301	KEK PS E462 (π^+, K^+) 1.05 GeV/c	p & n spectra, Γ_n/Γ_p for ${}^5_\Lambda$He
M.J.Kim PLB 641 (2006) 28	KEK PS E508 (π^+, K^+) 1.05 GeV/c	p & n spectra, Γ_n/Γ_p for ${}^{12}_\Lambda$C
Bhang EPJ A33 (2007) 259	KEK PS E462-E508 (π^+, K^+) 1.05 GeV/c	re-analysis of p & n spectra for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C, Γ_n/Γ_p for ${}^{12}_\Lambda$C
Parker PRC 76 (2007) 035501	BNL AGS, LESB II (K^-,π^-) 750 MeV/c	Γ_n, Γ_p, Γ_n/Γ_p for ${}^4_\Lambda$He
Agnello NPA 804 (2008) 151	LNF (K^-_{stop}, π^-)	p spectrum for ${}^5_\Lambda$He, ${}^7_\Lambda$Li and ${}^{12}_\Lambda$C
M.Kim PRL 103 (2009) 182502	KEK PS E508	re-analysis of p & n spectra, Γ_n, Γ_p, Γ_{2N} for ${}^{12}_\Lambda$C
Agnello PLB 685 (2010) 247	LNF (K^-_{stop}, π^-)	p spectrum for ${}^5_\Lambda$He, ${}^7_\Lambda$Li, ${}^9_\Lambda$Be, ${}^{11}_\Lambda$B ${}^{12}_\Lambda$C, ${}^{13}_\Lambda$C, ${}^{15}_\Lambda$N and ${}^{16}_\Lambda$O

NMWD total width

Lifetime measurements + MWD BRs



A	$\Gamma_{nm}/\Gamma_{\Lambda}$	Reference
$^{5}_{\Lambda}He$	0.404±0.020	KEK PS E462, E508: Kameoka, Okada NPA 2005
$^{12}_{\Lambda}C$	0.953±0.032	KEK PS E462, E508: Kameoka, Okada NPA 2005
180-225	1.82±0.14	COSY COSY-13: Cassing 2003

NMWD: Γ_n/Γ_p ratio

Single nucleon measurements

- Measurements of NMWD p spectra and Γ_p: Γ_n deduced as $\Gamma_{tot} - \Gamma_p - \Gamma_M \rightarrow$ Γ_n/Γ_p increased by missing p considered as n
- p missing due to rescattering inside the residual nucleus (FSI) and/or 2N induced decays
- "Γ_n/Γ_p puzzle": $(\Gamma_n/\Gamma_p)_{exp} \geq 1$ vs $(\Gamma_n/\Gamma_p)_{th} \sim 0.3 \div 0.7$

KEK PS E307 – p spectra ${}^{12}_{\Lambda}C$, ${}^{28}_{\Lambda}Si$, ${}_{\Lambda}Fe$
Y. Sato et al., PRC 71 (2005) 025203

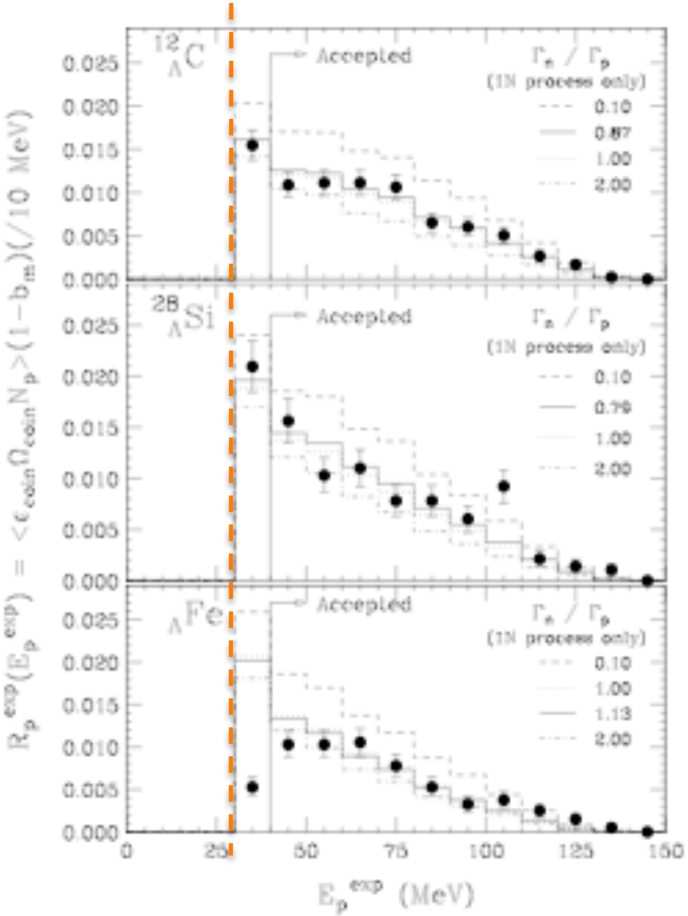
$R_p^{exp}(E_p) = Y_{coinc}(E_p) / Y_{hyp}$

compared with calculated $R_p^{calc}(E_p)$

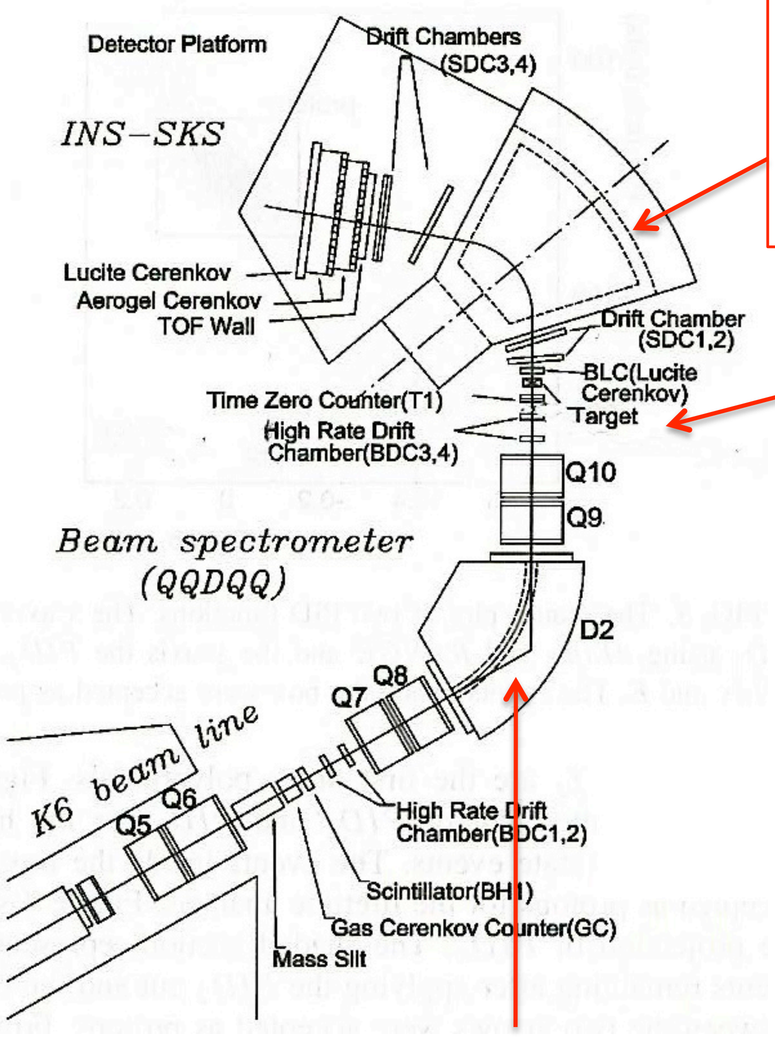
$R_p^{calc}(E_p) = N_p(E_p; \Gamma_n/\Gamma_p; 1N)\, \Omega_{coinc}\, \varepsilon_{coinc}\, BR_{NM}$

accounting for p due to p- & n- induced NMWD (OPE + LDA) and including INC & dE/dx

Ramos, PRC 55 (1997) 735
PRC 66 (2002) 039903



Γ_n/Γ_p from fit of simulated spectra to the exp. ones



SKS:

✓ scattered K^+ to reconstruct the hypernuclear mass spectrum (+ π^+ spectrometer)

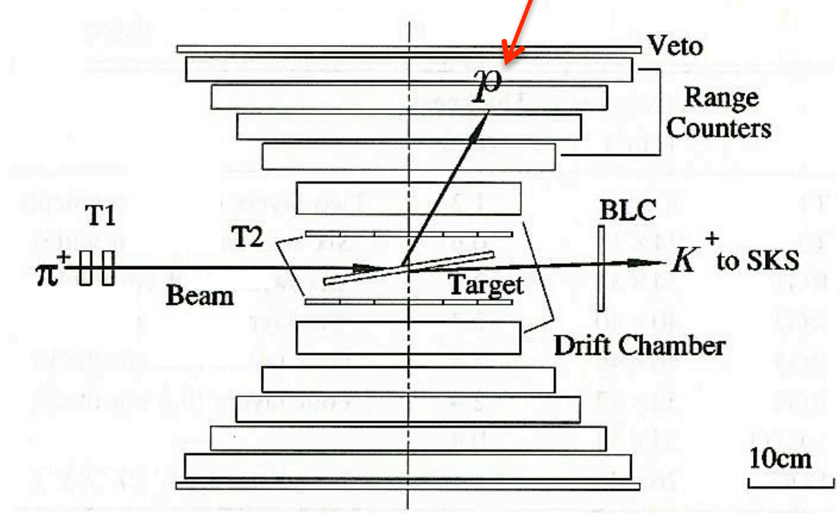
✓acceptance ~ 100 msr

✓$\Delta p/p$ 0.1% FWHM @ 720 MeV/c

target region (decay products detection)

π^+ beam (p_π=1.06 GeV/c)

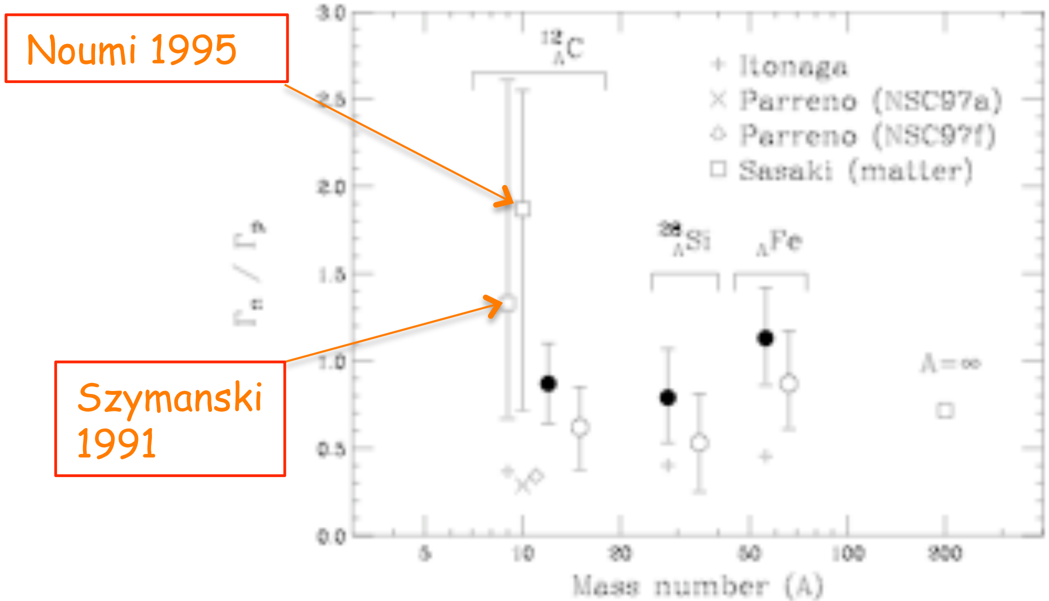
p energy from Range



KEK PS E307

NMWD: Γ_n/Γ_p ratio

Comparison with theory: puzzle!



n measurements needed !!

Experimental problems

• thick targets: dE/dx and deformation of spectra → calculated spectra as input to det. simulation

• BR_M contribution to the errors for medium-A targets

• FSI reduction of the high energy part of p spectra→ FSI strength in calc. spectra

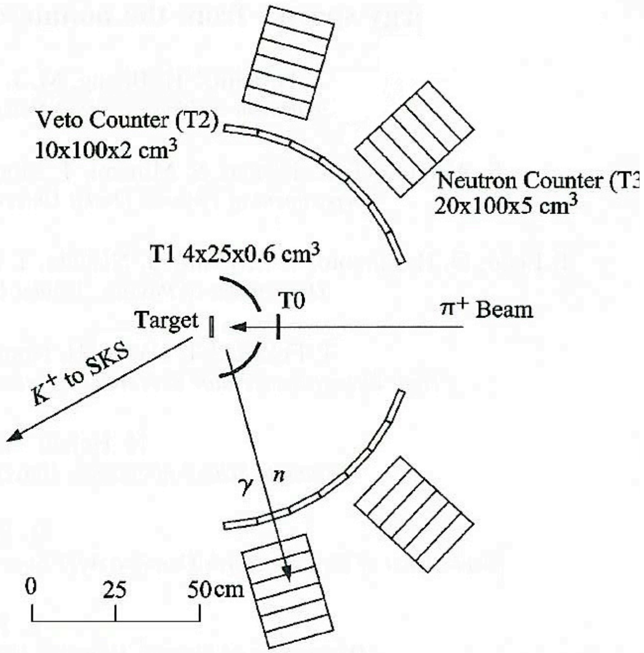
• dE/dx and experimental threshold → 2N induced NMWD gives low energy p which might not be detected → Γ_{2N} to de considered

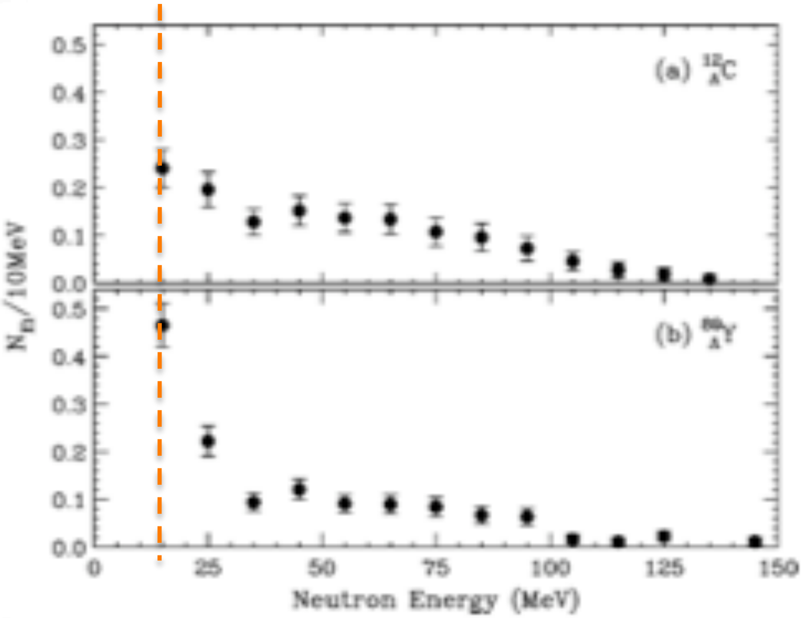
NMWD: Γ_n/Γ_p ratio

neutron spectra measurements

- no dE/dx inside targets
- no ambiguity from BR_M contribution: both N_p and N_n measured
- similar FSI for n and p due to charge symmetry of NN scattering → only FSI higher order corrections to N_n/N_p

KEK PS E369 – high resolution spectroscopy ${}^{12}_{\Lambda}C$, ${}^{89}_{\Lambda}Y$
J.H. Kim et al., PRC 68 (2003) 065201
n spectra as by-product



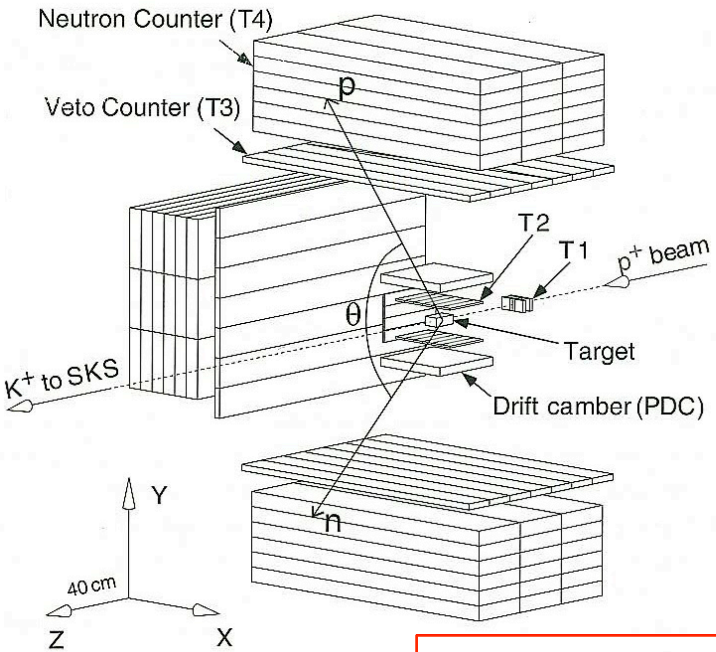


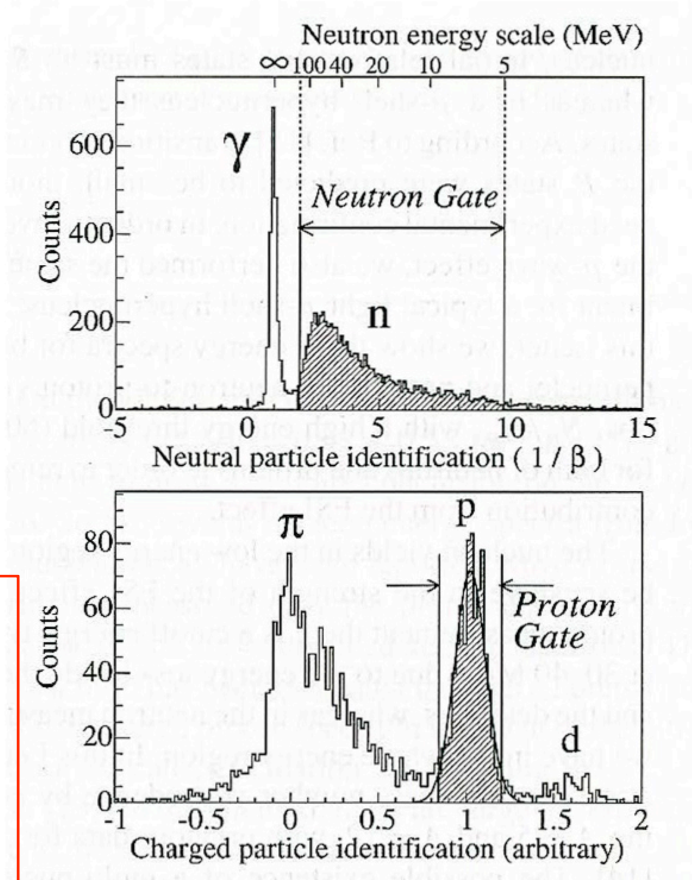
E369/E307
$\Gamma_n/\Gamma_p \sim 0.5$
${}^{12}_{\Lambda}C$

NMWD: Γ_n/Γ_p ratio

high statistics n and p spectra

KEK PS E462/E508 – NMWD n & p spectra ${}^{5}_{\Lambda}He$, ${}^{12}_{\Lambda}C$
S. Okada et al., PLB 579 (2004) 249





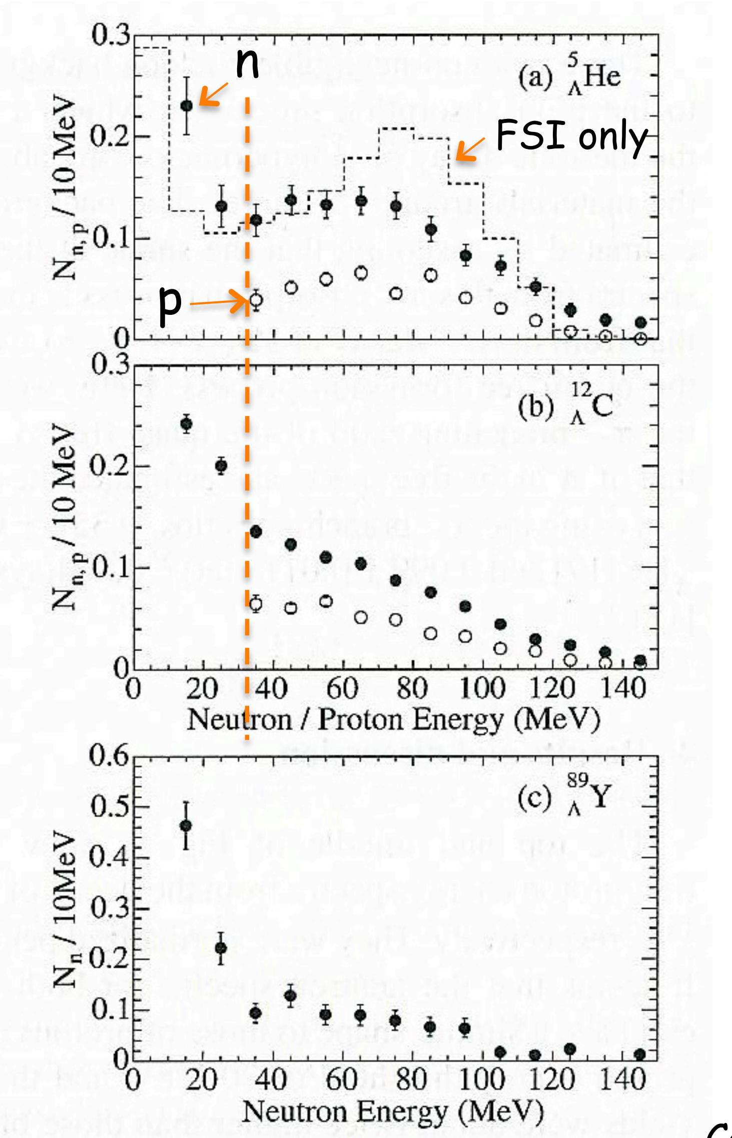
Charged particles (p,π):
dE/dx on T2, ΔE (T2, T3, T4)
TOF(T2-T3)

Neutral particles (n,γ):
TOF (T1-T4), T3 veto

$$N_{n,p}(E) = Y_{n,p\ coinc}(E) / [Y_{hyp} \bullet \Omega_{n,p} \bullet BR_{NM} \bullet \varepsilon_{n,p}(E)]$$

~27% n, ~10% p

from $BR_{\pi-}$, $BR_{\pi 0}$



- threshold at 60 MeV for both n & p (enhancement of low energy region by FSI)
- $N_n/N_p = 2.17 \pm 0.15$ $\quad ^{5}_{\Lambda}He$
  $= 2.00 \pm 0.09$ $\quad ^{12}_{\Lambda}C$
- $N_n/N_p \approx 2 (\Gamma_n/\Gamma_p) + 1$
- Γ_n/Γ_p = **0.5-0.6**

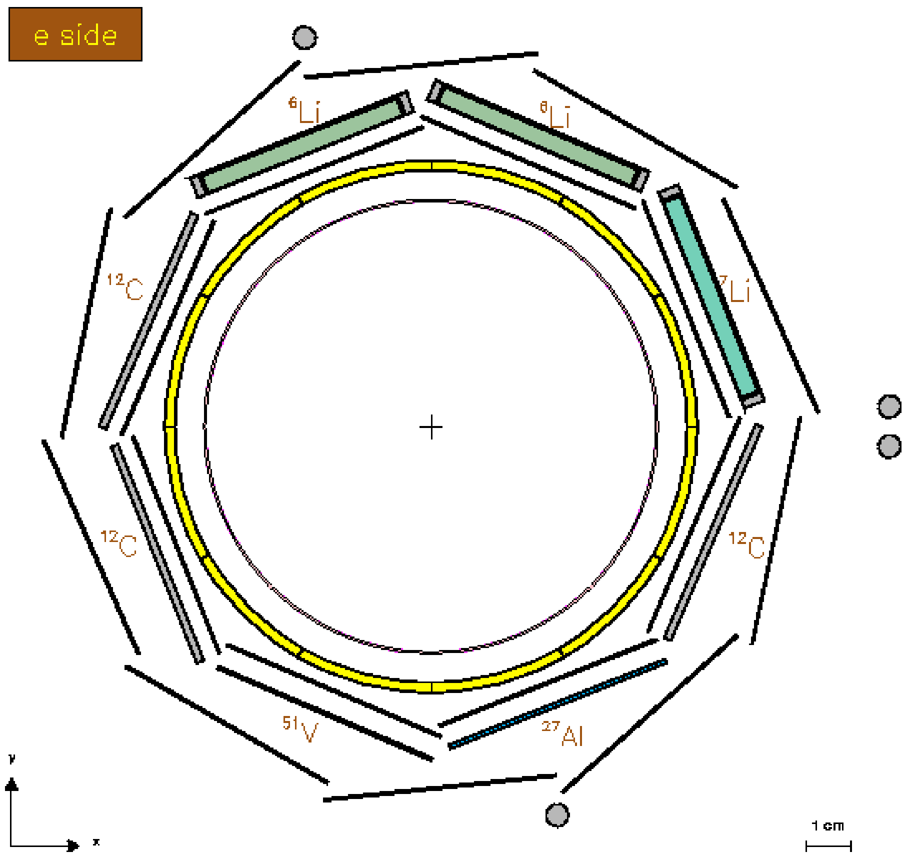
- suppression of high energy n with A
- enhancement below 30 MeV → FSI

Calculation: Garbarino et al., PRC69 (2004) 054603

NMWD: p spectra @ LNF

LNF FINUDA – NMWD p spectra $^{5}_{\Lambda}He$, $^{7}_{\Lambda}He$, $^{12}_{\Lambda}C$
M.Agnello et al., NPA 804 (2008) 151

$e^+ + e^- \rightarrow \phi\,(1020) \rightarrow K^+ + K^-$ (127 MeV/c)
$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$



Detector capabilities:

π, K, p, d, … P.I.D. (OSIM&LMDs d*E*/dx, TOF)

High momentum resolution

(6‰ FWHM for π- @270 MeV/c for spectroscopy)

(1% FWHM for π- @270 MeV/c for decay study)

(6% FWHM for π- @110 MeV/c for decay study)

(2% FWHM for p @400 MeV/c for decay study)

(tracker resolution + He bag + thin targets)

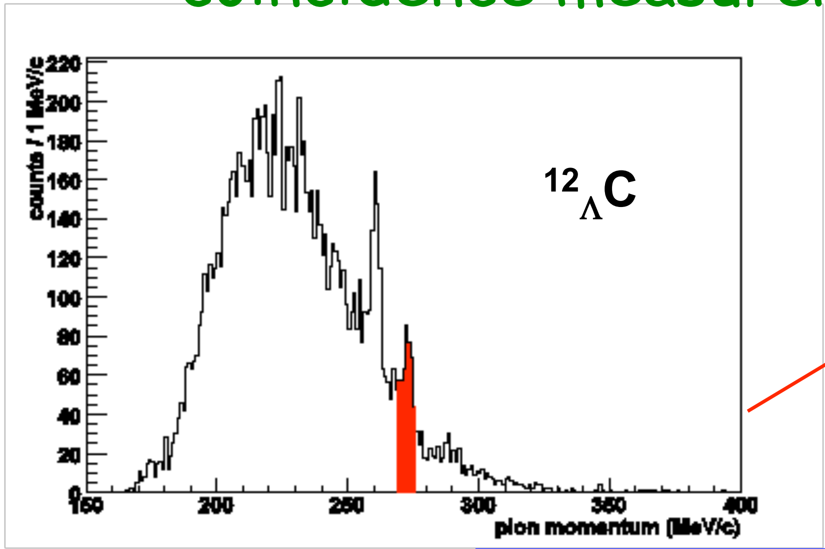
Solid angle ~ 2π srad

Thin targets:

^{6}Li: 4 mm → ~ 0.2 g/cm^2
^{7}Li: 4 mm → ~ 0.2 g/cm^2
^{12}C: 1.7 mm → ~ 0.4 g/cm^2

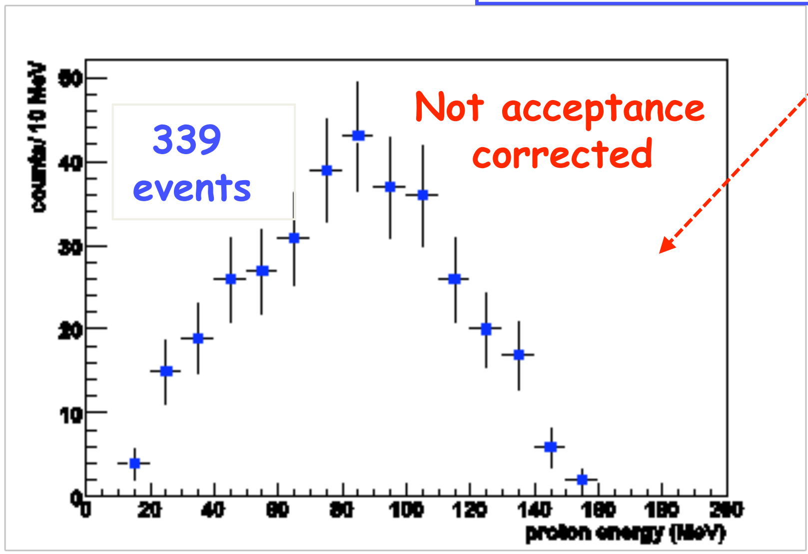
NMWD: p spectra @ LNF

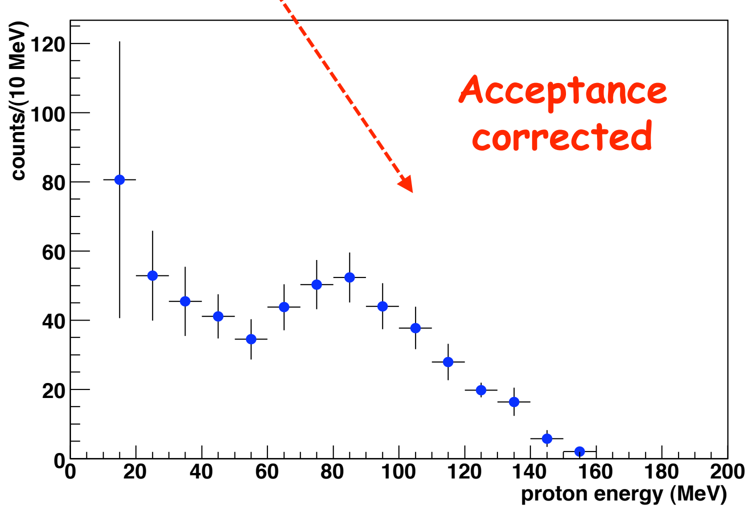
coincidence measurement: method



- Spectrum of negative pions for events in which a proton is detected in coincidence with a π^-
- Asking for the proton coincidence a clear peak emerges at 272 MeV/c (ground state)

Proton energy spectrum from $^{12}_{\Lambda}C$ p-induced NMWD before and after the acceptance correction





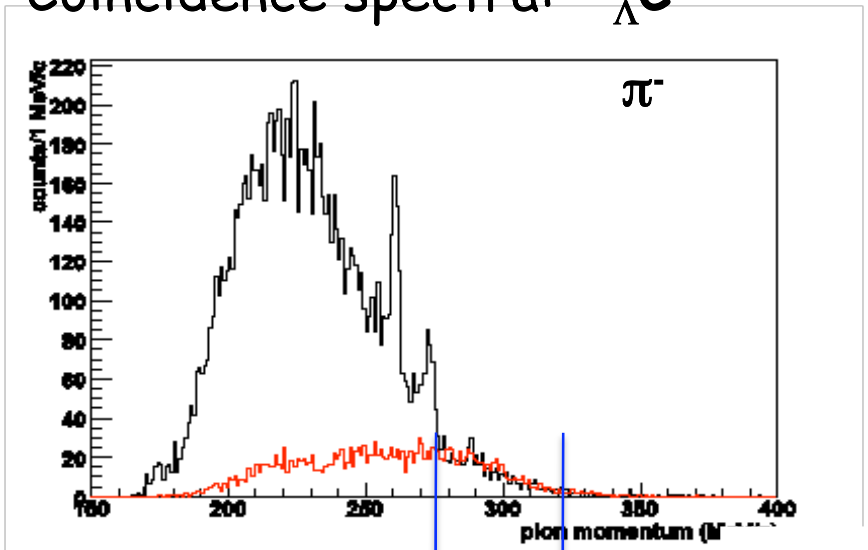
Coincidence measurement: FINUDA method

background reaction: $K^- np \rightarrow \Sigma^- p$

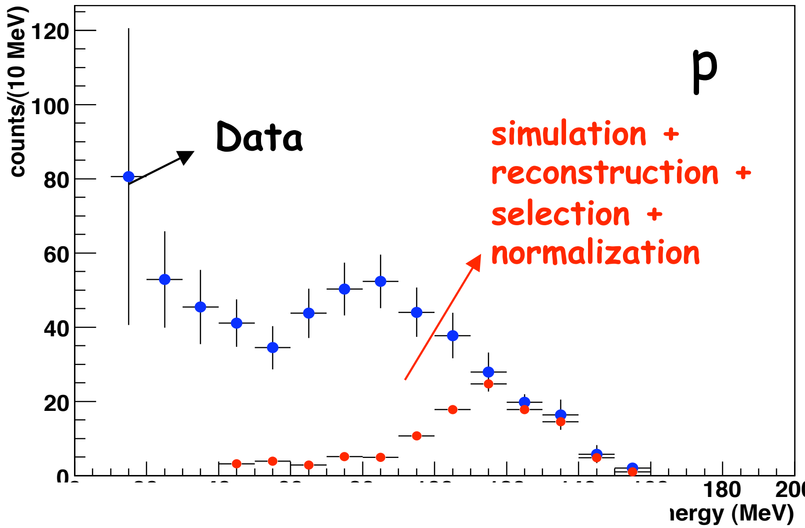
$\Sigma^- \rightarrow n \pi^-$

coincidence

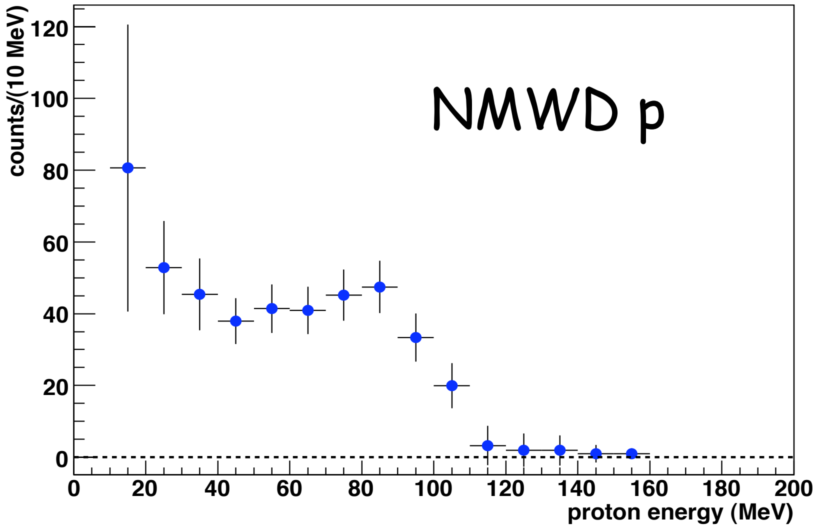
Coincidence spectra: $^{12}{}_{\Lambda}C$



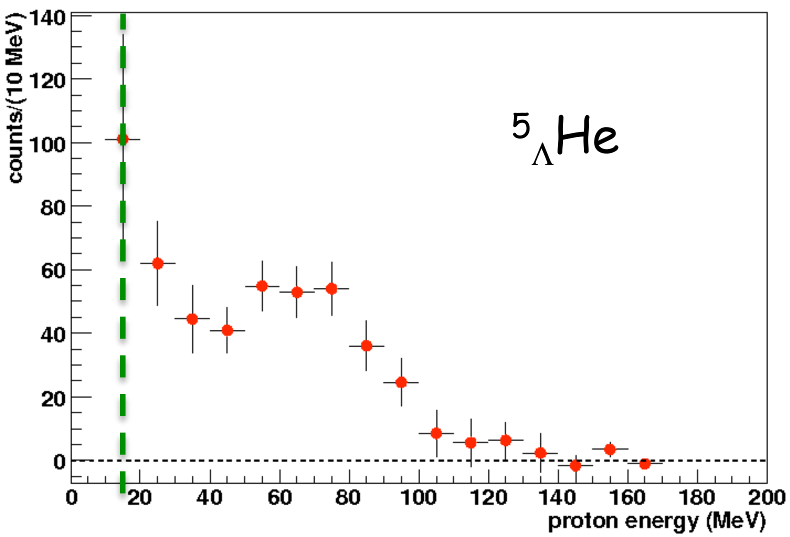
normalization region

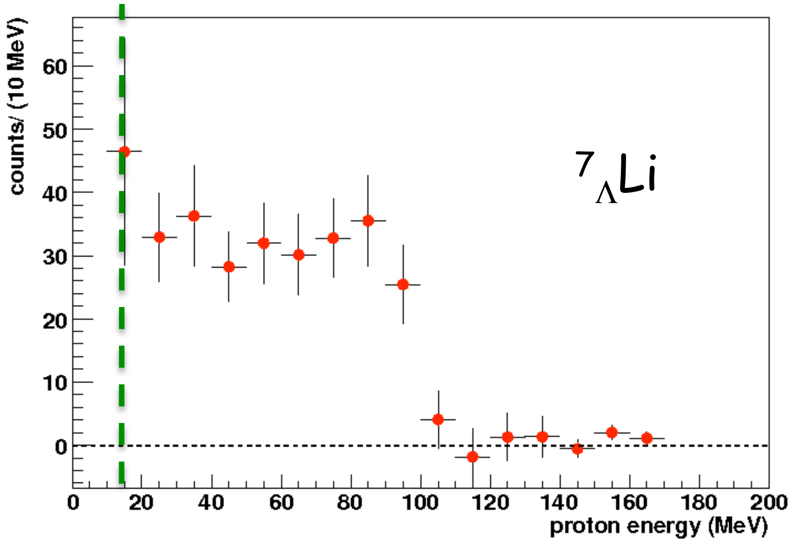


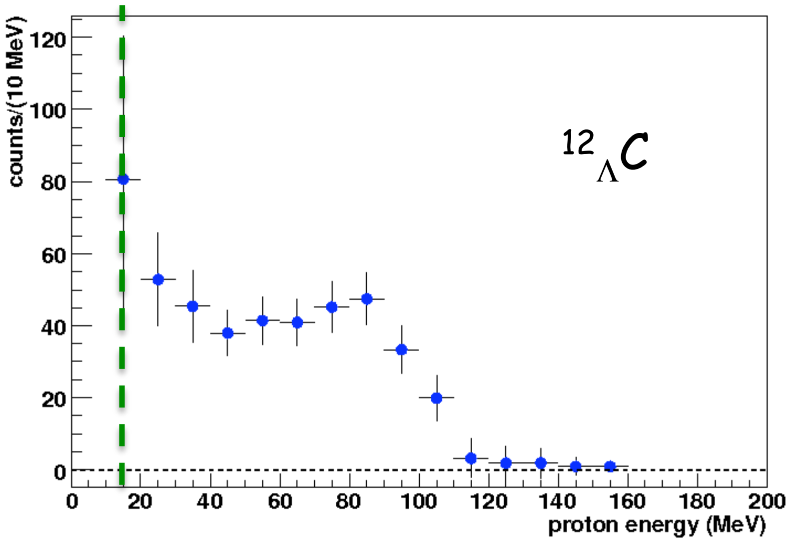
subtraction



M. Agnello et al., NPA 804 (2008), 151



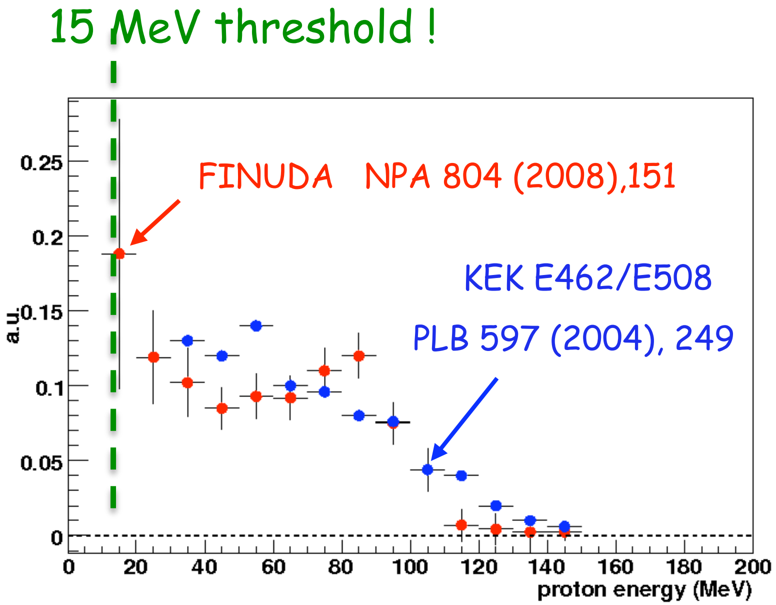


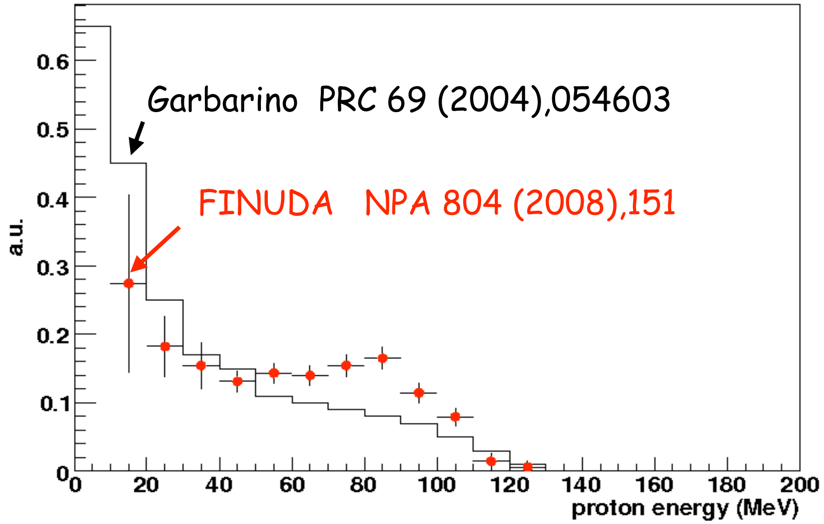


✓ Similar shape for $^{5}{}_{\Lambda}He$, $^{7}{}_{\Lambda}Li$ and $^{12}{}_{\Lambda}C$
✓ Peak at ~ 80 MeV (Q/2 value), broadened by N Fermi motion, visible even for $^{12}{}_{\Lambda}C$ → no strong FSI effect in low energy region
✓ FSI & 2N contribution in the low energy region ?

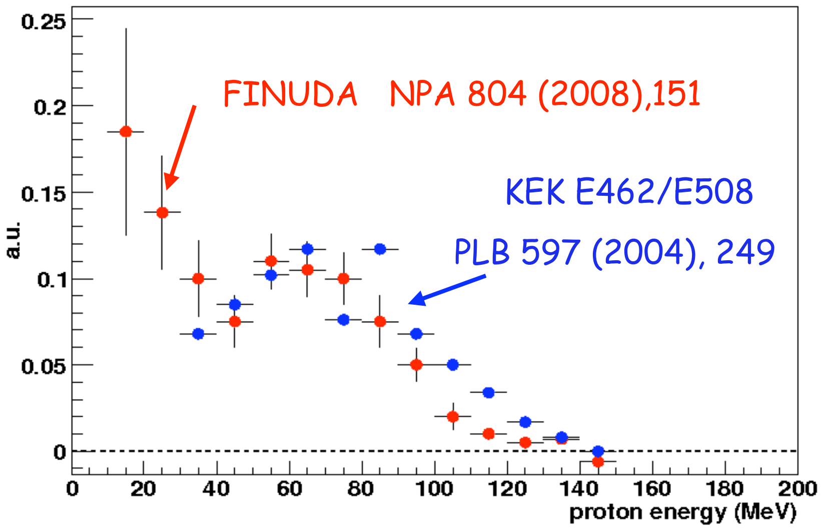
Comparisons with theory and KEK results

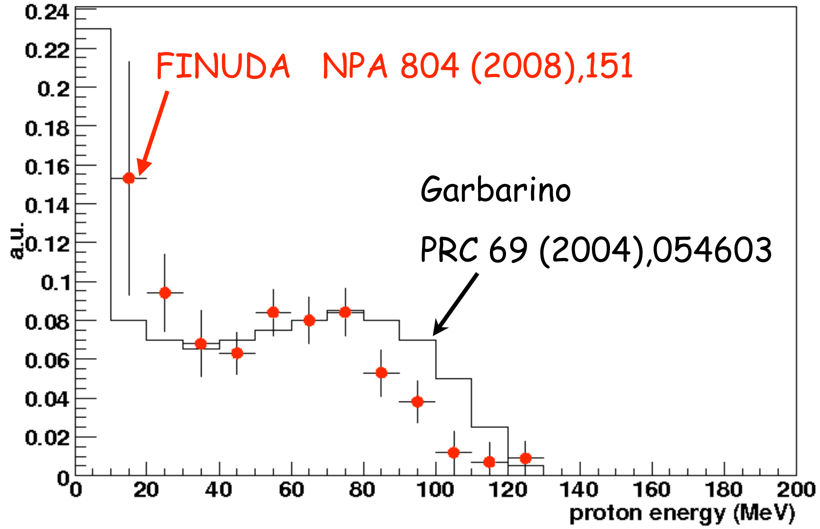
$^{12}_{\Lambda}C$





$^{5}_{\Lambda}He$





Comparisons with theory and KEK results

- Comparison between FINUDA and KEK data: normalization beyond 35 MeV (KEK data threshold)
- Kolmogorov-Smirnov test: 75% compatibility for ${}^{5}_{\Lambda}He$, 20% for ${}^{12}_{\Lambda}C$

- Comparison between FINUDA and theory: normalization beyond 15 MeV (FINUDA data threshold)
- Kolmogorov-Smirnov test: 80% compatibility for ${}^{5}_{\Lambda}He$, 5% for ${}^{12}_{\Lambda}C$

Strong disagreement between experiments and with theory

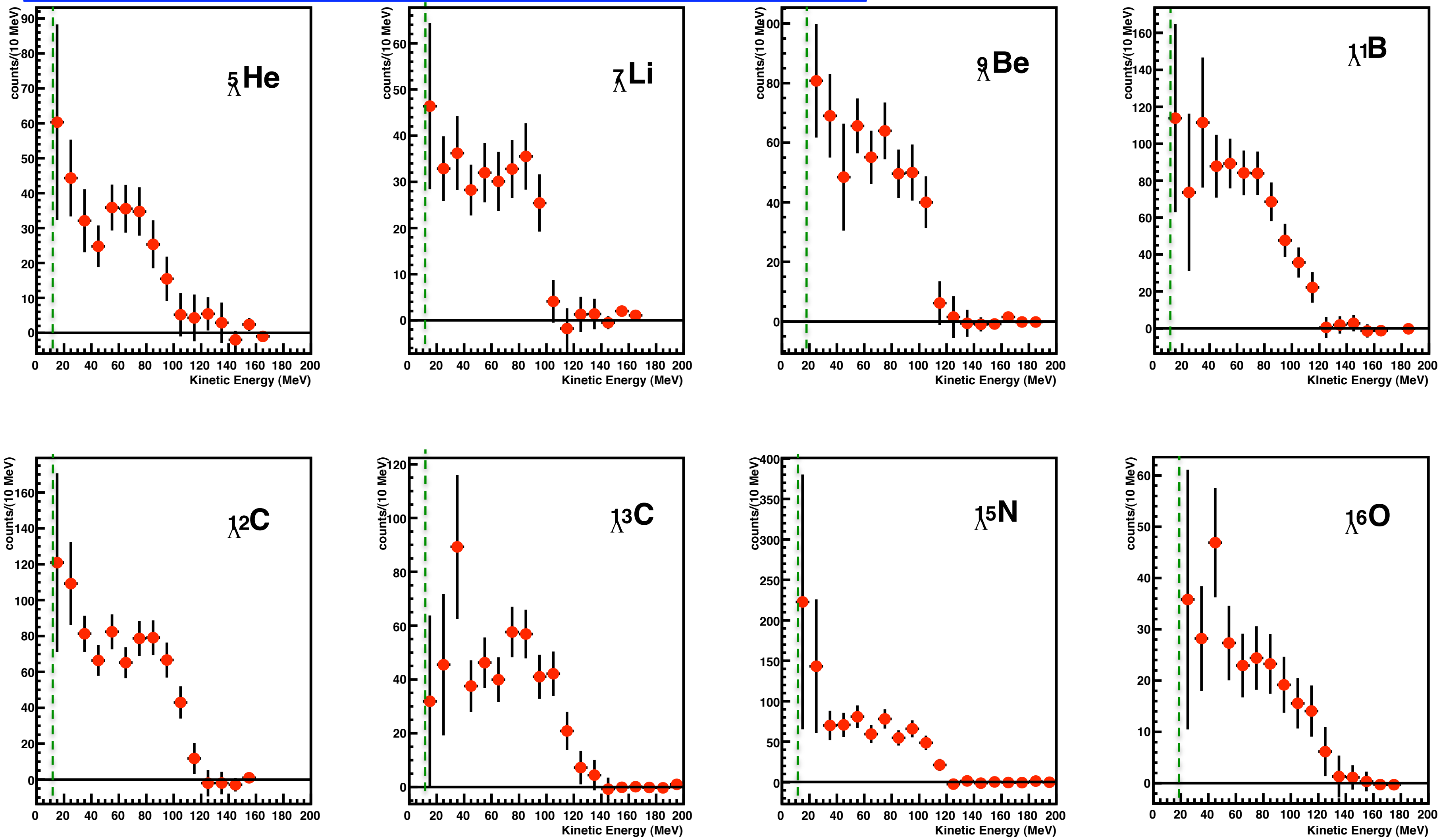
- KEK: thick targets → strong correction
  FINUDA: thin targets& transparent detectors
- KEK: p energy from TOF and range + dE/dx → poor energy resolution above 100 MeV, distortion
  FINUDA: p momentum from magnetic analysis, 2% energy resolution FWHM @ 80 MeV, no distortion

- Inputs of calculations

NMWD p spectra p-shell hypernuclei

LNF FINUDA – M.Agnello et al., PLB 685 (2010) 247

Background subtracted & acceptance corrected



NMWD: p spectra of p-shell hypernuclei

- ✓ similar shape for all spectra
- ✓ trend as a function of A (5-16):
  - peak at ~ 80 MeV (Q/2 value), broadened by N Fermi motion
  - smearing at low energy with increasing A
- ✓ FSI & 2N contribution: systematics

Target	Hypernucleus	R_p (T_p>15 MeV)
^{6}Li & ^{7}Li	$^5_\Lambda$He	0.25±0.07
^{7}Li	$^7_\Lambda$Li	0.37±0.09
^{9}Be	$^9_\Lambda$Be	0.38±0.04
^{12}C	$^{11}_\Lambda$B	0.40±0.05
^{12}C	$^{12}_\Lambda$C	0.43±0.07
^{13}C	$^{13}_\Lambda$C	0.47±0.10
^{16}O	$^{15}_\Lambda$N	0.45±0.05
^{16}O	$^{16}_\Lambda$O	0.32±0.07

systematic error less than 5%

$$R_p = N_p^{detected} / (N_{hyp}^{detected}\ \varepsilon_p)$$

Γ_p not measurable: FSI & 2N

NMWD: Γ_n/Γ_p ratio

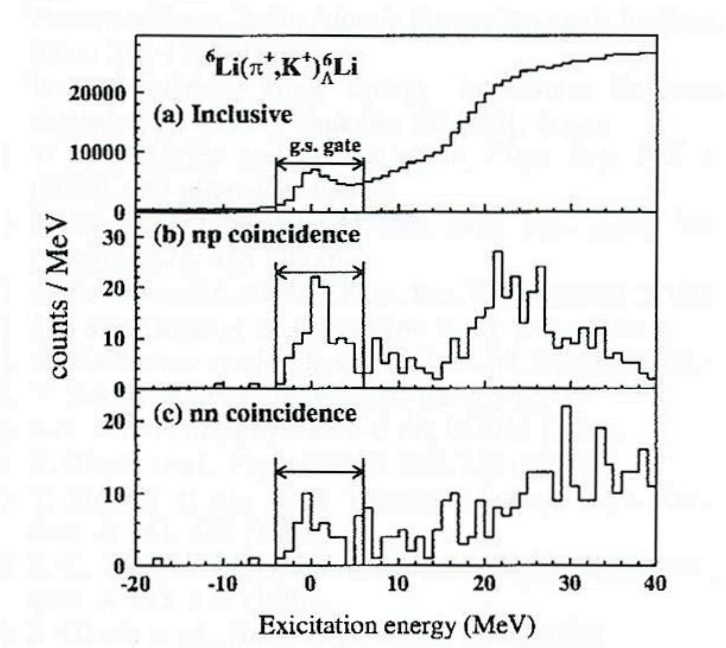
n+p and n+n spectra

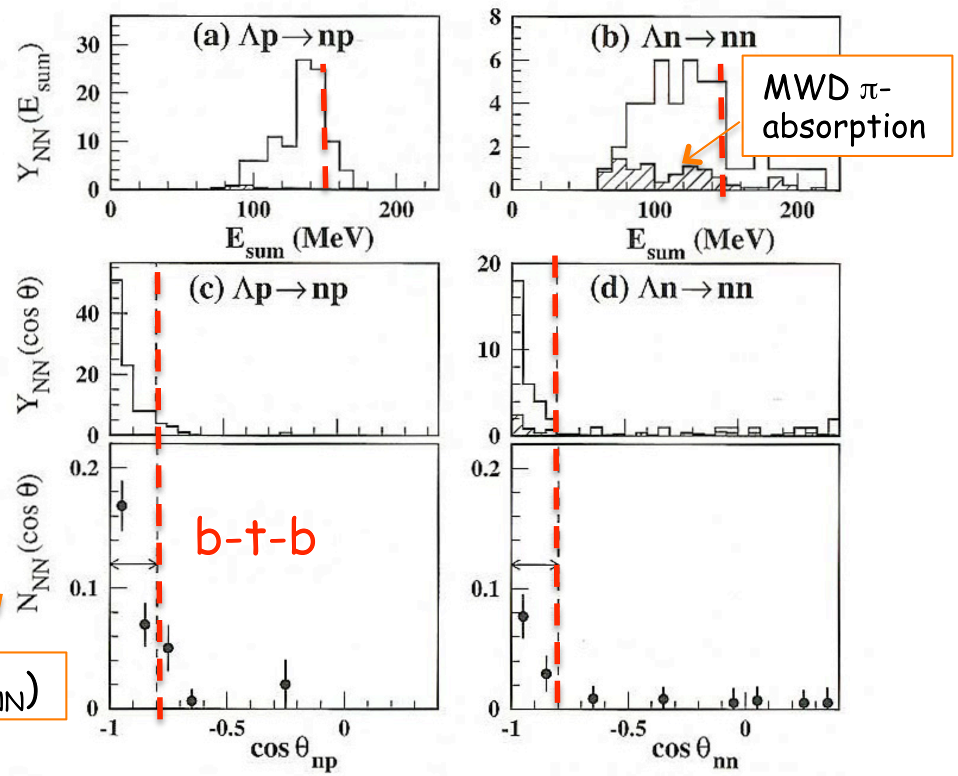
- FSI correction needed, based on calculations
- 2N-induced contributions ?
- → measurement of n & p in coincidence !!

$\Lambda p \to np$, $\Lambda n \to nn$ 2-body decays → b-t-b correlation; $E_p + E_n$ = Q value — if not FSI and not 2N

KEK PS E462 – NMWD n & p spectra in coincidence $^5_\Lambda He$
B.H. Kang et al., PRL 96 (2006) 062301

- top&bottom decay coincidence modules
- side module for non b-t-b spectra
- light target to reduce FSI : $^5_\Lambda He$





$N_{NN} = Y_{NN} / (Y_{hyp}\, BR_{NM}\, \varepsilon_{NN})$

$Y_{nn}(\theta) = Y_{hyp}\, BR_{NM}\, r_n\, \varepsilon_{nn}(\theta)\, f_n^2 \qquad r_{n/p} = \Gamma_{n/p} / \Gamma_{NM}$

$Y_{np}(\theta) = Y_{hyp}\, BR_{NM}\, r_p\, \varepsilon_{np}(\theta)\, f_n\, f_p \qquad \varepsilon_{nn}(\theta) = \Omega_{n,n}(\theta)\, \varepsilon_n^2$

f_n, f_p = FSI reduction factor for n & p above 30 MeV

$$\mathbf{r_n / r_p} = \Gamma_n / \Gamma_p = (Y_{nn}/Y_{hyp}\, BR_{NM}\, \varepsilon_{nn}\, f_n\, f_p) / (Y_{np}/Y_{hyp}\, BR_{NM}\, \varepsilon_{np}\, f_n^2)$$
$$= (\mathbf{Y_{nn}}\, \Omega_{n,p}\, \boldsymbol{\varepsilon_p}) / (\mathbf{Y_{np}}\, \Omega_{n,n}\, \boldsymbol{\varepsilon_n}) = \mathbf{N_{nn} / N_{np}}$$

NMWD: Γ_n/Γ_p ratio

n +p and n+n spectra

KEK PS E462 - NMWD n & p spectra in coincidence $^{5}{}_{\Lambda}He$
B.H. Kang et al., PRL 96 (2006) 062301

$$\Gamma_n / \Gamma_p (^{5}{}_{\Lambda}He) \cong N_{nn} / N_{np} = 0.45 \pm 0.11 \pm 0.03$$

KEK PS E508 - NMWD n & p spectra in coincidence $^{12}{}_{\Lambda}C$
M.J. Kim et al., PLB 641 (2006) 28

$$\Gamma_n / \Gamma_p (^{5}{}_{\Lambda}He) \cong N_{nn} / N_{np} = 0.51 \pm 0.13 \pm 0.05$$

n & p detection in coincidence b-t-b removes ambiguities of FSI and 2N NMWD

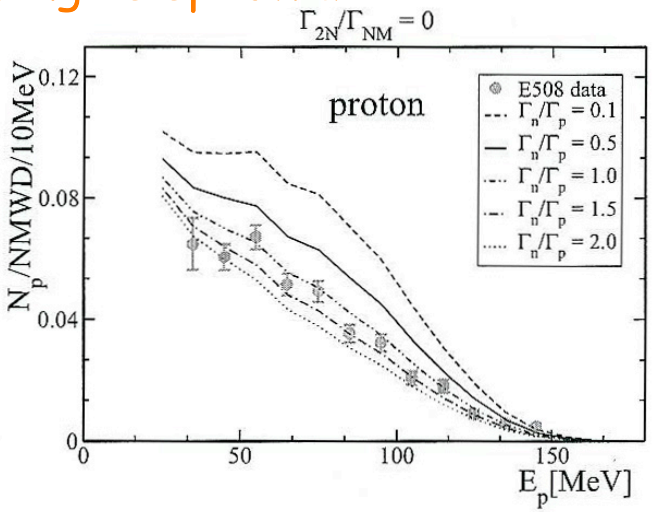
NMWD: Γ_n/Γ_p ratio

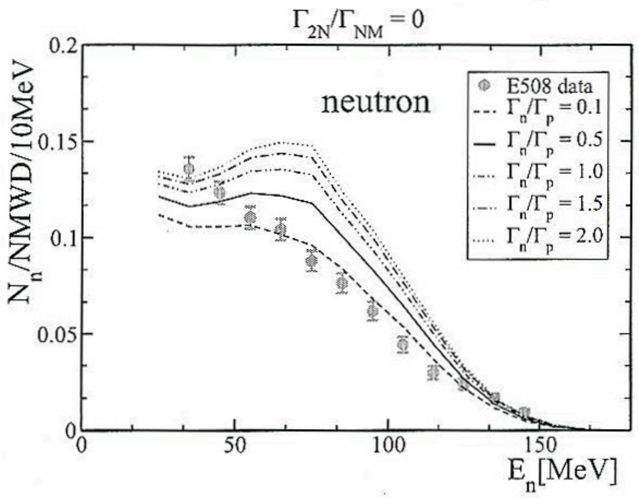
2N-induced contribution

KEK PS E508 reanalysis ${}^{12}_{\Lambda}C$
H. Bhang et al., PRL 96 (2006) 062301

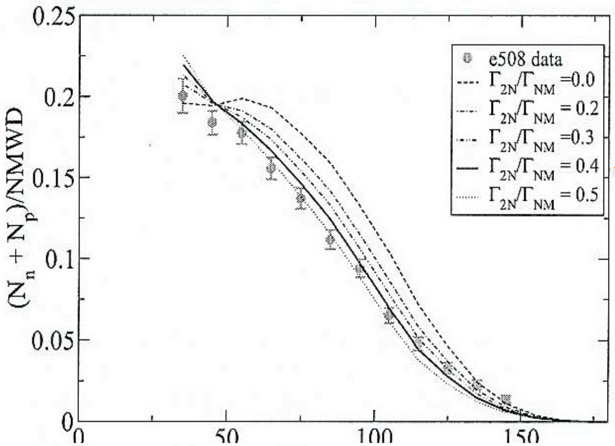
quenching of high energy N due to Γ_{2N}

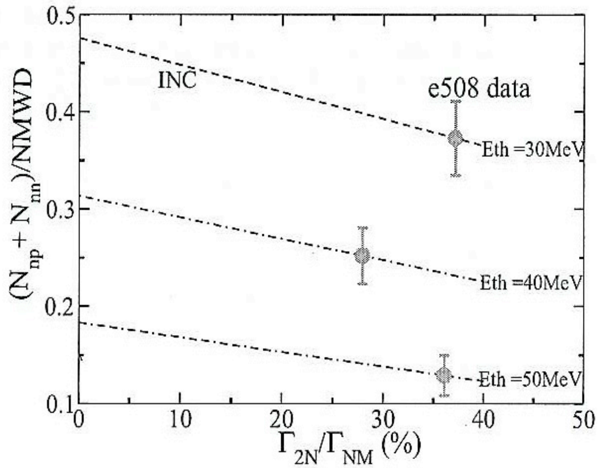
Singles spectra





Coincidence spectra





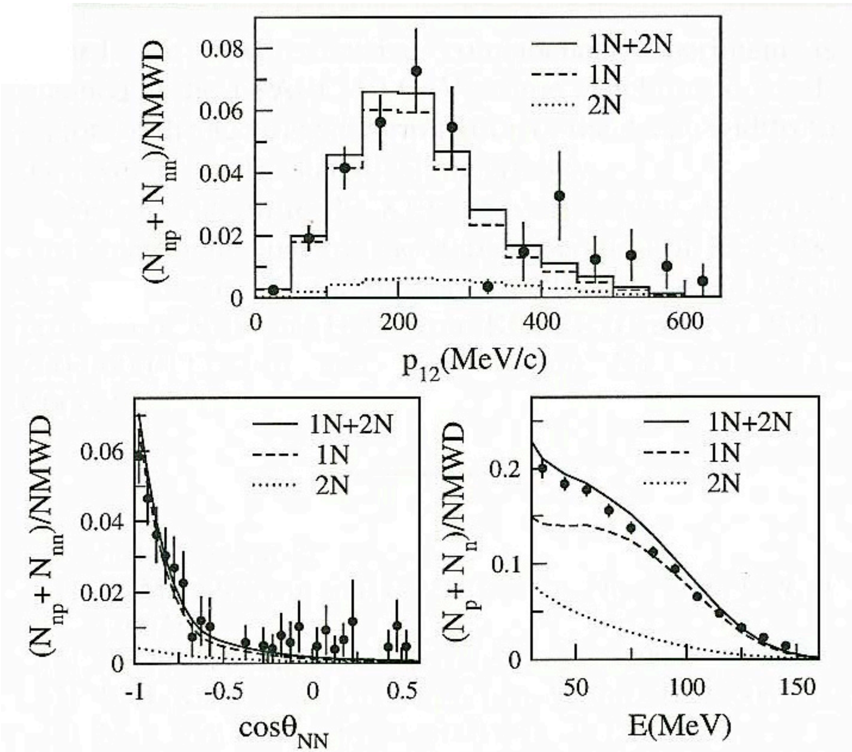
Γ_{2N}/Γ_{NM} ~ 0.4

strong contribution of 2N-induced NMWD

NMWD: Γ_n/Γ_p ratio

2N-induced contribution

KEK PS E508 reanalysis $^{12}{}_{\Lambda}C$
M. Kim et al., PRL 103 (2009) 182502



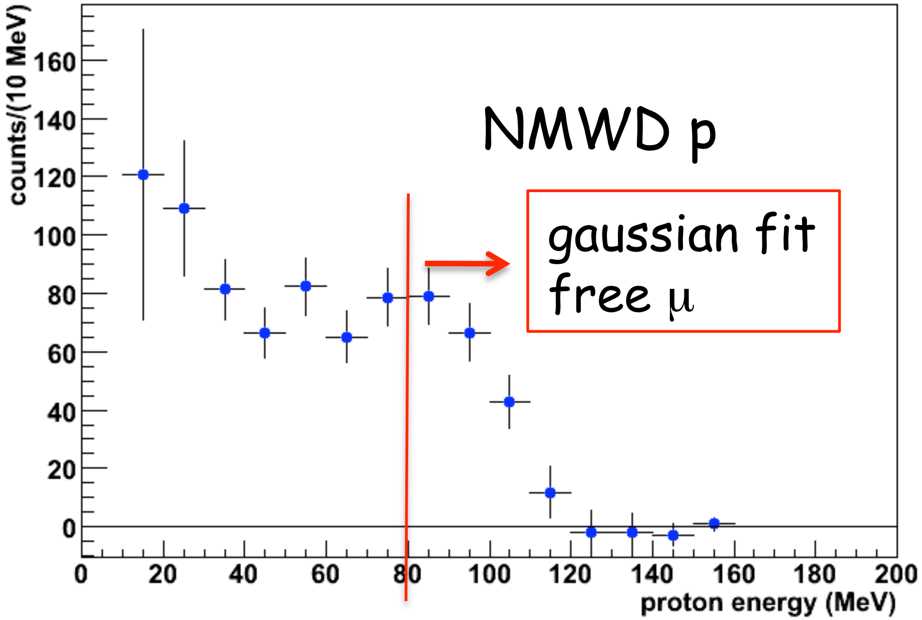
- quenching of low energy N due to FSI & 2N which share the same phase space
- no kinematical separation
- Γ_{2N} from measured spectra by accurate accounting of FSI
- FSI from INC introduces uncertainties
- FSI by varying INC strength to fit measured inelastic total cross section data: $^{12}C(p, p')$

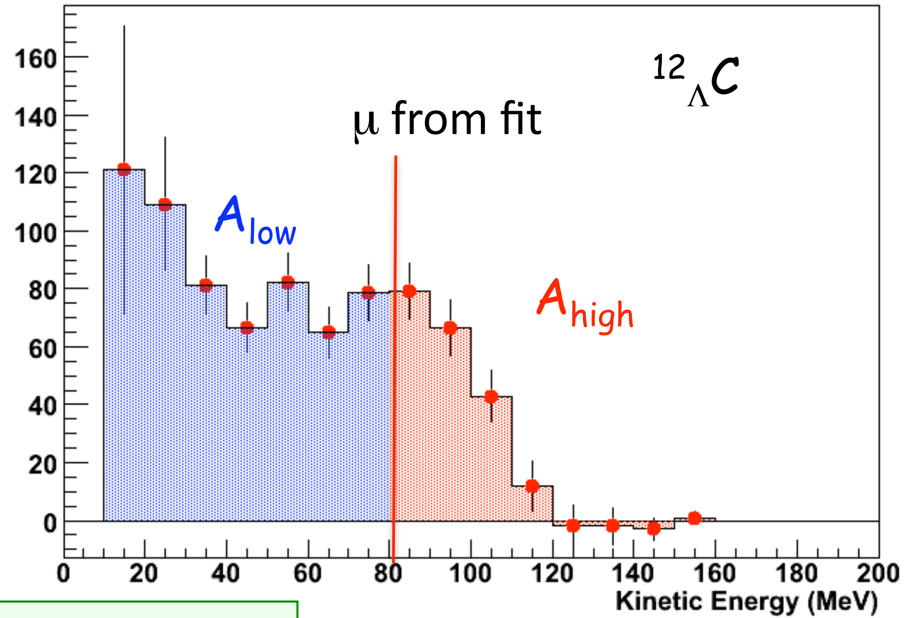
$\Gamma_{2N}/\Gamma_{NM} = 0.29 \pm 0.13$
$\Gamma_{2N} = 0.27 \pm 0.13$
$\Gamma_{1N} = 0.68 \pm 0.13$
$\Gamma_n = 0.23 \pm 0.08$
$\Gamma_p = 0.45 \pm 0.10$

NMWD: Γ_{2N}

LNF – FINUDA M.Agnello et al., PLB 685 (2010) 247

2N / NM & Γ_n/Γ_p independent on A ⇐ assumption — W.Alberico and G.Garbarino, Phys. Rev. 369 (2002) 1.





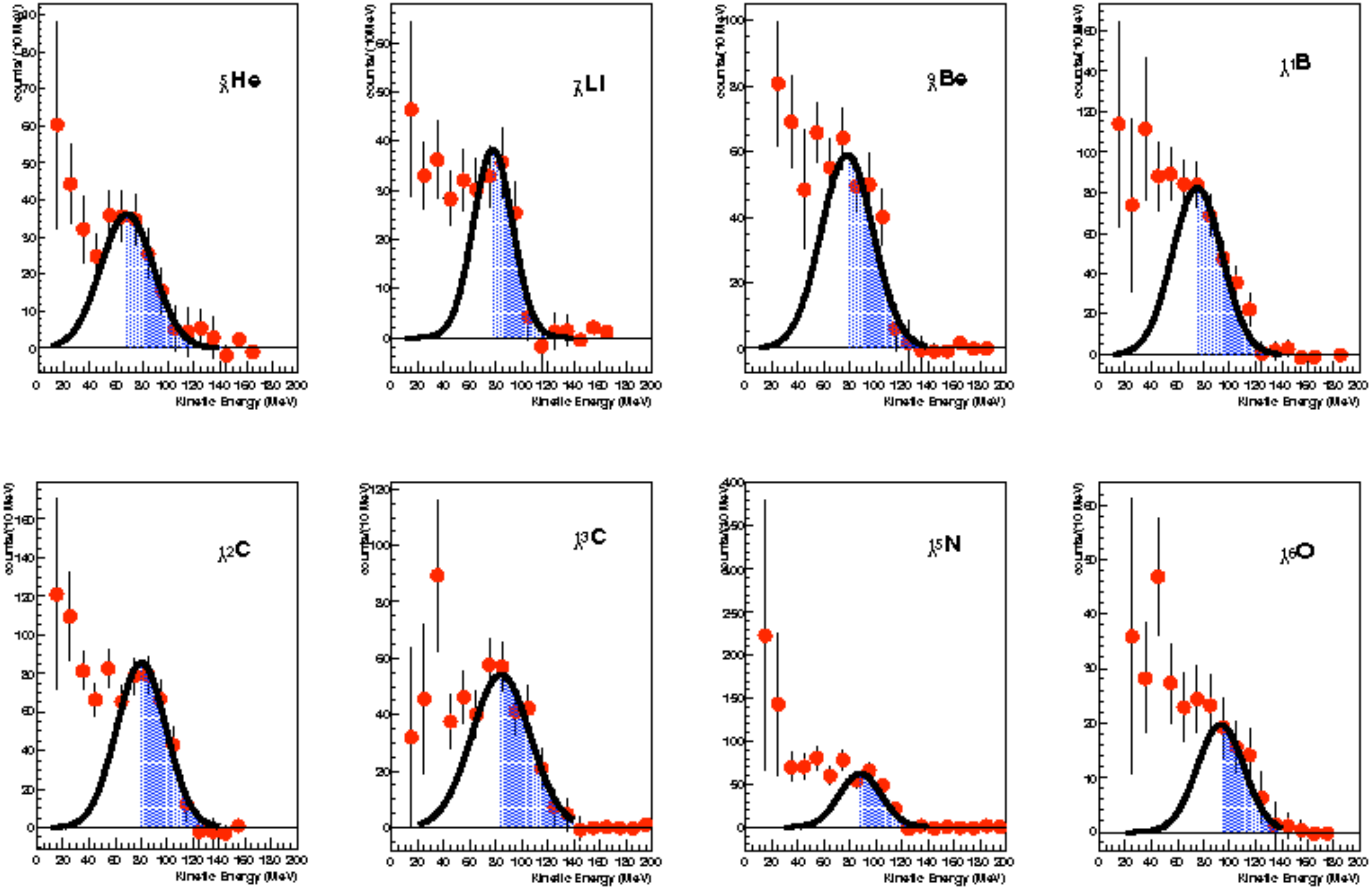
A_{low}: spectrum area below μ
1N + 2N + FSI

A_{high}: spectrum area above μ
1N + FSI
2N(>70 MeV) ~ 5% $2N_{tot}$ ⇐ assumption

G,Garbarino, A.Parreno and A.Ramos, Phys.Rev.Lett. 91 (2003) 112501.
Phys.Rev. C 69 (2004) 054603.

NMWD: Γ_{2N}

FSI & ΛNN contribution evaluation: systematics



NMWD: Γ_{2N}

FSI & ΛNN contribution evaluation

$N_p^{FSI\text{-}low} = (N_p^{det} - N_p^{1N\&2N\ primary})_{<\mu}$ (> 0 G. Garbarino et al.,PRL 91 (2003) 112501
G. Garbarino et al.,PRC 69 (2004) 054603)

$N_p^{FSI\text{-}high} = (N_p^{det} - N_p^{1N\ primary})_{>\mu}$ (< 0)

$A_{low} = 0.5\ N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{FSI\text{-}low}$

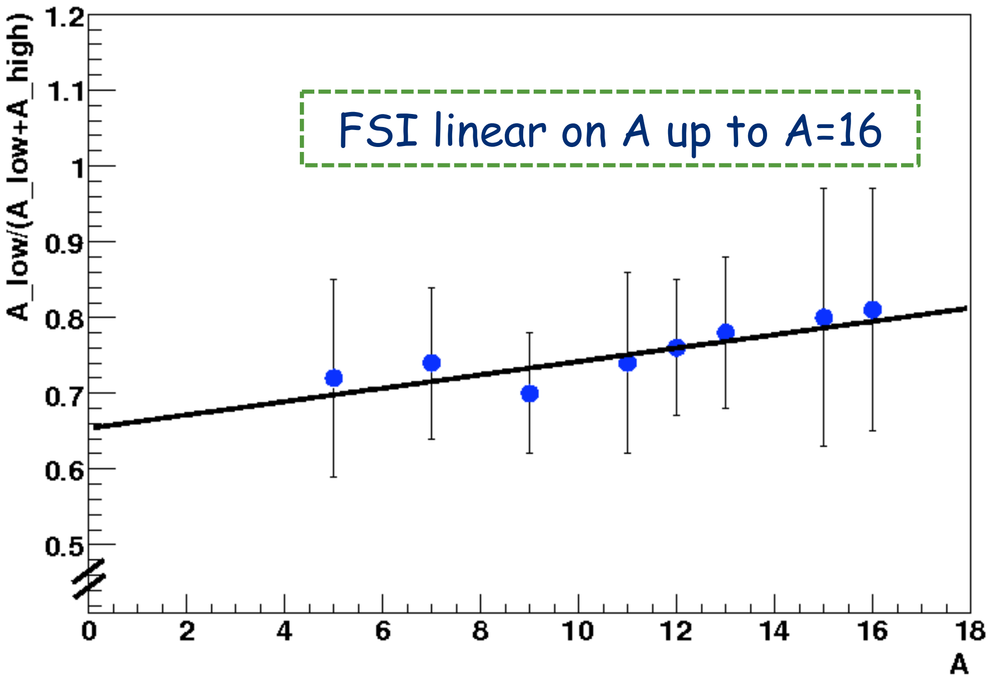
$A_{high} = 0.5\ N(\Lambda p \rightarrow np) + N_p^{FSI\text{-}high}$

$$\frac{N(\Lambda np \rightarrow nnp)}{N(\Lambda p \rightarrow np)} = \frac{\Gamma_{np}}{\Gamma_p} \approx \frac{\Gamma_2}{\Gamma_p}$$

assumption

$\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$
E. Bauer and G.Garbarino,
Nucl.Phys. A 828 (2009), 29.

$$R = \frac{A_{low}}{A_{low} + A_{high}} = \frac{0.5\ N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{FSI\text{-}low}}{N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{FSI\text{-}low} + N_p^{FSI\text{-}high}}$$



systematics: all p-shell

Assumption: Γ_2/Γ_1 and Γ_n/Γ_p indipendent from A→ supported by exp and theory

$$R(A) = a + b\,A = \frac{0.5 + \Gamma_2/\Gamma_p}{1 + \Gamma_2/\Gamma_p} + b\,A$$

$$\frac{\Gamma_2}{\Gamma_p} = \frac{[R(A) - bA] - 0.5}{1 - [R(A) - bA]} = 0.43 \pm 0.25 \text{ weighted mean}$$

$$\frac{\Gamma_2}{\Gamma_{NM}} = \frac{\Gamma_2/\Gamma_p}{\Gamma_n/\Gamma_p + 1 + \Gamma_2/\Gamma_p} = 0.24 \pm 0.10$$

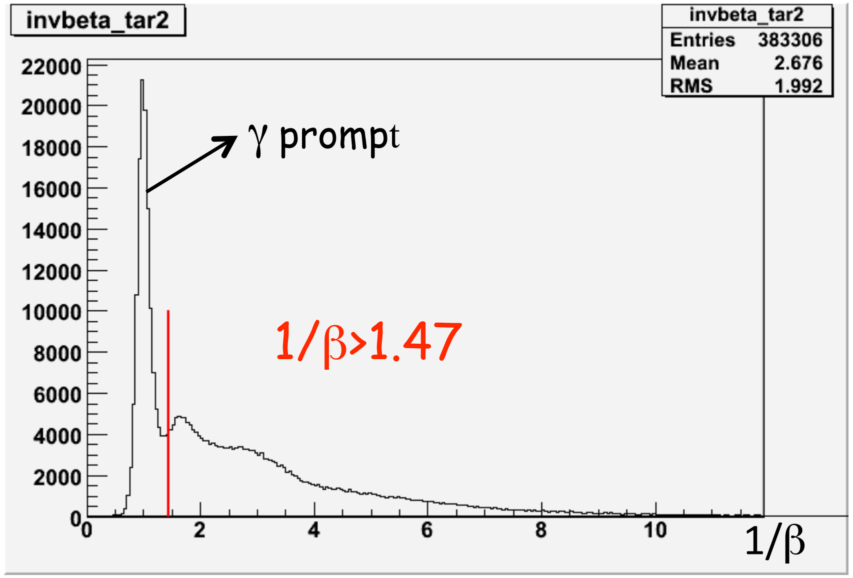
Bhang et al., EPJ A33 (2007) 259.

Bauer et al., NPA 828 (2009) 29

Bhang et al., EPJ A33 (2007) 259: ~ 0.4 $^{12}_{\Lambda}C$
M. Kim et al., PRL 103 (2009) 182502:
0.29 ± 0.13 $^{12}_{\Lambda}C$
J.D.Parker et al., PRC 76 (2007), 035501:
≤ 0.24 (95% CL) $^{4}_{\Lambda}He$

NMWD: Γ_{2N}

NMWD: n+p coincidence @ FINUDA



n detection efficiency ~10%

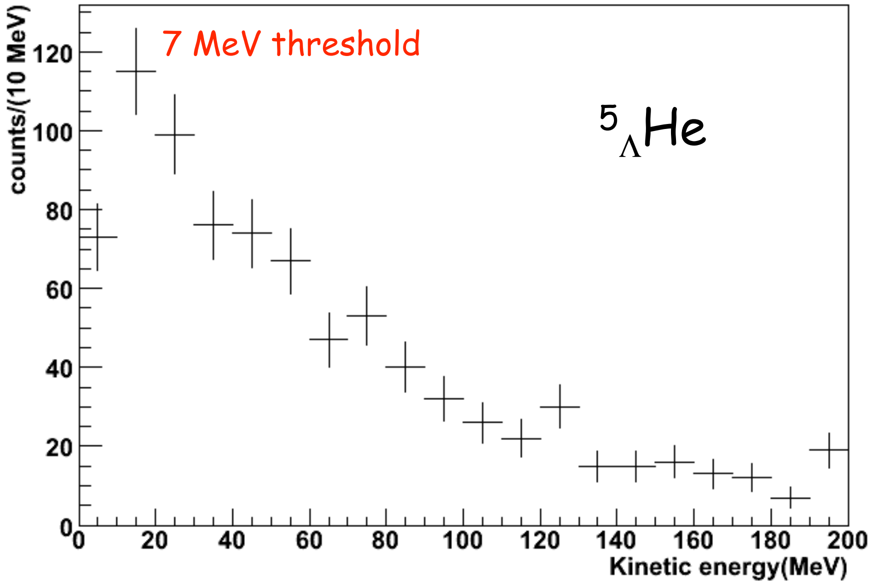
n energy resolution ~9% at 80 MeV

TOF allows n/γ discrimination

background prevails if no correlations or selections are imposed

$n + \pi^-_{bound}$

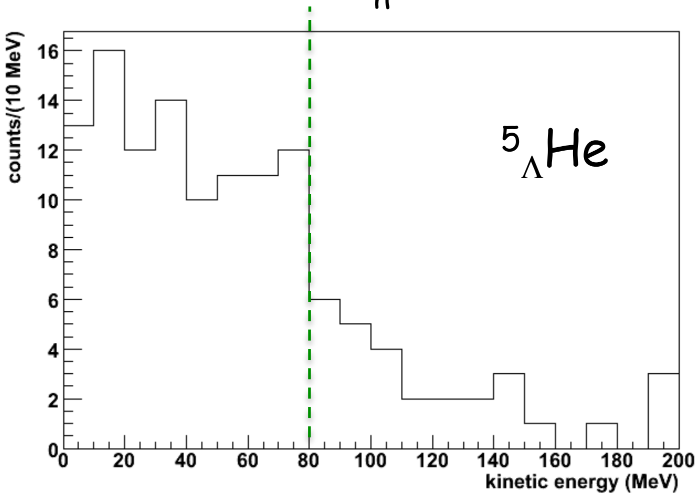
single n spectra shape cannot be directly analyzed due to background



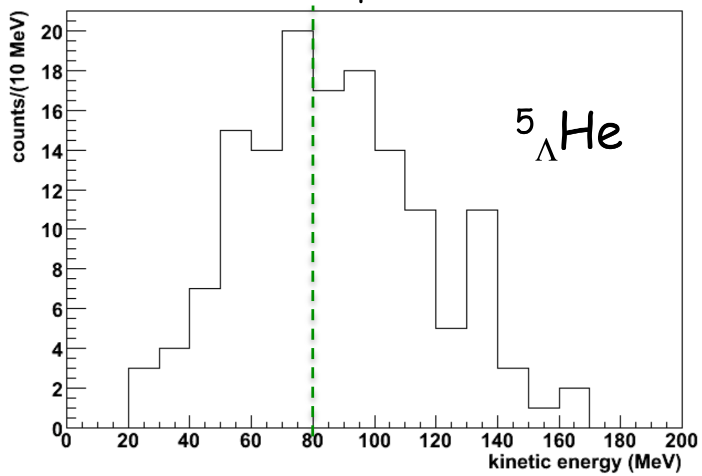
NMWD: Γ_{2N}

low statistics !! $n + p + \pi^-_{bound}$

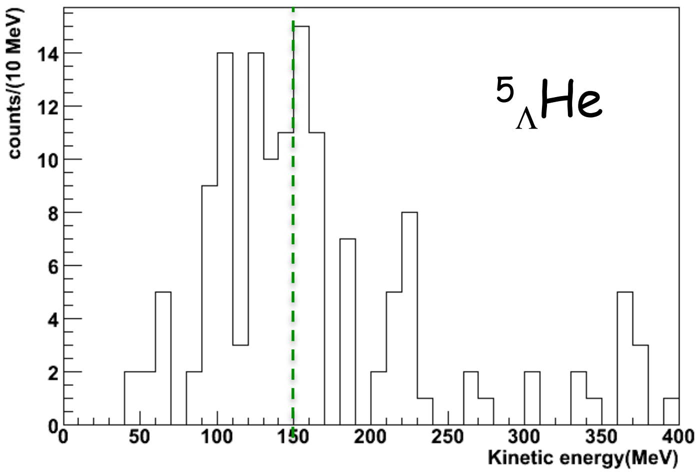
E_n



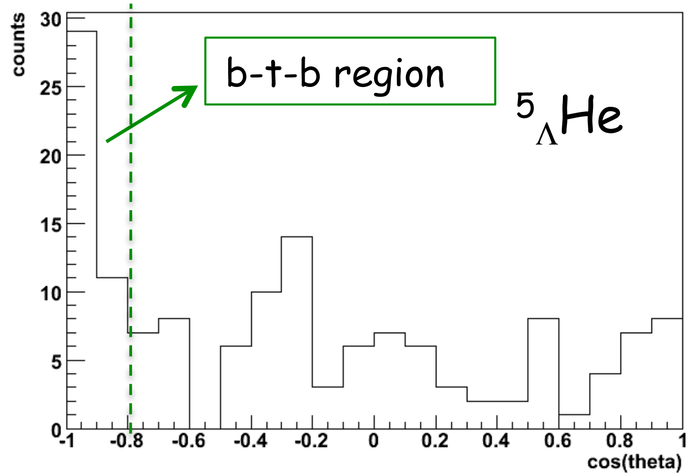
E_p



E_p+E_n



cos θnp



not acceptance corrected

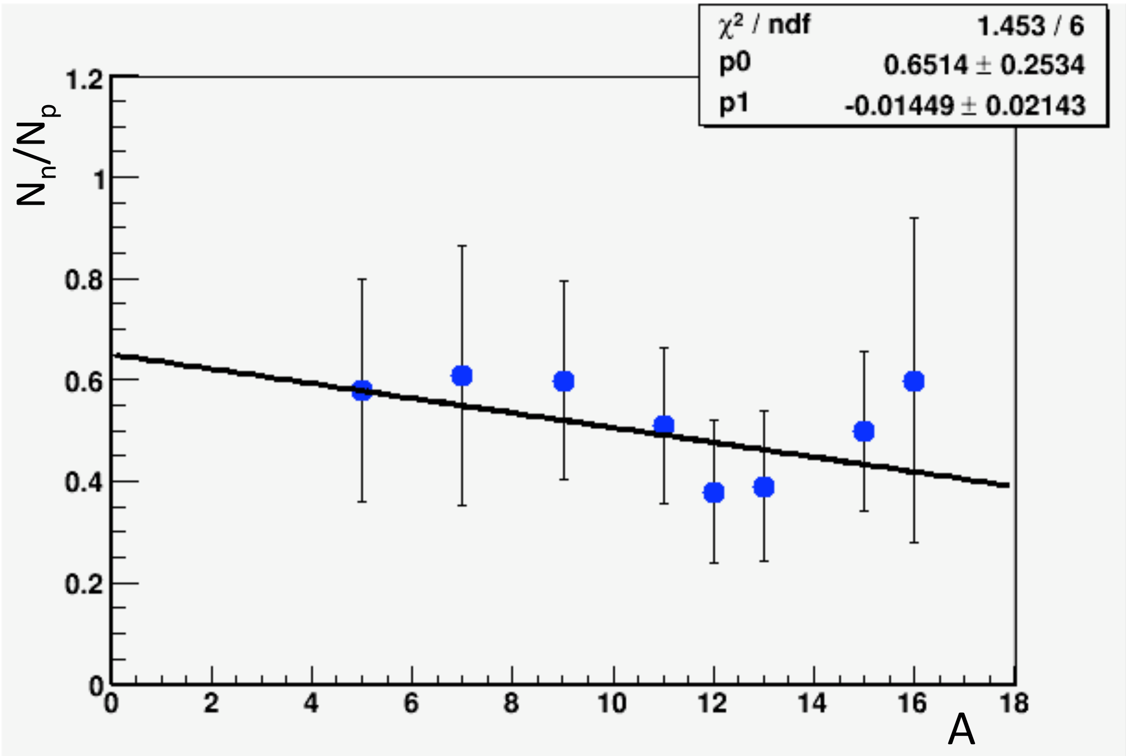
NMWD: Γ_{2N}

systematics: all *p*-shell

$$R(A) = \frac{N_n\ (\cos\theta \geq -0.8,\ E_p < \mu - 20\ \text{MeV})}{N_p\ (E_p > \mu\ \text{p singles spectra fit})} = \frac{N(\Lambda np \to nnp) + N^{FSI}}{0.5\ N(\Lambda p \to np) + N^{FSI}}$$

$$R(A) = a + b\,A = \frac{\Gamma_2}{0.5\,\Gamma_p} + b\,A$$

Γ_2/Γ_p indep. on A



weighted mean

$\Gamma_2/\Gamma_p = 0.33 \pm 0.07$

$\Gamma_2/\Gamma_{NM} = 0.18 \pm 0.03$

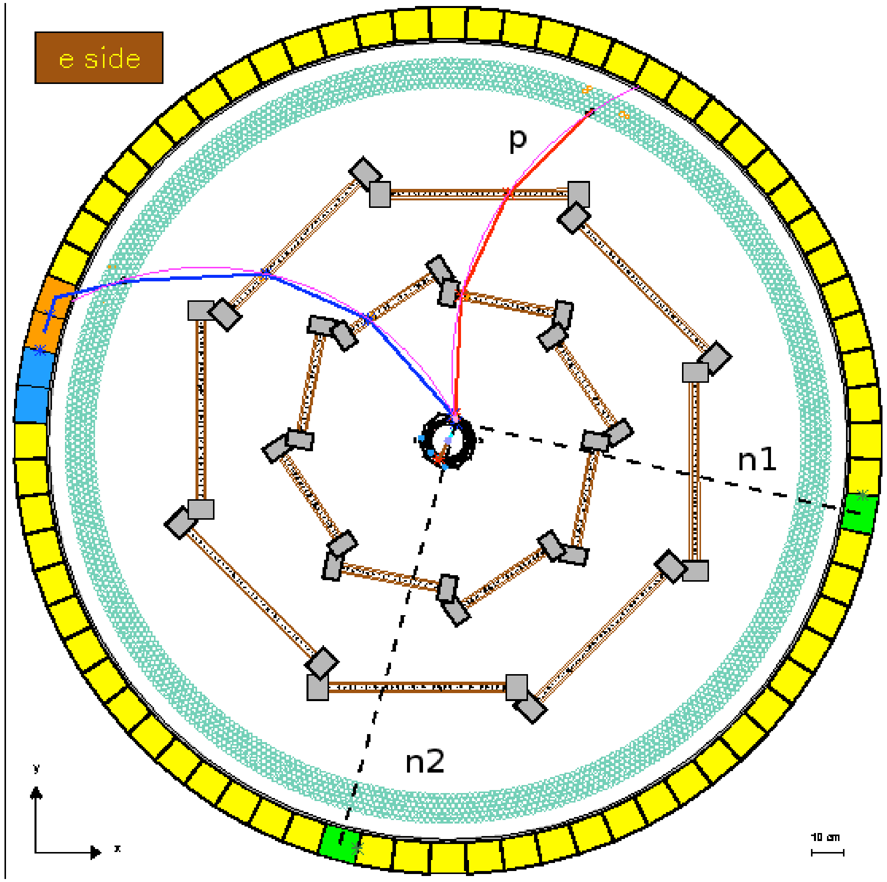
+ 10 % due to systematics

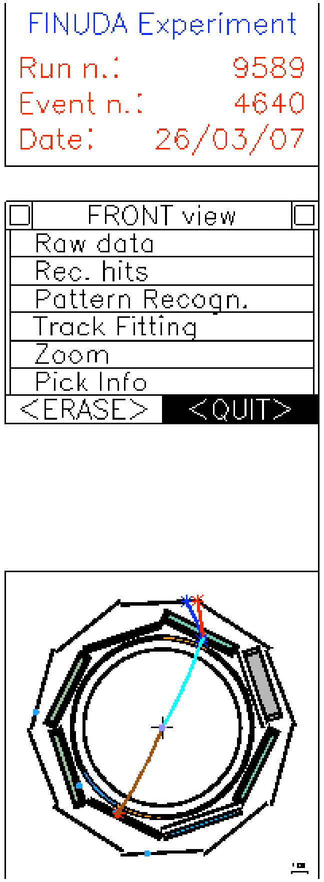
- low statistics
- direct measurement
- error lowered by a factor 3

NMWD: Γ_{2N}

Triple coincidence (n+n+p) events @ FINUDA

exclusive $\Lambda np \rightarrow nnp$ $^{7}_{\Lambda}Li \rightarrow {}^{4}He + p + n + n$ decay event





p_{π^-} = 276.93 MeV/c
E_{tot} = 178.3 MeV
Q-value = 167 MeV
p miss = 216.6 MeV/c

E(n1) = 110.2 MeV
E(n2) = 16.9 MeV
E(p) = 51.0 MeV

θ (n1 n2) = 95°
θ (n1 p) = 102°
θ (n2 p) = 154°
no n-n scattering

First direct experimental evidence of 2N-induced NMWD !!

NMWD: rare decays

2-body NMWD of light hypernuclei @ FINUDA

M.Agnello et al., NPA 835 (2010) 439

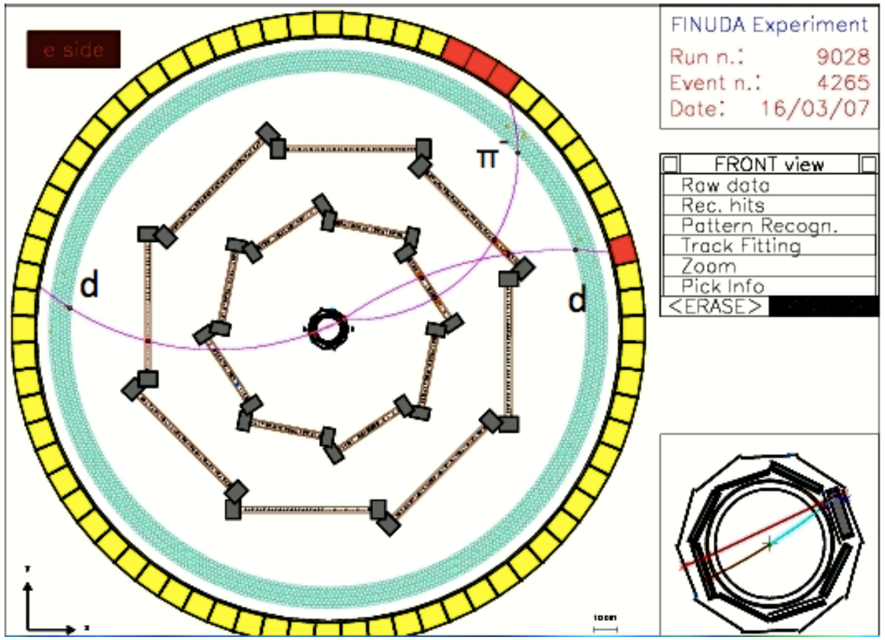
hyperfragments

$^4_\Lambda He \to d + d$ p_d = 570 MeV/c all targets 1 event observed

$\to p + t$ p_p = 508 MeV/c all targets ever observed

$^5_\Lambda He \to d + t$ p_d = 597 MeV/c ^6Li & ^7Li targets 1 event observed

b-t-b topology



$Y(^4_\Lambda He \to d+d) = (2.82 \pm 0.62)10^{-5}/K^-_{stop}$
(12 events)

$Y(^4_\Lambda He \to p+t) = (5.42 \pm 3.43)10^{-5}/K^-_{stop}$
(12 events)
$R(^4_\Lambda He \to d+d/^4_\Lambda He \to p+t) = 0.52 \pm 0.35$

$Y(^5_\Lambda He \to d+t) = (1.23 \pm 0.70)10^{-5}/K^-_{stop}$
(3 events)
$BR(^5_\Lambda He \to d+t) = (2.8 \pm 1.4)10^{-3}$
$BR(^5_\Lambda He, NMWD) = 0.28 \pm 0.07$

WD: perspectives

- lifetimes/total width $A \geq 50$
- MWD spectra, J^{π}, $\Delta I=1/2$
- NMWD: spectra, Γ_n/Γ_p puzzle systematics, Γ_{2N}, $\Delta I=1/2$

J-PARC

Production reactions kinematics

$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$ in flight ($p_\pi = 1.06$ GeV/c)

$$[p^2_\pi + m^2_\pi]^{1/2} + m_A = [p^2_{hyp} + m^2_{hyp}]^{1/2} + [p^2_K + m^2_K]^{1/2}$$
$$\vec{p}_\pi = \vec{p}_{hyp} + \vec{p}_K$$

energy & momentum conservation

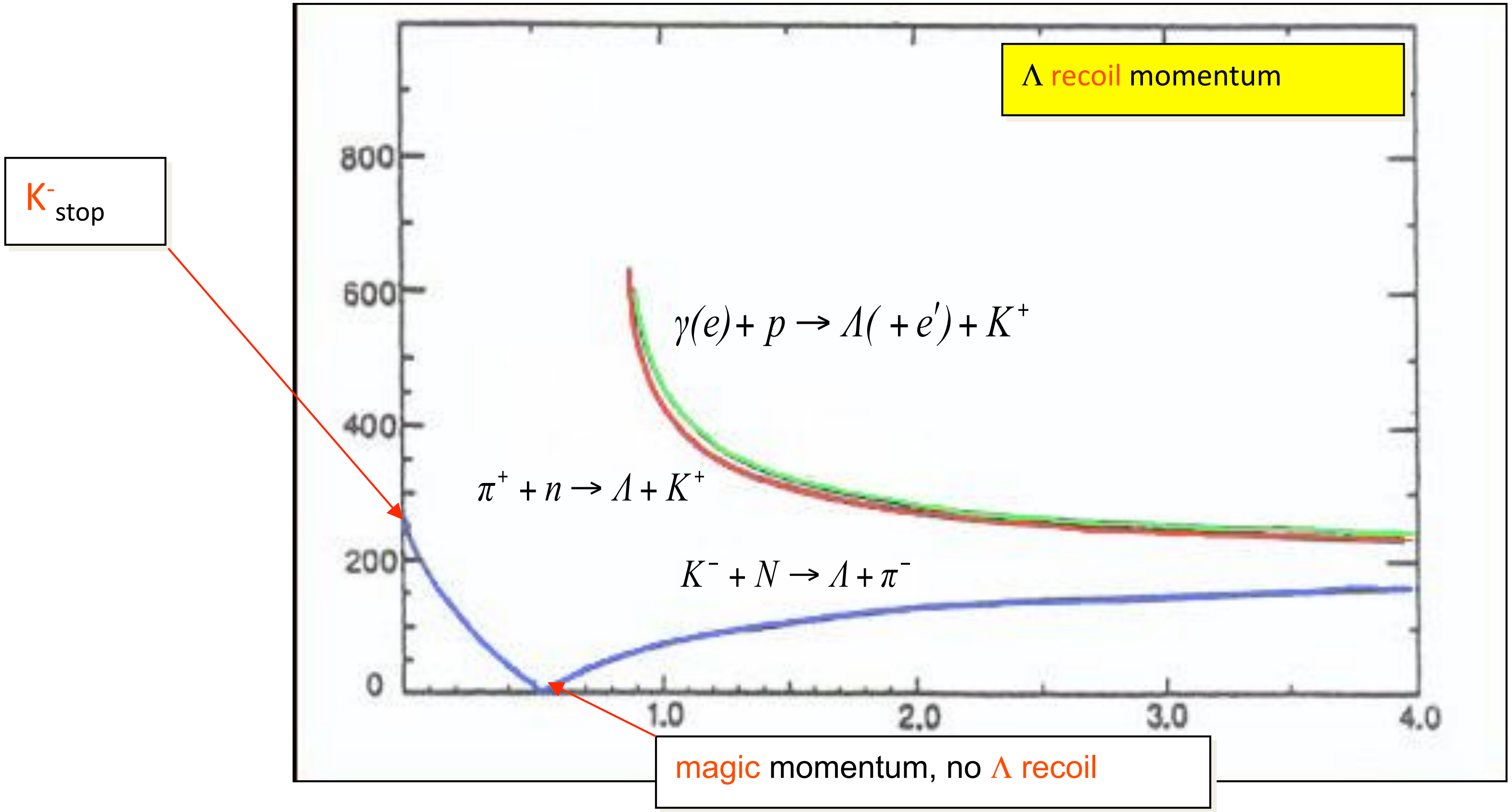
$$m_{hyp} = \{[[p^2_\pi + m^2_\pi]^{1/2} + m_A - [p^2_K + m^2_K]^{1/2}]^2 - [p^2_\pi + p^2_K - 2p_\pi p_K \cos\theta]\}^{1/2}$$
$$m_{hyp} = m_{A-1} + m_\Lambda - B_\Lambda \quad \rightarrow B_\Lambda = m_{A-1} + m_\Lambda - m_{hyp}$$
$$m_{hyp} - m_A = m_\Lambda - B_\Lambda - m_n + B_n$$

$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$

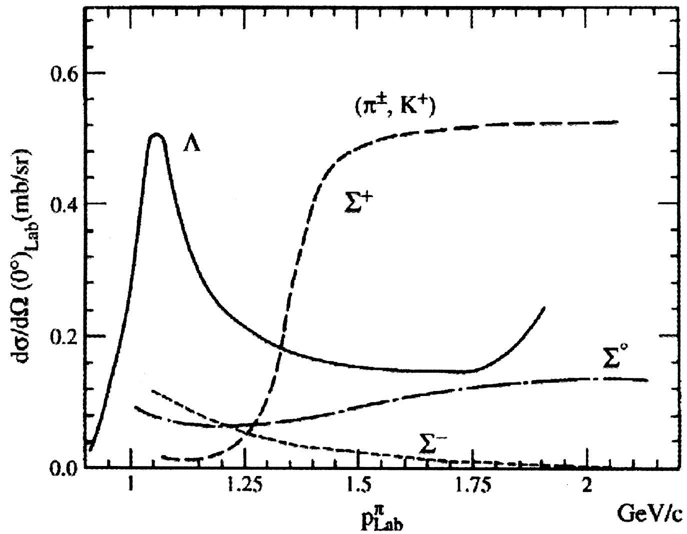
$$m_k + m_A = [p^2_{hyp} + m^2_{hyp}]^{1/2} + [p^2_\pi + m^2_\pi]^{1/2}$$
$$\vec{p}_\pi = -\vec{p}_{hyp}$$

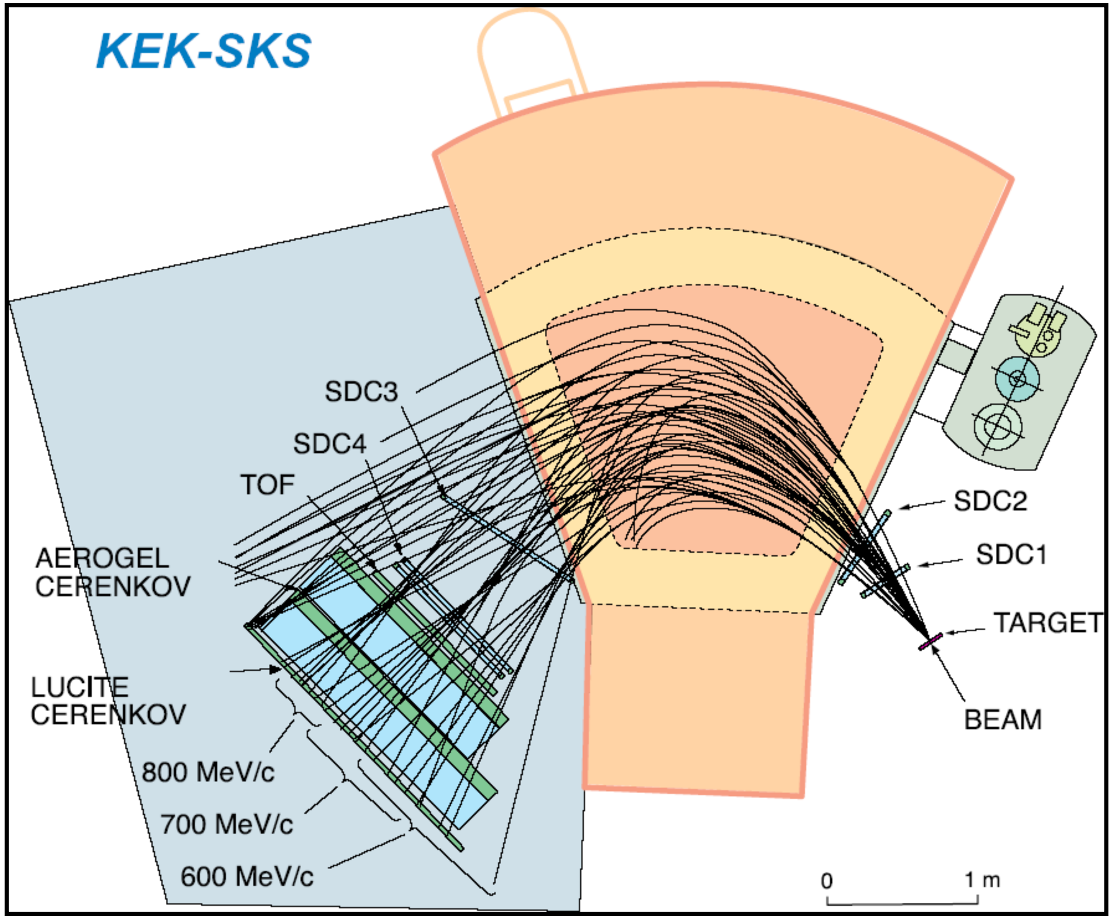
energy & momentum conservation

$$m_{hyp} = \{[m_k + m_A - [p^2_\pi + m^2_\pi]^{1/2}]^2 - p^2_\pi\}^{1/2}$$
$$B_\Lambda = m_{A-1} + m_\Lambda - m_{hyp}$$



(π^+, K^+) elementary reaction




KEK-SKS
SDC3
SDC4
TOF
AEROGEL
CERENKOV
LUCITE
CERENKOV
800 MeV/c
700 MeV/c
600 MeV/c
SDC2
SDC1
TARGET
BEAM
0
1 m

NMWD s-shell: $\Delta I = 1/2$
NMWD A=180-225: $\Delta I = 1/2$

?

KEK vs LNF

KEK: $(\pi+, K+)$

$N_{hyp} = N_\pi \bullet \sigma \bullet \Delta x \bullet K$

$N_\pi \approx 3\ 10^9/h$

$\sigma = \int_{\Omega'} \frac{d\sigma}{d\Omega} d\Omega'$ SKS angular acceptance (2°-16°)

$\Delta x \approx 3$ cm ^{12}C target

$K = \rho N_A / A \approx 10^{23}$ atoms/cm^3

5-8 events/10^9 π^+/g cm^{-2}

1000 events/day 2 g cm^{-2} ^{12}C

(3000 events/day)

Hashimoto, Proc. Part. Nucl. Phys. 57 (2006), 564

LNF: $e^+ + e^- \rightarrow \phi \rightarrow K^+ + K^-;\ K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$

$N(\Phi)/s = \mathcal{L} \bullet \sigma\ (e^+ e^- \rightarrow \Phi$, 1020 MeV$)$ $\quad \sigma = 3.26\ \mu$barn

$\mathcal{L}_{int} = \langle \mathcal{L} \rangle\ \Delta t$

$N(\Phi)$/day $= \mathcal{L}_{int\ day} \bullet \sigma = 9$ pb^{-1}/day $\bullet$ 3.26 μbarn $\approx 3\ 10^7\ \Phi$/day $\rightarrow 1.5\ 10^7$ K^-/day

N_{hyp}/day $\approx N(K^-)$/day $\bullet 0.7 \bullet 1/8 \bullet 10^{-3} \approx 1300$ / day $\bullet 0.5 \approx 650$ /day (no efficiency)

0.7: fraction of K- stopped in target

1/8: 1 target out of 8

10^{-3}: capture rate. for $^{12}{}_\Lambda C$ g.s

0.5: FINUDA angular acceptance

NMWD theory summary

OPE: the π emitted by $\Lambda \to \pi N$ decay is recaptured by a different nucleus; $\Gamma_{TOT} \sim$ 2-4 Γ_Λ ($\Gamma_{TOT\ exp} \sim 1.2\ \Gamma_\Lambda$ medium-heavy hyp.)
OPE + ρ: Γ_n/Γ_p~0.05-0.3<<$(\Gamma_n/\Gamma_p)_{exp}$ ($(\Gamma_n/\Gamma_p)_{exp}$ ~ 1-2): Oset, Takeuchi, Shinmura, Parreno, Itonaga

OME: $\pi + \rho$ + K + K*+ $\omega + \eta$ to enlarge Γ_n/Γ_p: Dubach, Parreno, Sasaki

Quark current and hybrid model: long-range interaction (r>0.8 fm) by OPE (ΔI=1/2) + short range interaction by six quark cluster model (ΔI=1/2 and 3/2): Cheung, Heddele, Kisslinger

DQ: contact 4-quark interaction between constituent quarks without exchanging mesons (ΔI=1/2 and 3/2): significant ΔI=3/2 contribution in the L=0 channel, Γ_n/Γ_p~1: Oka

π+K+DQ: DQ + OME for the long range part; Γ_n/Γ_p~0.5-0.7, $\Gamma_{TOT} \sim 2.5\ \Gamma_\Lambda$: Sasaki

Microscopic models: Λ self-energy in nuclear matter + LDA: Ramos, Alberico, Garbarino

Exchange terms: Λ self-energy with exchange terms: Bauer, Garbarino