Hypernuclear Weak Decay Experiments at KEK:
Nucleon Inclusive Measurements

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CONTENTS

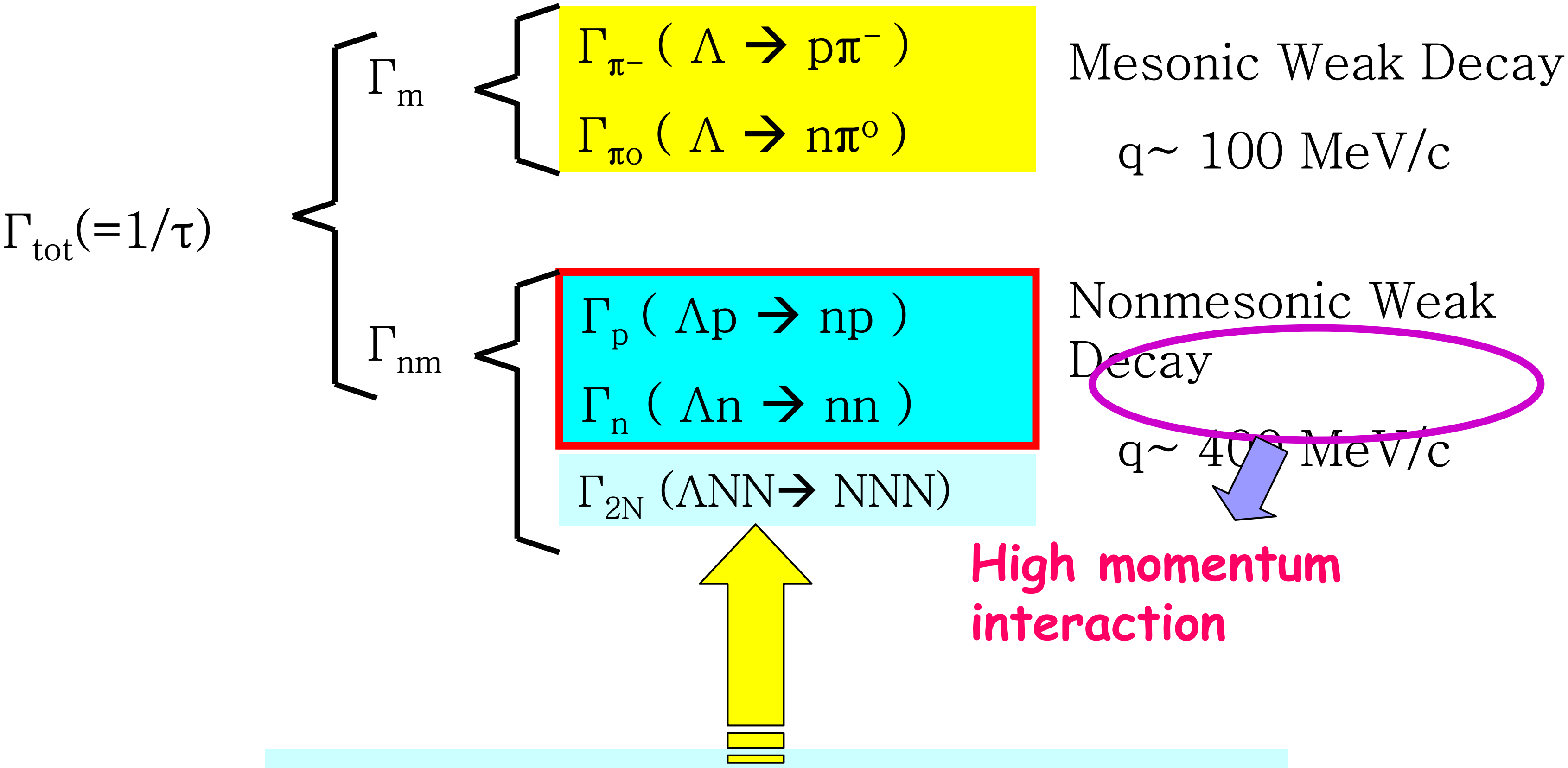
I. Background
- 1. Weak Decay Modes of Λ hypernuclei
- 2. Nonmesonic Weak Decay (NMWD)
- 3. Status of Γ_n/Γ_p puzzle

II. Experiments/Set up
- 1. KEK-PS E307 ; N_p
- 2. E369 ; N_n
- 3. Exclusive Measurement of Weak Decay : Nn•Np (E462/E508)

III. Results and Discussion
- 1. Γ_n/Γ_p obtained from N_p/N_n
- 2. Limitation of the results of Inclusive meas.
- 3. Asymmetry status and Preliminary Results

IV. Summary

Weak Decay Modes of Λ Hypernuclei



$\Gamma_{tot}(=1/\tau)$

- Γ_m
  - $\Gamma_{\pi^-}\ (\Lambda \rightarrow p\pi^-)$
  - $\Gamma_{\pi^o}\ (\Lambda \rightarrow n\pi^o)$
- Γ_{nm}
  - $\Gamma_p\ (\Lambda p \rightarrow np)$
  - $\Gamma_n\ (\Lambda n \rightarrow nn)$
  - $\Gamma_{2N}\ (\Lambda NN \rightarrow NNN)$

Mesonic Weak Decay

q~ 100 MeV/c

Nonmesonic Weak Decay

q~ 400 MeV/c

High momentum interaction

Main focus of this talk

Non-Mesonic Weak Decay (NMWD) & Issues

1. B-B Weak Interaction ;

$\Lambda + N \rightarrow N + N$ ($\Delta S=1$ B-B Weak Interaction)

- The crutial importance of NMWD is that it provides the only practical means of exploring the four fermion, strangeness changing $\Lambda N \rightarrow NN$ weak interaction.

2. Long standing puzzle on : Γ_n/Γ_p **(≡np ratio)**

3. 2N NMWD: Predicted to be a significant component of NMWD, though not experimentally identified yet.

4. Asymmetry ; The relative phase concern of PC and PV part of NMWD interaction.

5. Final State Interaction : It seems one of the important elements to understand NMWD.

Status of Γ_n/Γ_p puzzle

$\Gamma_n/\Gamma_p^{exp} \gg \Gamma_n/\Gamma_p^{th}$

$\sim 1 \qquad\qquad \sim 0.1$

≡ **Γn/Γp Puzzle**

Until Recently,

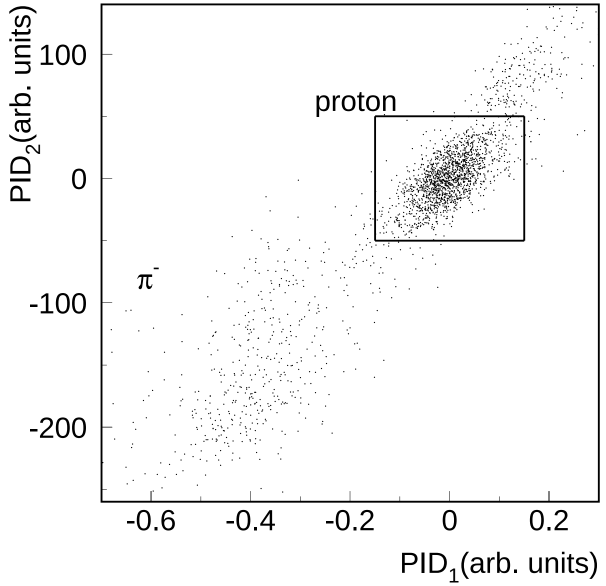
		Hyp Nuc.	Γ_{nm}		Γ_n/Γ_p	
			π	all	π	all
Theory	Dub'96	$^{5}_{\Lambda}$He	0.9	0.5	0.05	0.48
		$^{12}_{\Lambda}$C	0.5	0.2	0.20	0.83
	Ram'97	$^{5}_{\Lambda}$He	0.5	0.41		0.07
		$^{12}_{\Lambda}$C	0.89	O,75	0.104	0.07
Experiment	BNL	$^{5}_{\Lambda}$He	0.41±0.14		.93±0.55	
		$^{12}_{\Lambda}$C	1,14±0.2		1.33±1.12/0.81	
	KEK'95	$^{12}_{\Lambda}$C	0.89±0.18		1.87±0.91/1.59	

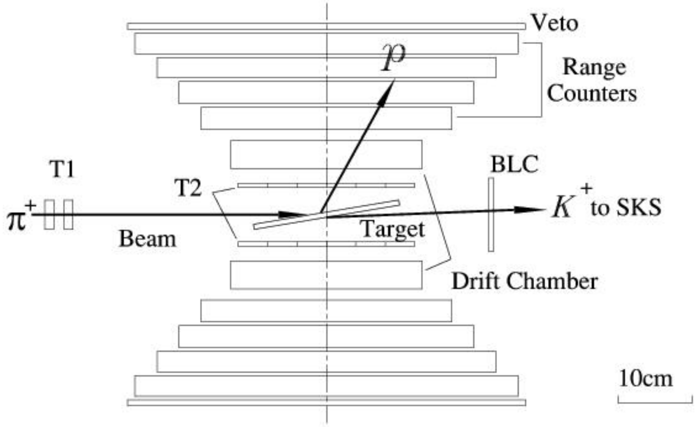
The exp. error bars are too large to distinguish different models.

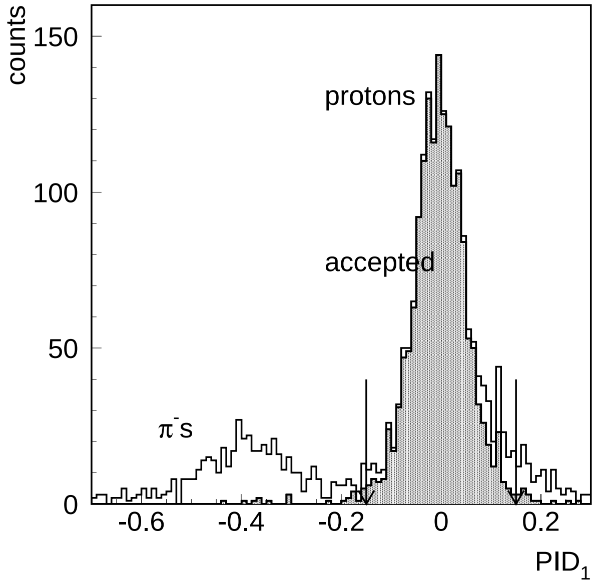
Improvement of the experimental accuracy **of the ratio seemed very** urgent. In this regards, the two experiments, KEK-PS E307 and E369, has been implemented at KEK.

E307 Experiment/Setup

1. **Objectives**
   1) τ for ${}^{12}_{\Lambda}C$, ${}^{28}_{\Lambda}Si$ and ${}_{\Lambda}Fe$
   2) Proton energy spectrum
   3) Γ_p, Γ_{π^-}
2. **Set up**
   1) (π^+, K^+) reaction
   2) Large solid angle, ~100msr, SKS
   3) Decay spectrometer



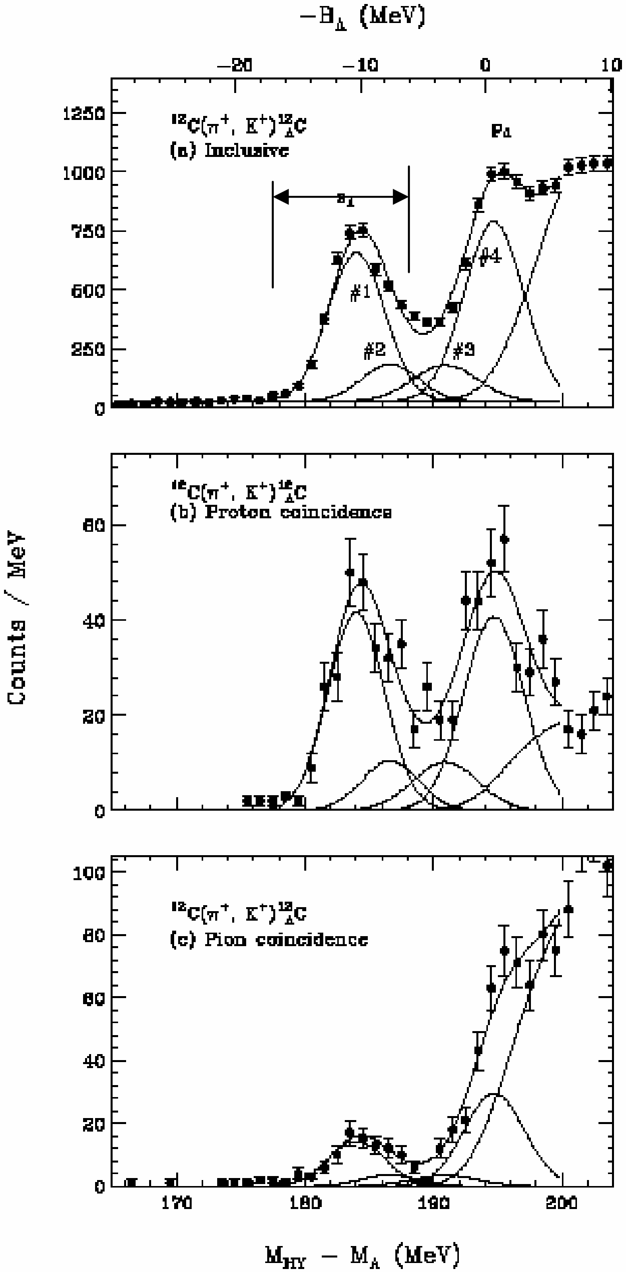




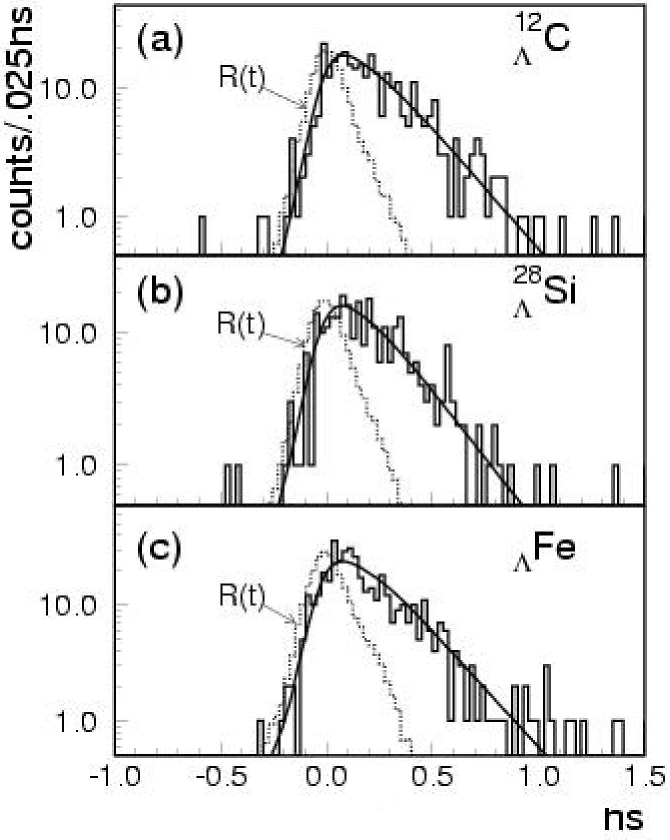
$$\mathrm{TOFn} = (\mathrm{T2} - \mathrm{tof_d}) - (\mathrm{T1} + \mathrm{tof_b})$$

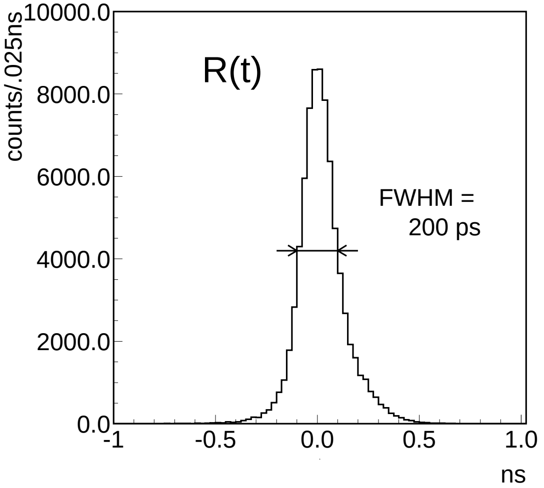
E307 Experiment

Mass spectrum

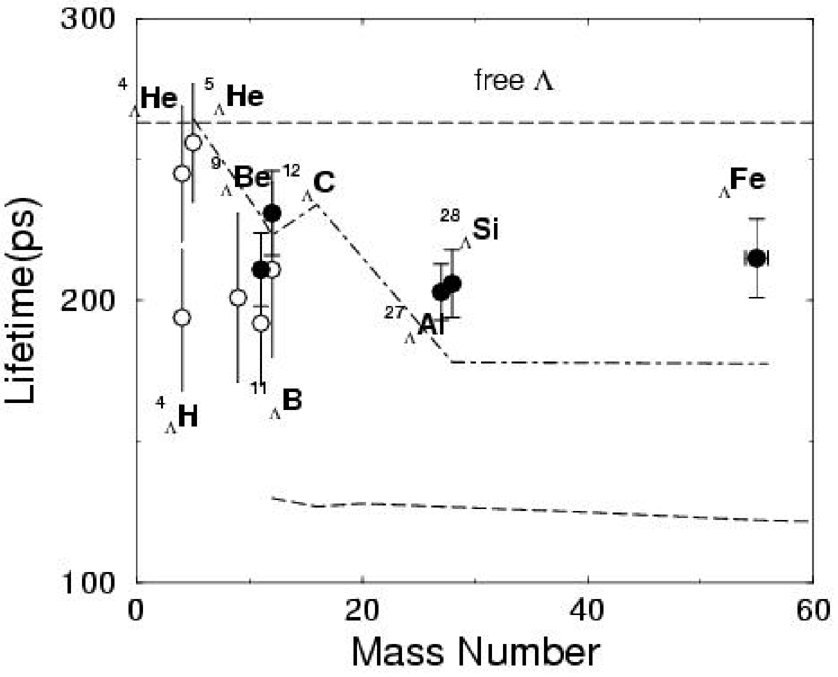


Life times





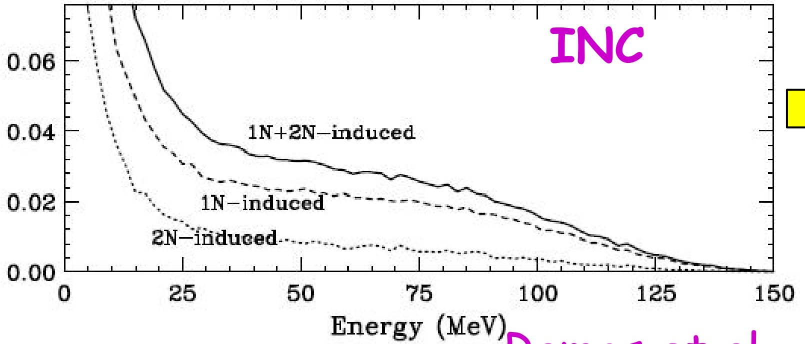
Prompt time spec.



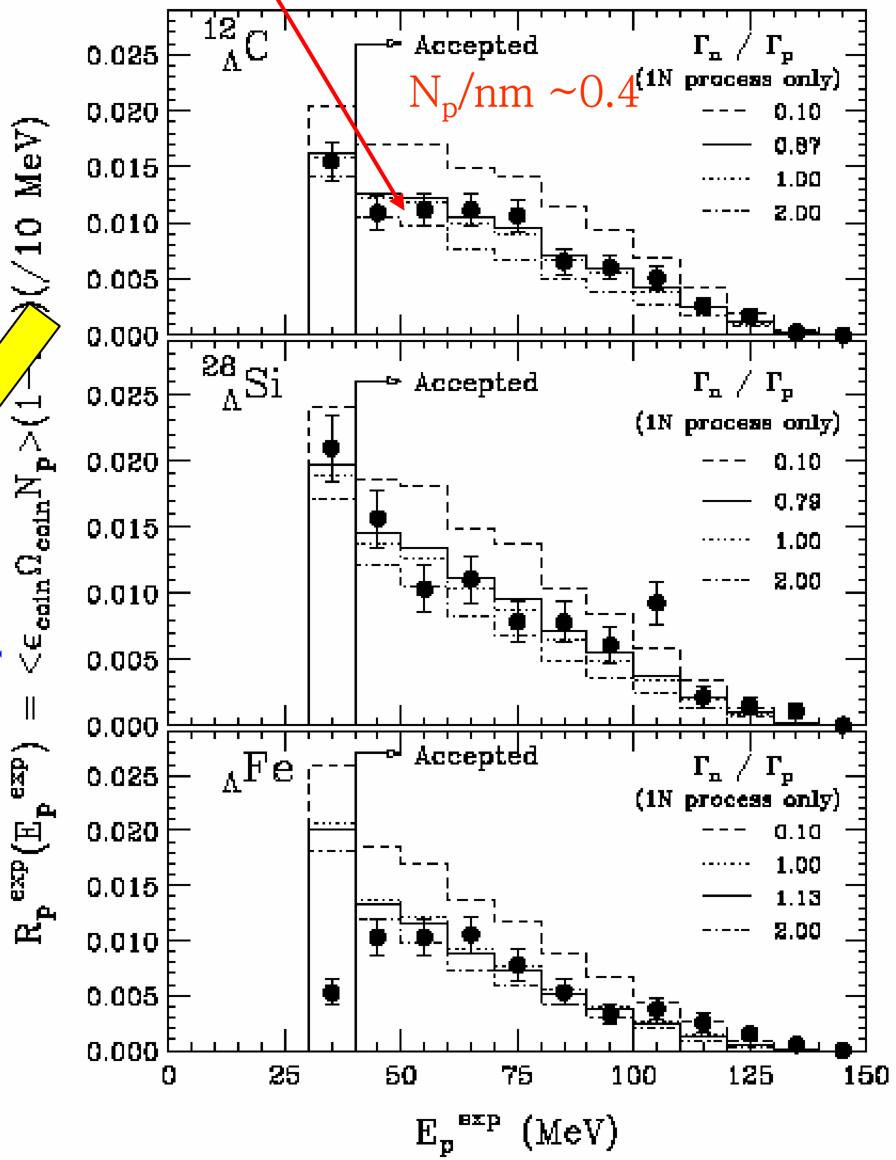
$\Lambda + n \rightarrow n + n$

$\Lambda + p \rightarrow n + p$

Proton Energy spectrum



Ramos et al.



N_p/decay

$$\frac{\Gamma_n}{\Gamma_p} = \begin{pmatrix} 1.17 \pm 0.09 \pm 0.20 \ \ (1N) \\ 0.96 \pm 0.10 \pm 0.22 \ \ (1N+2N) \end{pmatrix}$$

PRL89 (2002)

INC revision →
$$\begin{pmatrix} 0.87 \pm 0.09 \pm 0.21 \ \ (1N) \\ 0.60 \pm 0.11 \pm 0.23 \ \ (1N+2N) \end{pmatrix}$$

Sato et al., PRC submitted

where 2N ; $\Lambda NN \rightarrow NNN$.

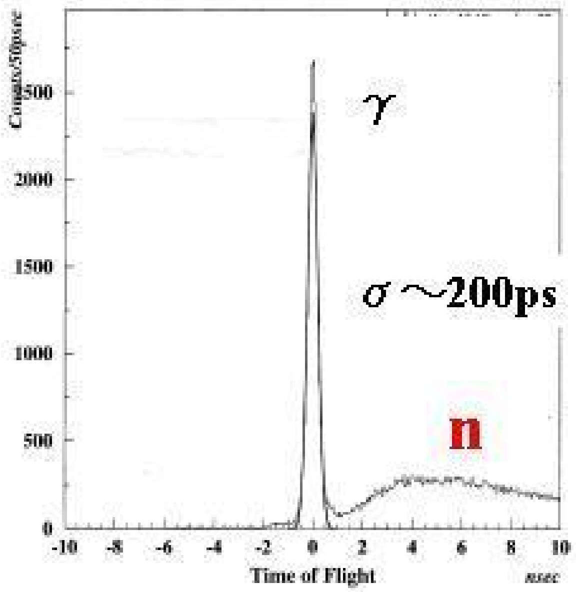
E369 Experiment/Setup

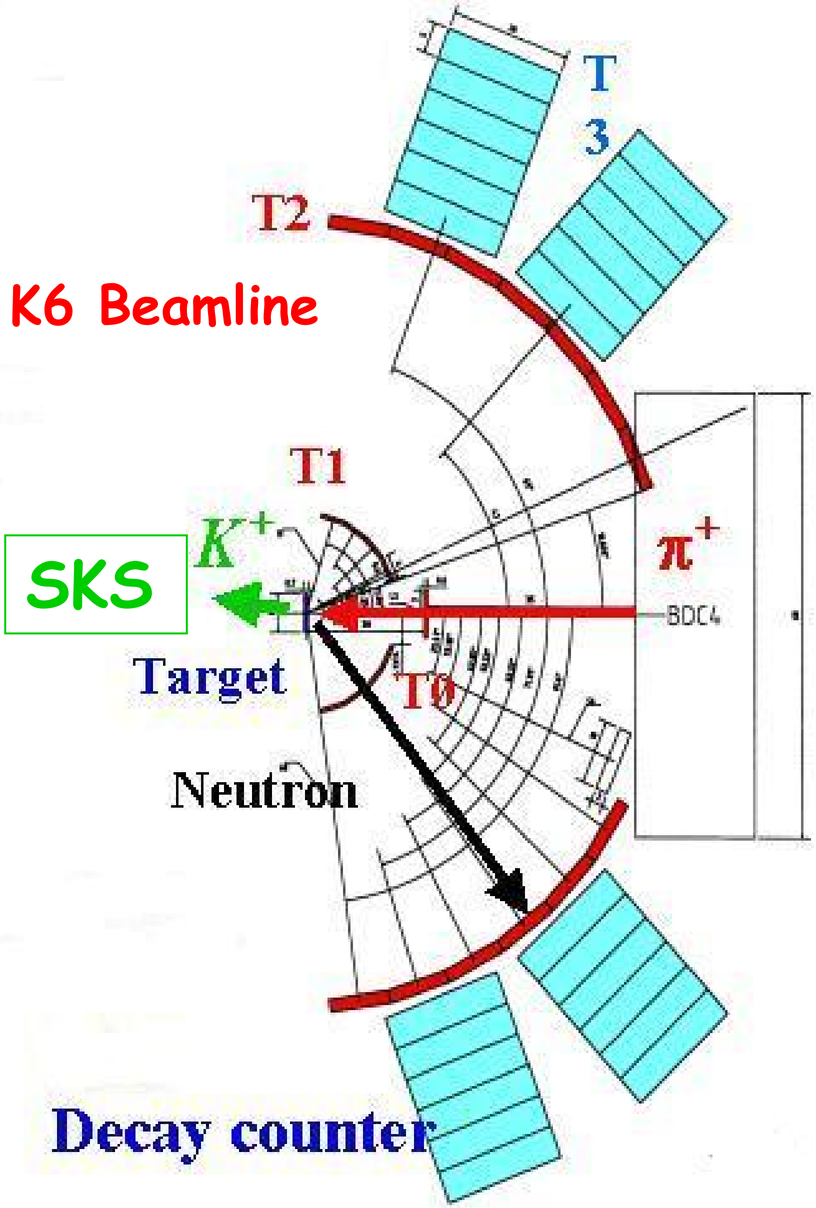
To derive the Γ_n/Γ_p experimently, one need n measurement.

Neutron spectra measured.

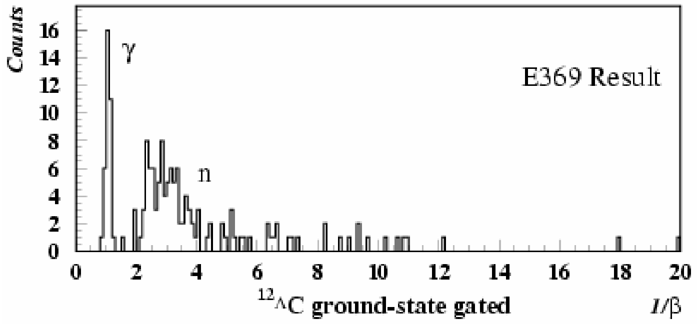
target: ^{12}C, ^{51}V and ^{89}Y

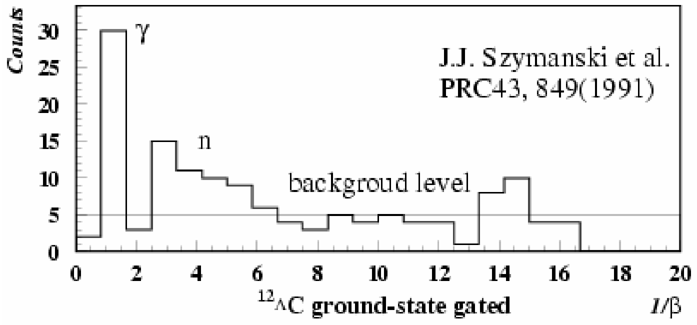
n / γ separation by TOF method

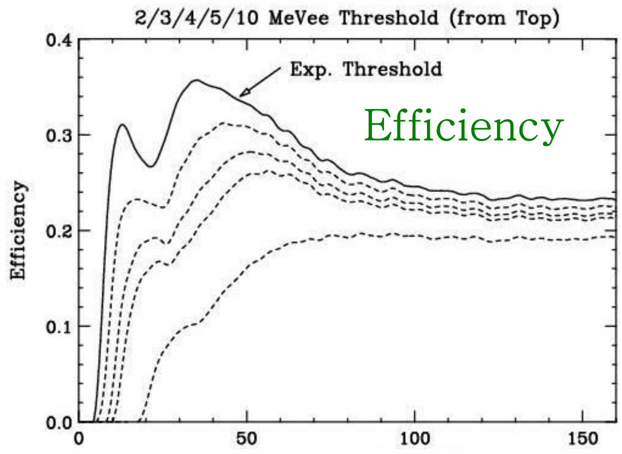


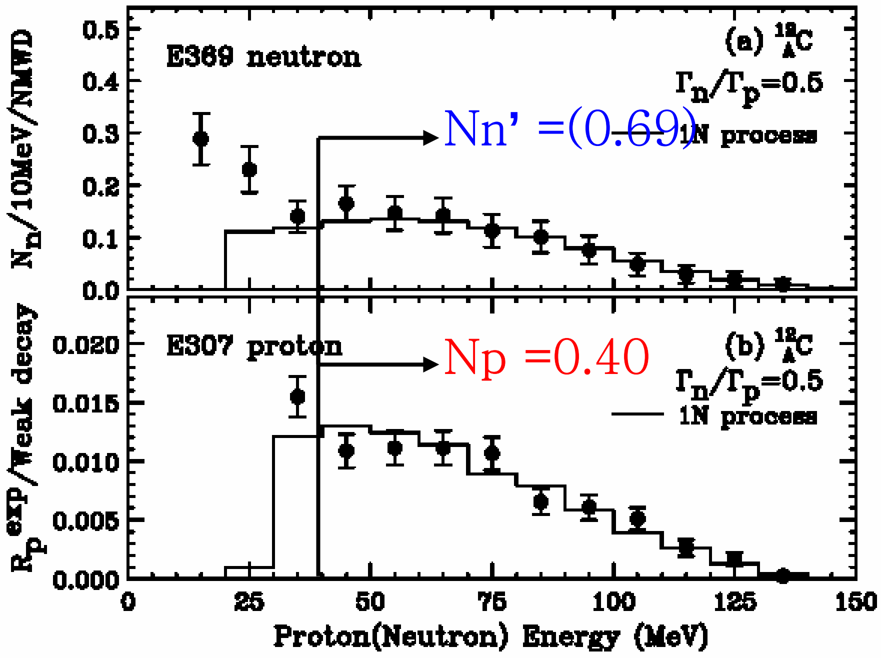


Neutron Spectrum









Nn' =(0.69)

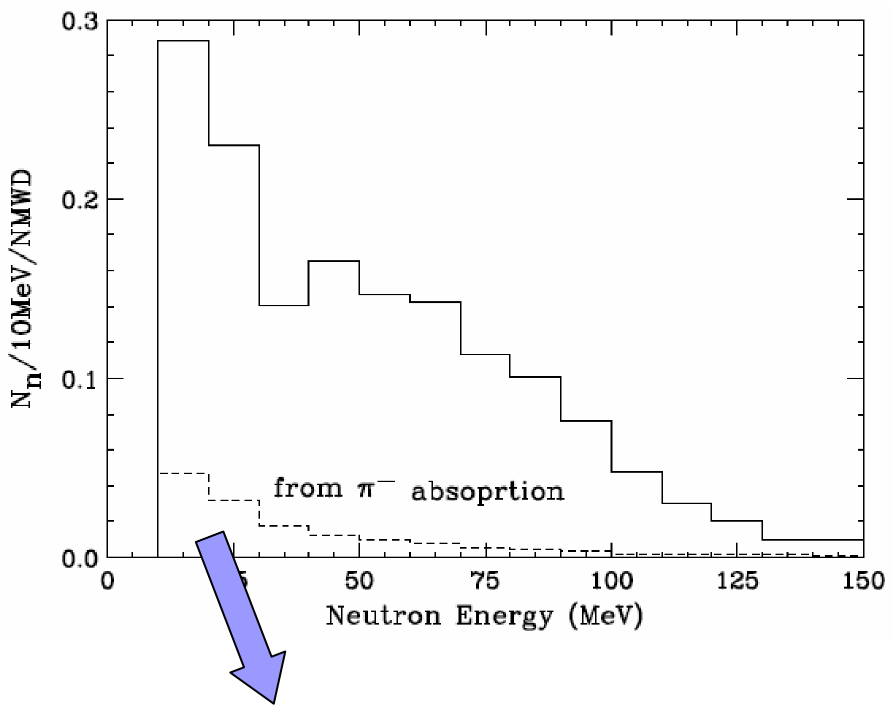
Np =0.40

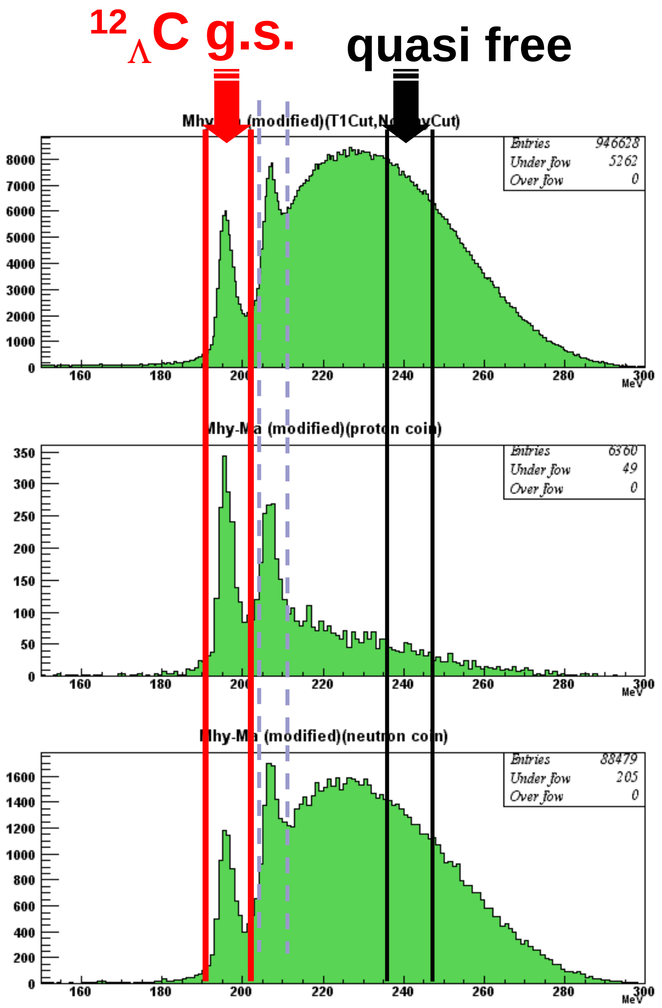
1. **n yield is compared with that of p.**
2. **Nn above 40 MeV** is about (**0.69**) **while Np is 0.40 (E307)**
3. **Now can directly compare the their relative decay rates.**

submitted to PRC(03)

HYP03 Conf.

π- absorption background





π^- absorption background subtraction

Discussion

- Now we can **directly compare n and p spectra** to estimate Γ_n/Γ_p ratio.
- To estimate Γ_n/Γ_p **ratio simply from Nn/Np number ratio.**

  \- Assume NMWD **1N process only** ; $r_n + r_p = 1$.

  \- The neutron (proton) number per NMWD for full solid angle and $\varepsilon = 1$.

$$N_n = Y_n / N_{nm} \Omega_n \varepsilon_n = (2r_n + r_p) f + r_p g$$

$$N_p = Y_p / N_{nm} \Omega_p \varepsilon_p = r_p f + (2r_n + r_p) g$$

where **f ; loss due to FSI, and**

g ; channel cross over influx due to FSI.

\- Assumed **$f_n = f_p$, $g_n = g_p$.** , **considering the isospin independece of the strong interaction and the isospin symmetric propagating medium.**

Therefore,

$$\frac{N_n}{N_p} = \frac{2 - r_p + r_p\beta}{(2 - r_p)\beta + r_p} = \alpha = 1.73$$

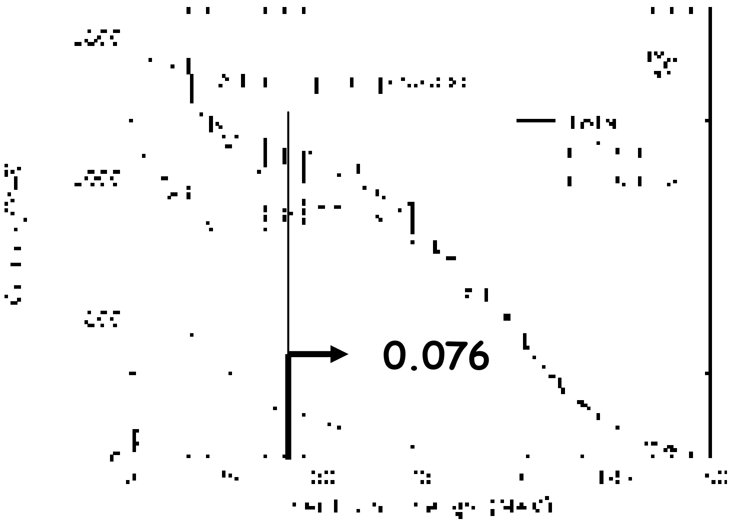
Where

$$\beta = \frac{g}{f} \cong (.076 - .11) \ \leftarrow \text{INC}$$

$$\frac{\Gamma_n}{\Gamma_p} = \frac{1 - r_p}{r_p} \cong (0.45 - 0.51).$$

→ **Γ_n/Γ_p = (0.45~0.51)±0.15**

INC calculation



- A Γ_n/Γ_p **significantly smaller than unity**.
- Obtained **model independently** simply assuming $f_n=f_p$.
- The INC β value is used only for second order correction.

Γn/Γp ratio

E307/E369 :

$\Gamma_n / \Gamma_p ({}^{12}{}_{\Lambda}C)|_{1N} = (0.45 \sim 0.51) \pm 0.15$ (stat. only)

- **Almost** model independent.
- **A** significantly smaller ratio than unity.
- **This ratio agrees well with the most recent theoretical values (~.5)**

However, **ambiguities due to**

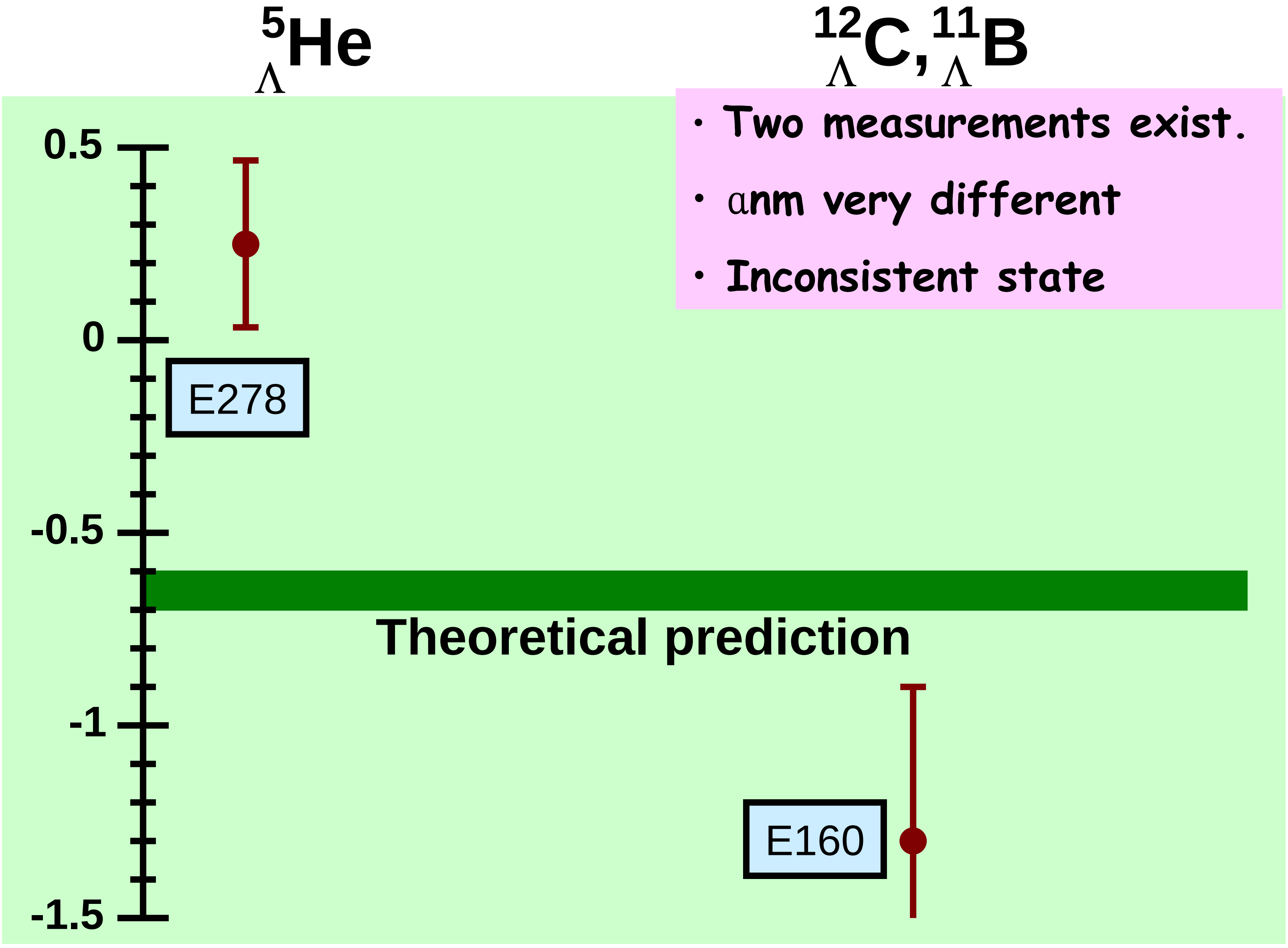
- **final state int.**
- **2N induced NMWD.**

- **Asymmetry issue: Large inconsistency among a_{nm}**

In order to resolve the difficulties,

- Exclusive measurements
- ${}^{5}{}_{\Lambda}He$ → E462
- ${}^{12}{}_{\Lambda}C$ → E508

Status of Asymmetry Parameter, α_{nm}

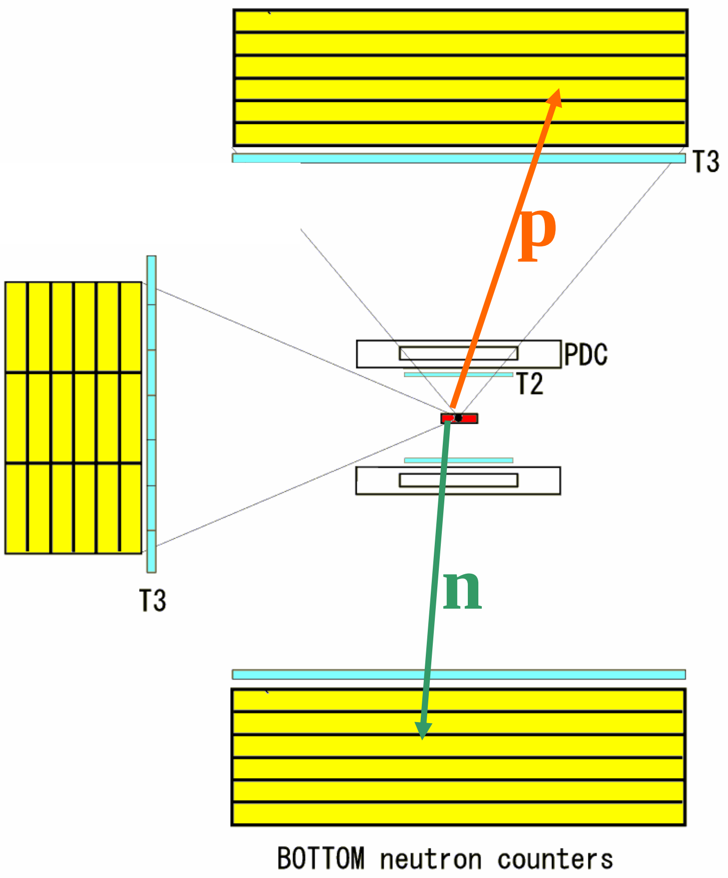


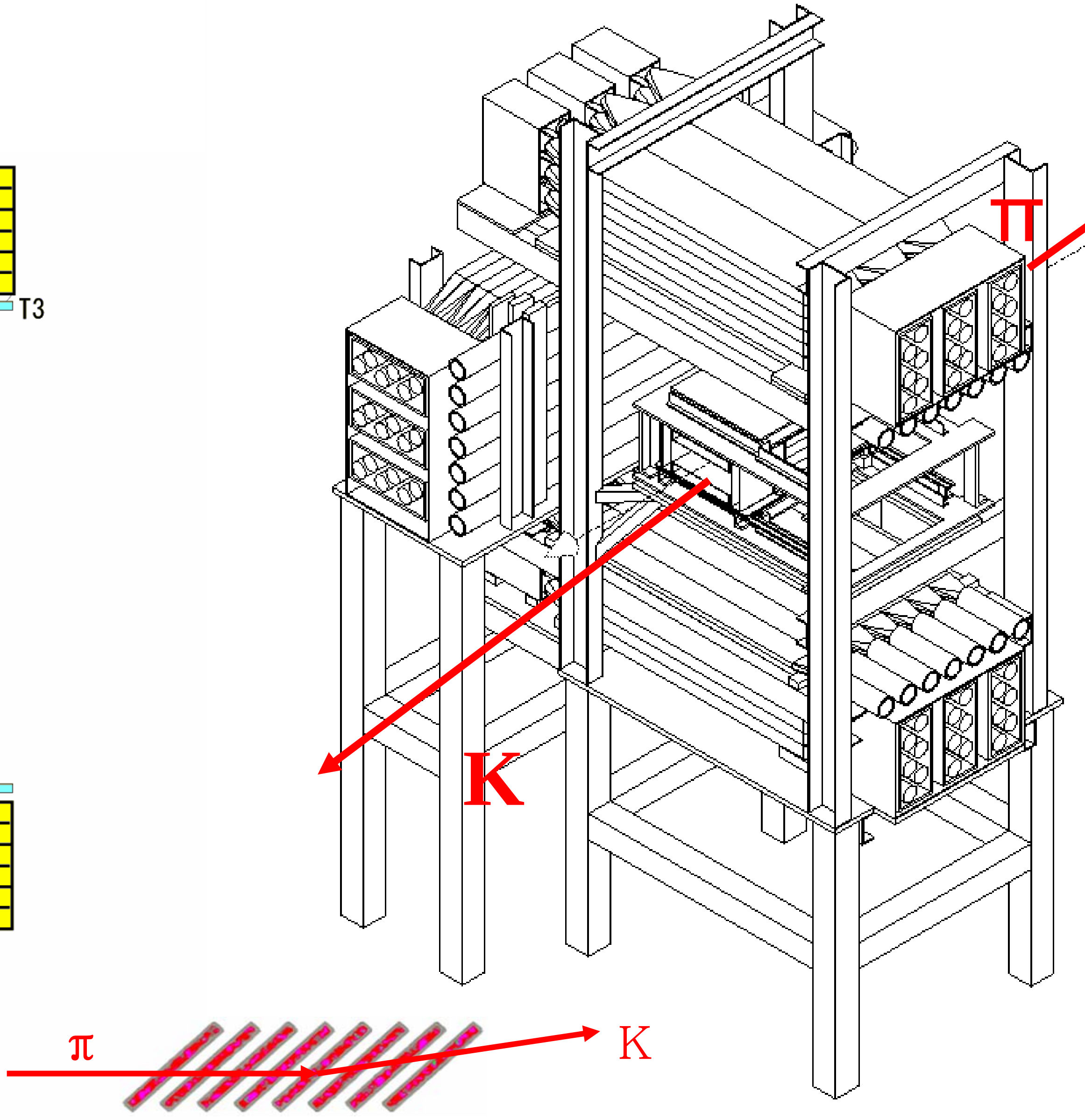
- Two measurements exist.
- αnm very different
- Inconsistent state

Setup E462/E508

(KEK-PS K6 beamline & SKS)

Solid angle: 26%
9(T)+9(B)+8(S)

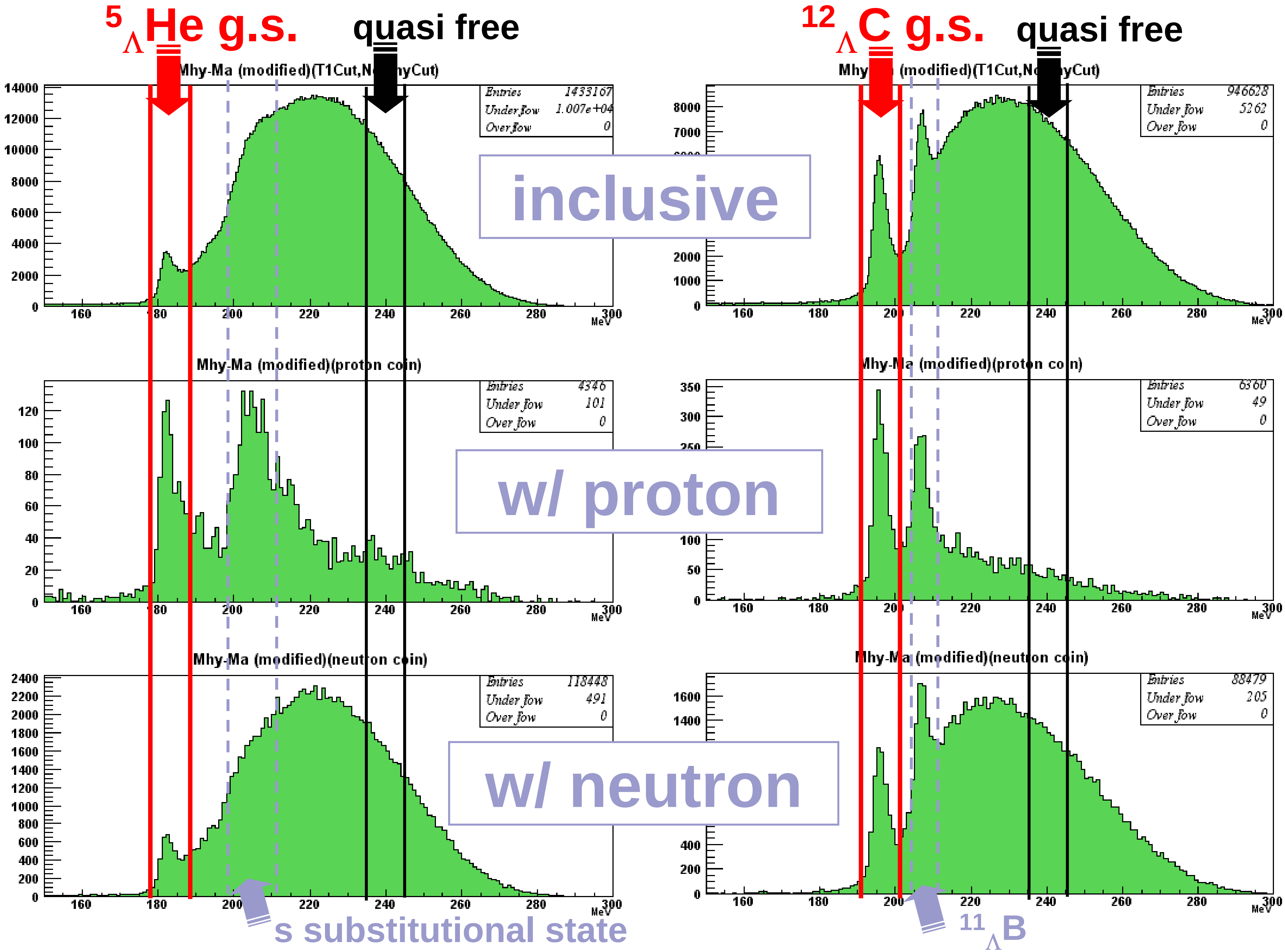




N: 20cm×100cm×5cm
T3: 10cm×100cm×2cm
T2: 4cm×16cm×0.6cm

Mass spectra for ^{6}Li(π^{+},K^{+})

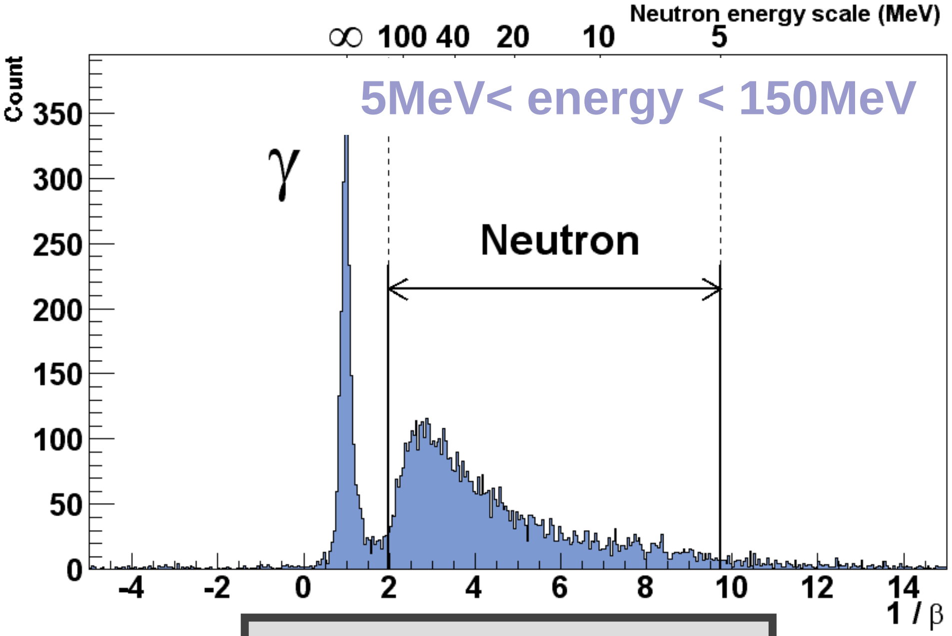
Mass spectra for ^{12}C(π^{+},K^{+})



Particle identification

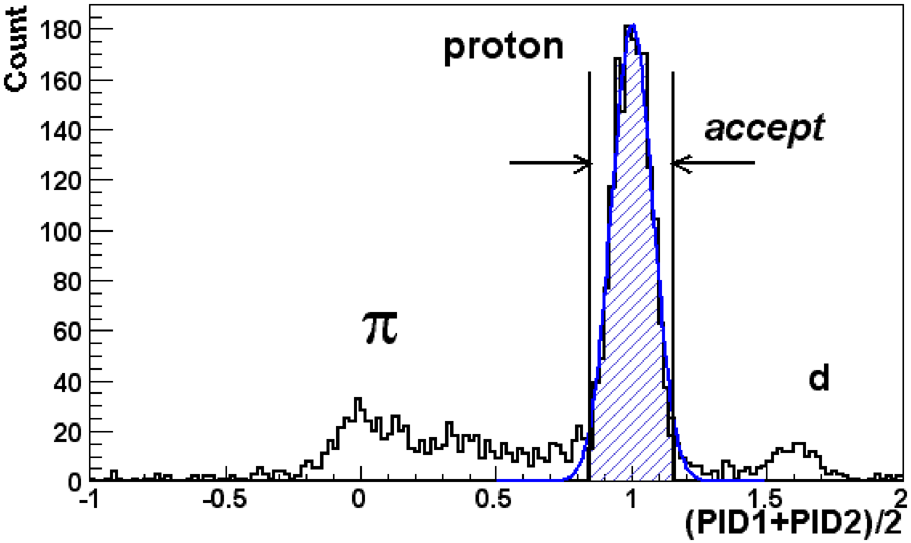
Neutral particle

1 / β spectra



Energy resolution
σ ~ 8MeV

Charged particle

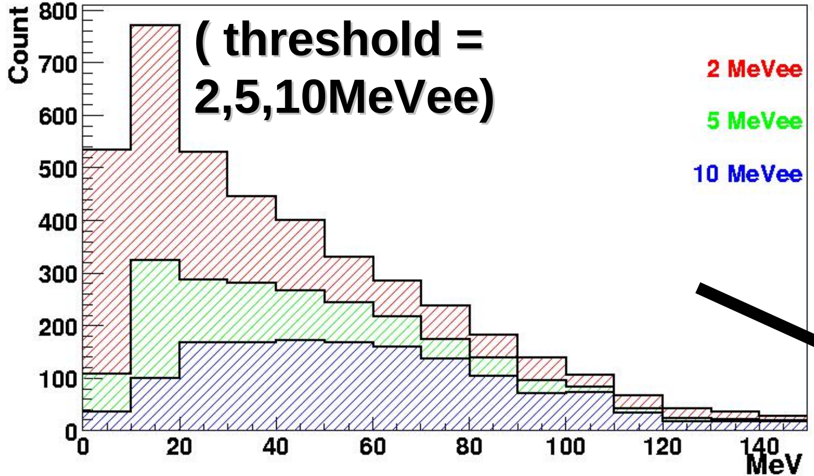


PID1 : total energy vs dE/dx
PID2 : total energy vs TOF
→ (PID1-PID2) / 2

gated ${}^{12}_{\Lambda}$C ground state

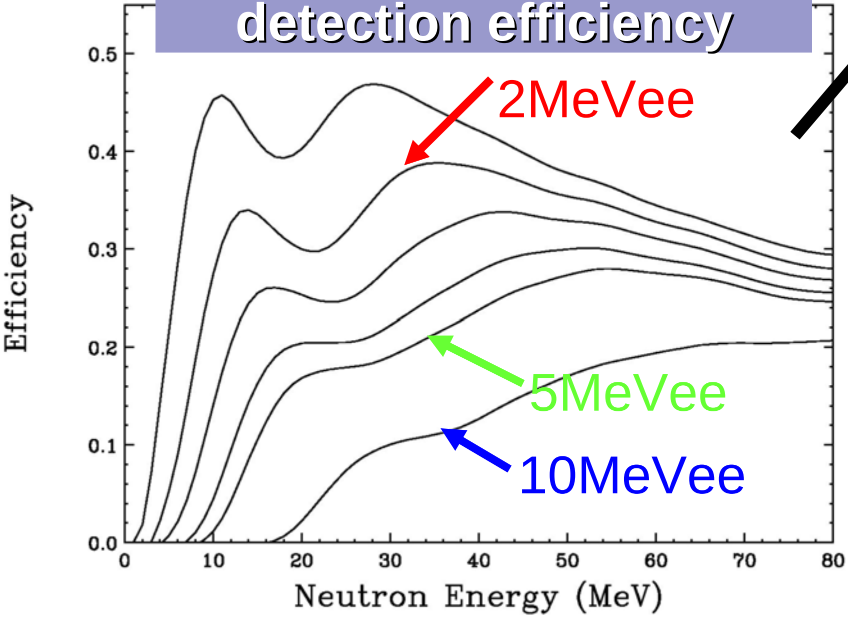
Neutron efficiency correction

Raw neutron spectra



(threshold = 2,5,10MeVee)

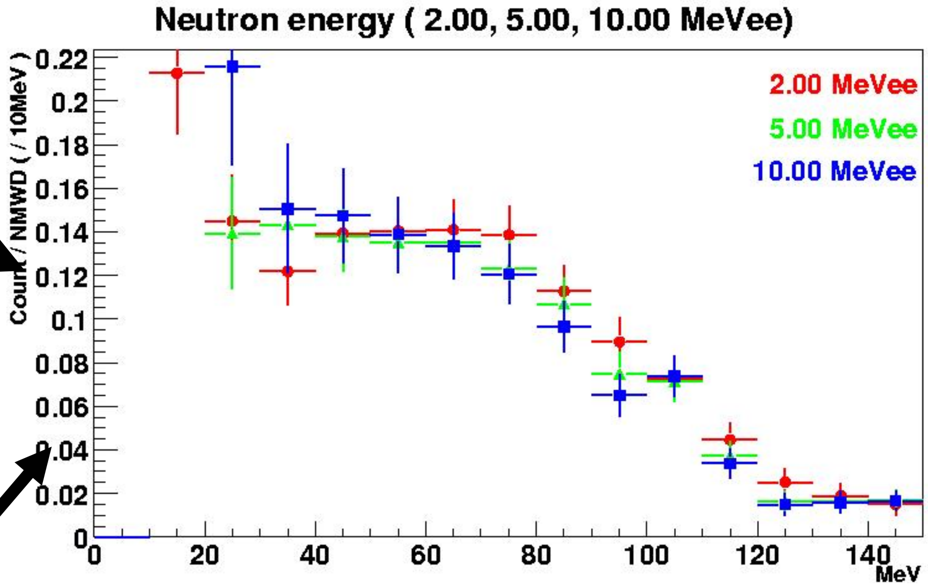
Simulated neutron detection efficiency



2MeVee

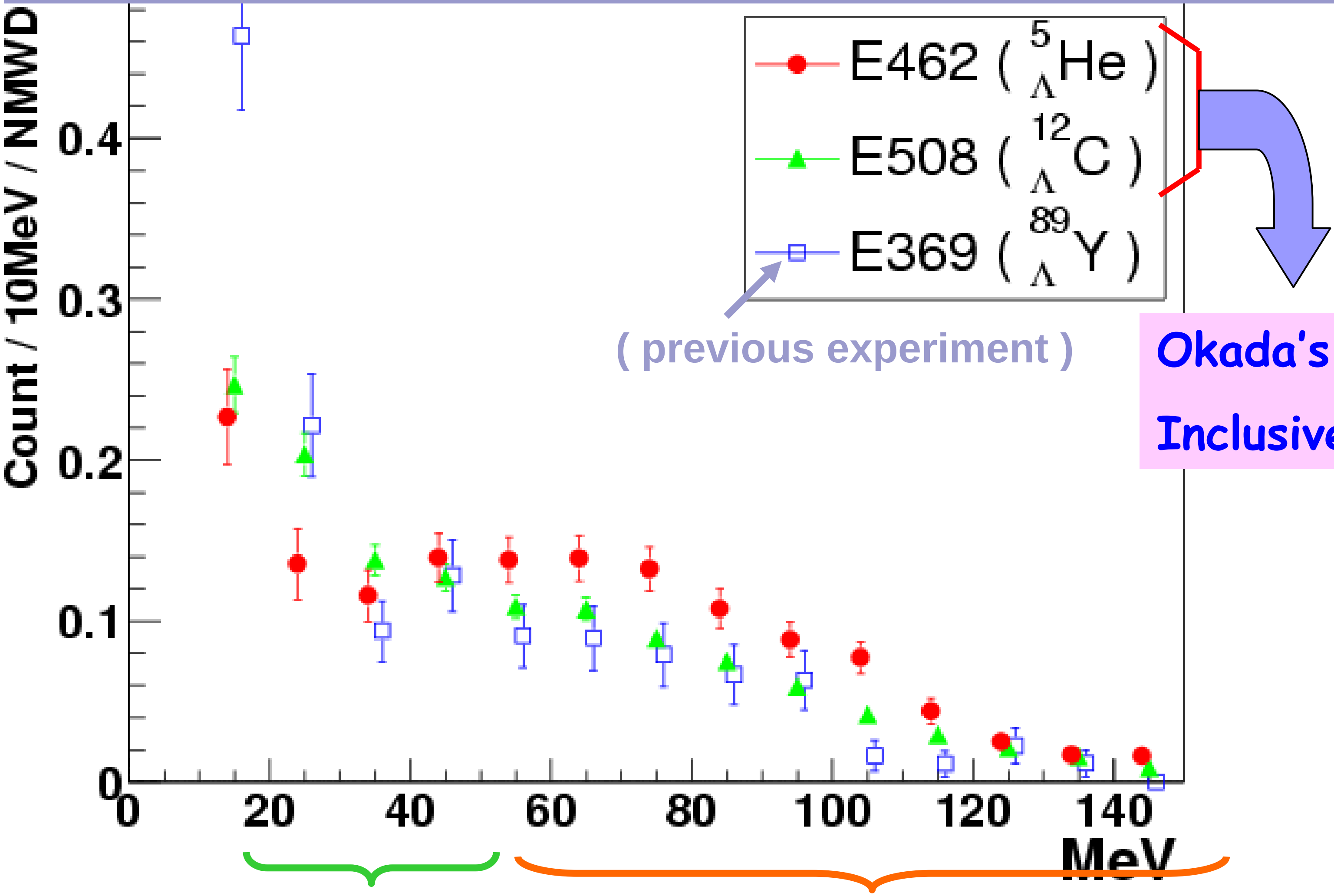
5MeVee

10MeVee



Threshold control is worked well.

Mass number dependence of neutron energy spectra (A=5,12,89)



(previous experiment)

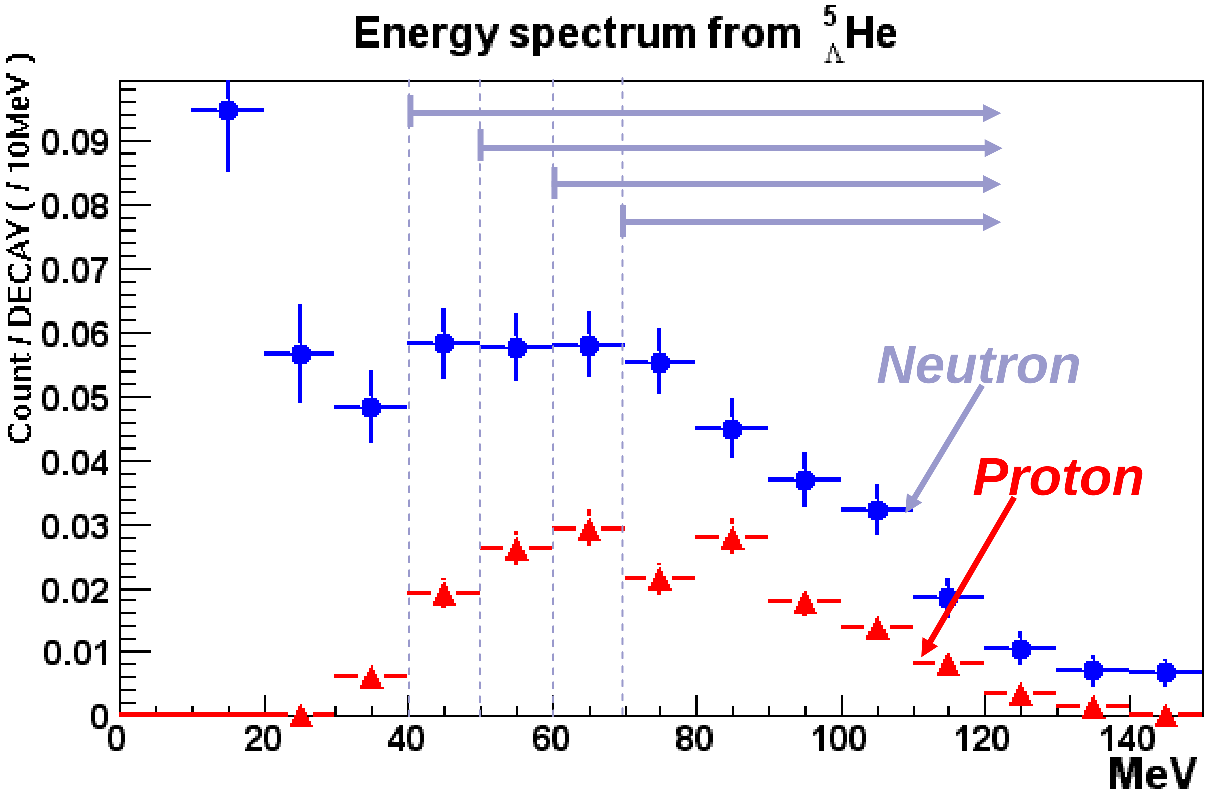
Okada's Poster;

Inclusive analysis

As the mass number become lager, the number of neutron become lager in the low energy part, and smaller in the high energy part.

Neutron and Proton Energy spectra from $^{5}_{\Lambda}$He

N_n / N_p Ratio for $^{5}_{\Lambda}$He



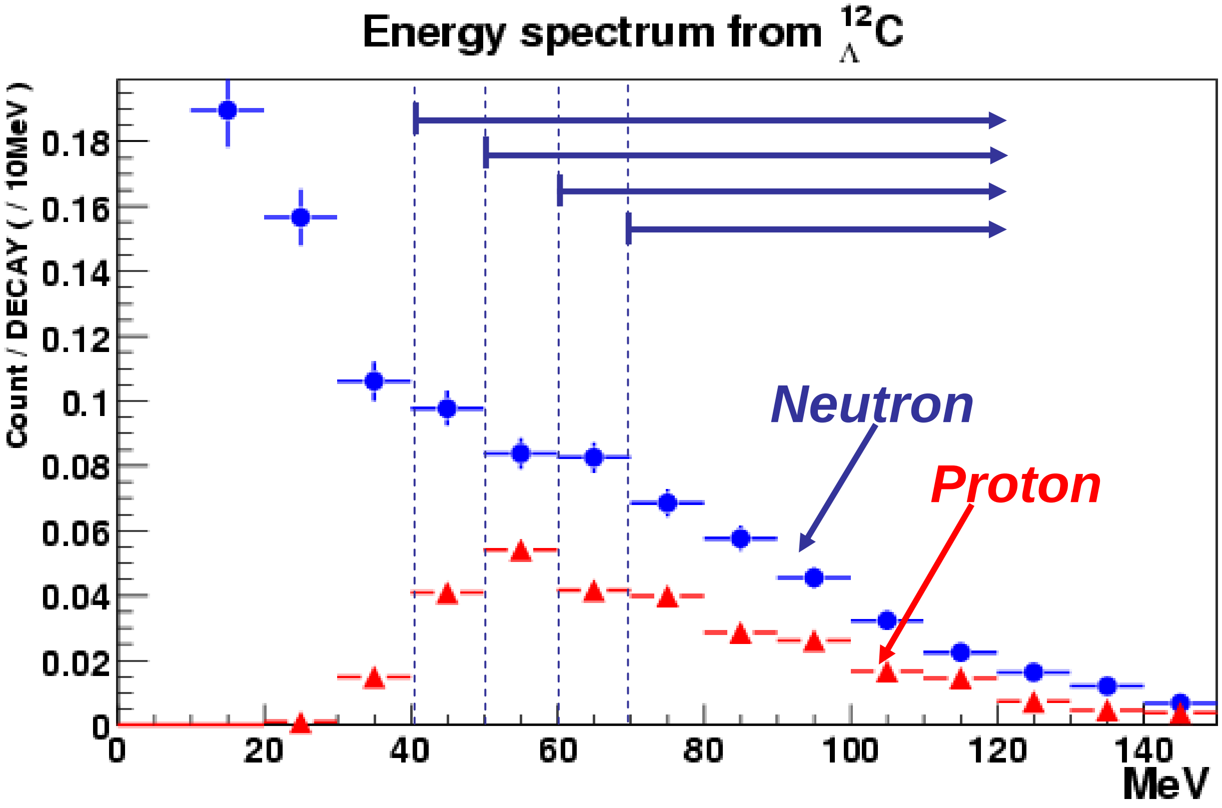
E>40MeV	2.29 ± 0.13
E>50MeV	2.20 ± 0.13
E>60MeV	2.20 ± 0.14
E>70MeV	2.27 ± 0.17

N_n / N_p (E>50MeV)
~ 2.20±0.13±0.15

systematic error :
efficiency(6%) + acceptance(3%)

Neutron and Proton Energy spectra from $^{12}_{\Lambda}C$

N_n / N_p Ratio for $^{12}_{\Lambda}C$



E>40MeV	1.89 ± 0.07
E>50MeV	1.80 ± 0.07
E>60MeV	1.89 ± 0.08
E>70MeV	1.85 ± 0.09

N_n / N_p (E>50MeV)
~ 1.80±0.07±0.12

systematic error :
efficiency(6%) + acceptance(3%)

Discussion

Similiarly to that of E307/E369, we can estimate Γ_n/Γ_p.

Again assuming 1N processes only in NMWD,

$$\frac{N_n}{N_p} \equiv \alpha = \frac{2 - r_p + r_p\beta}{(2 - r_p)\beta + r_p}$$

where α=1.80, β=(0.067~0.10).

We get $\frac{\Gamma_n}{\Gamma_p} = \frac{r_n}{r_p} = \frac{1 - r_p}{r_p} =$ **(0.49~0.55) from E508**

for $^{12}{}_{\Lambda}$C (E508) → $\Gamma_n/\Gamma_p(^{12}{}_{\Lambda}C)$ = (0.49~0.55) ± 0.10.

Similarly, for $^{5}{}_{\Lambda}$He (E462) → $\Gamma_n/\Gamma_p(^{5}{}_{\Lambda}He)$ = (0.66~0.69) ± 0.12.

↔ **(0.45~0.51)±0.15 from E307/E369.**

Asymmetry (Maruta's Parallel talk)

- Another important Issue in NMWD study.
- When a hypernucleus polarized, weak decay particles have an asymmetric angular distribution. Namely,

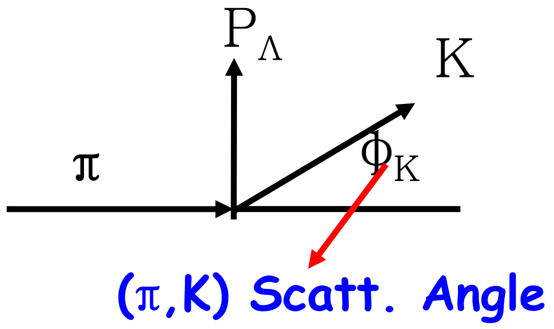
$$N(\Theta) = No\ (1 + P_\Lambda \alpha \cos\Theta)$$

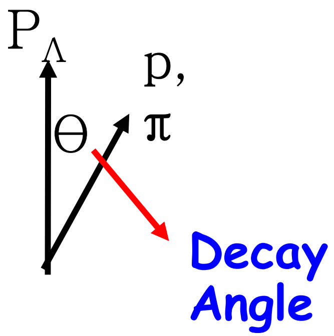
$$= No\ (1 + A \cos\Theta),$$

where P ; polarization of the hypernucleus,

A ; Asymmetry of the decay ang. dist.

α ; Asymmetry parameter.





- π mesonic Decay of Λ:

$$H_\pi = ig_w \overline{\psi_N}(1+\lambda\gamma_5)\tau\Psi_\Lambda\phi_\pi$$

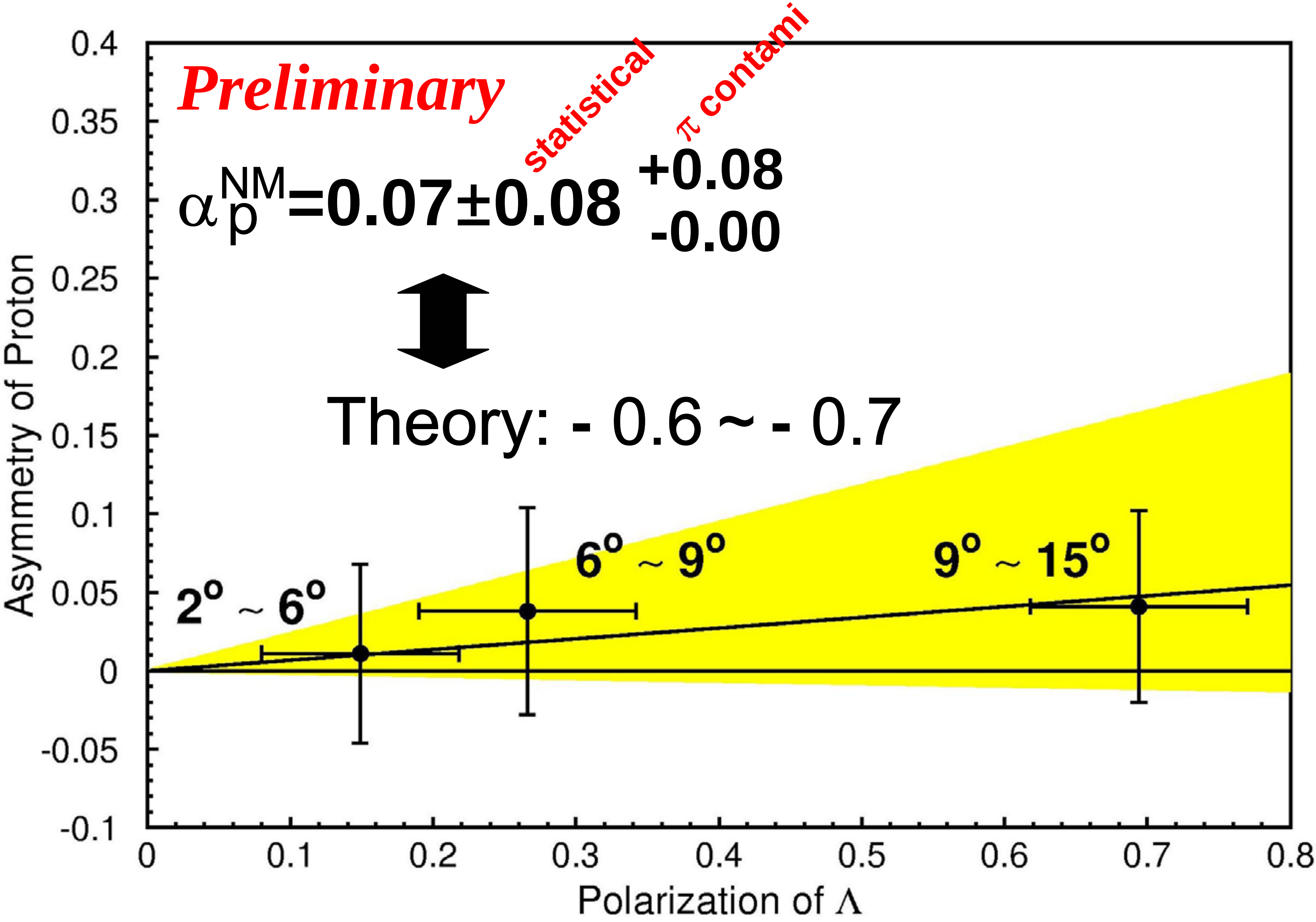
Asym. of π, A_π → $\alpha_\pi \equiv \alpha_m = -0.64$

→ $\lambda = -6.9$

- Nonmesonic Weak Decay ;

$$\alpha_{nm} = ?$$

Asymmetry parameter of $^{5}_{\Lambda}He$ (E462)

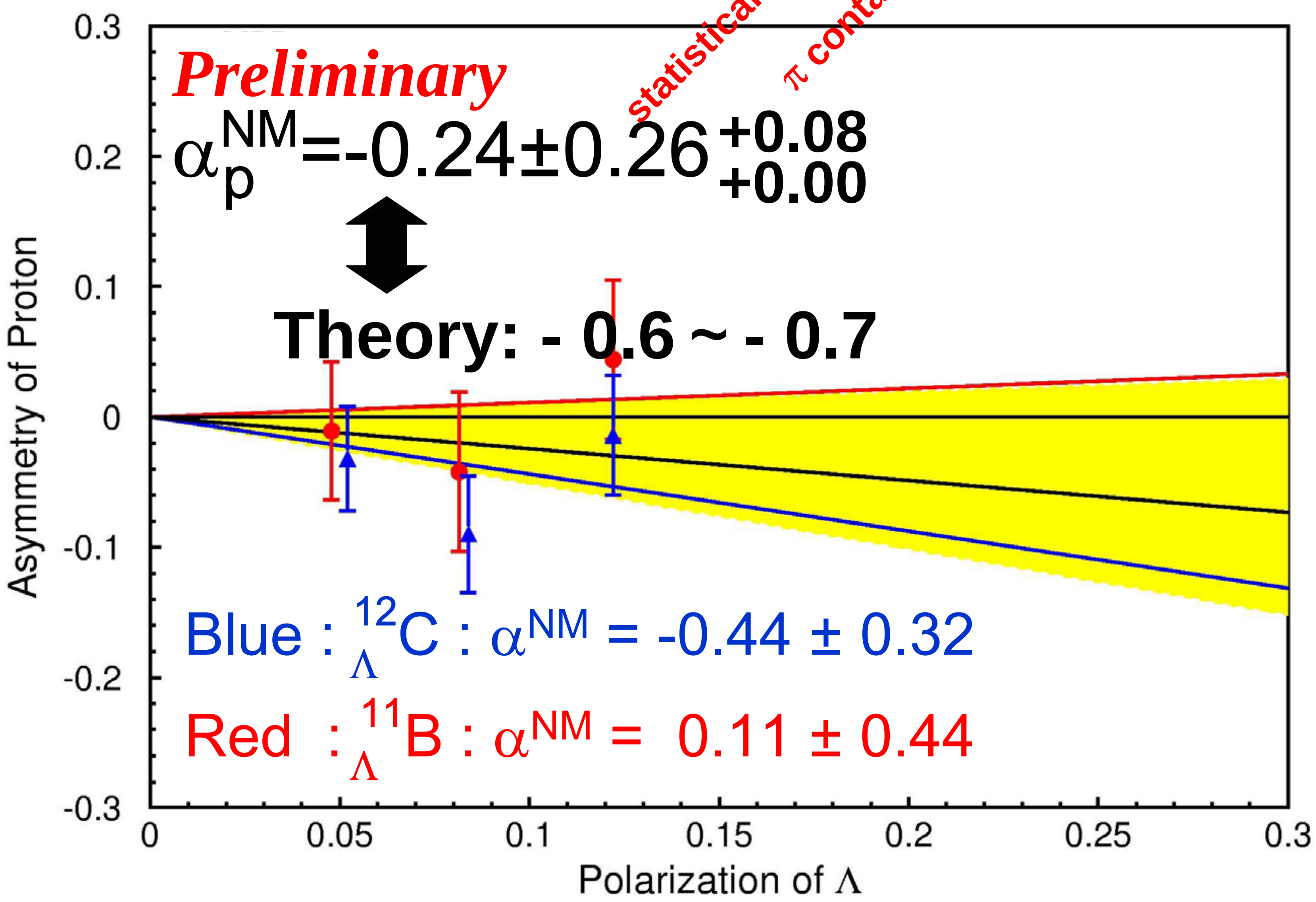


Preliminary

$\alpha_p^{NM} = 0.07 \pm 0.08 \, {}^{+0.08}_{-0.00}$

Theory: - 0.6 ~ - 0.7

Asymmetry parameter of $^{12}_{\Lambda}C$, $^{11}_{\Lambda}B$ (E508)



Preliminary

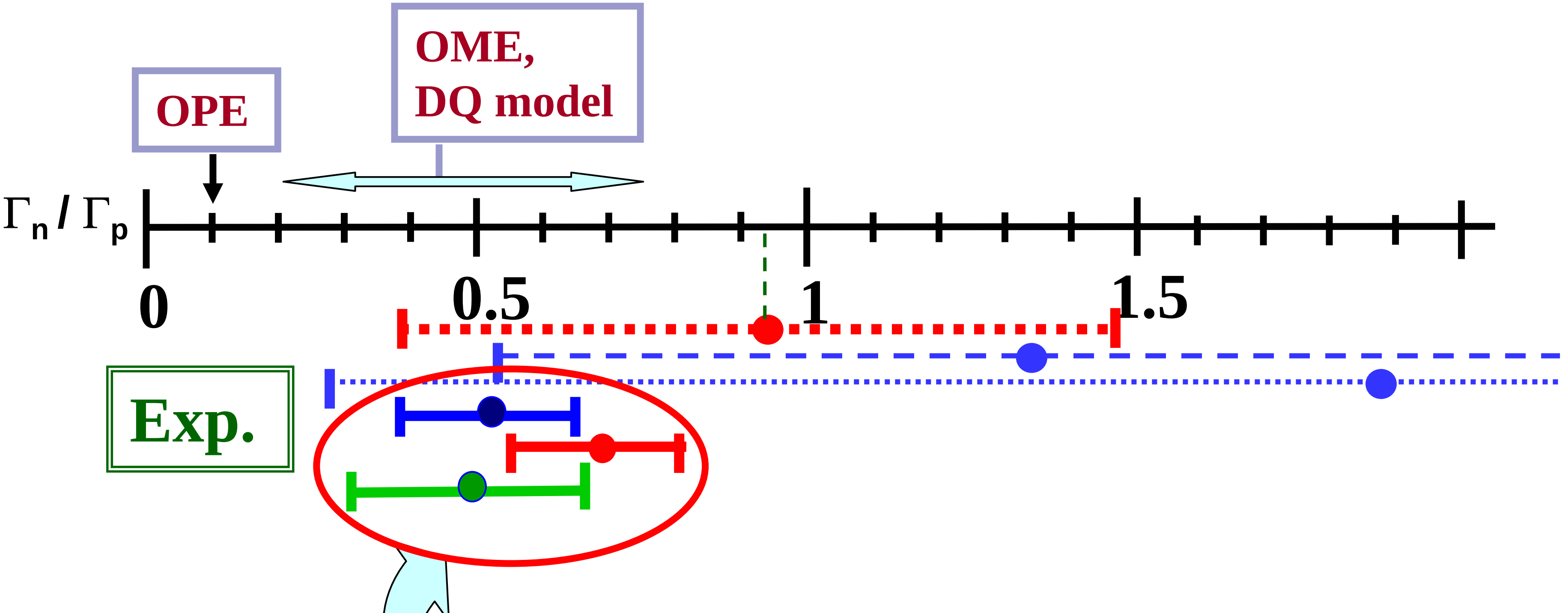
$$\alpha_p^{NM} = -0.24 \pm 0.26 ^{+0.08}_{+0.00}$$

Theory: - 0.6 ~ - 0.7

Blue : $^{12}_{\Lambda}C$: $\alpha^{NM} = -0.44 \pm 0.32$

Red : $^{11}_{\Lambda}B$: $\alpha^{NM} = 0.11 \pm 0.44$

Γ_n/Γ_p from Inclusive Yields



$^{5}_{\Lambda}$He : (0.66~0.69)±0.12 (E462)

$^{12}_{\Lambda}$C : (0.49~0.55)±0.10 (E508)

: (0.45~0.51)±0.15 (E307/E369)

Current Status of Γ_n/Γ_p

Theory

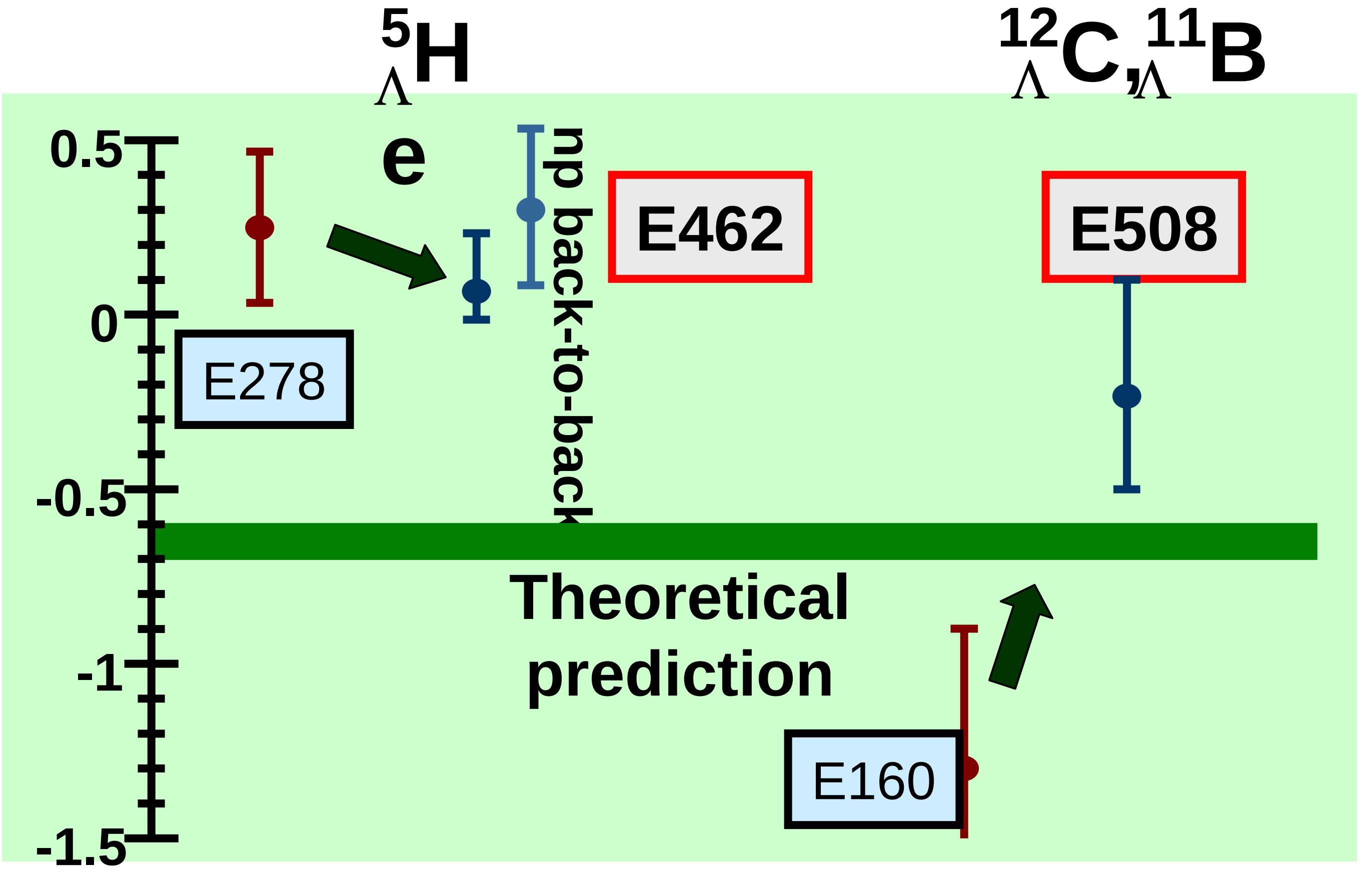
	N_{hyp}	$\Gamma n/\Gamma p$
sas02	$^{5}_{\Lambda}$He	0.70
Ito02	$^{5}_{\Lambda}$He	0.39
Gar03	$^{5}_{\Lambda}$He	0.46
Ose01	$^{12}_{\Lambda}$C	0.53
Ito03	$^{12}_{\Lambda}$C	0.57
Gar03	$^{12}_{\Lambda}$C	0.34

Experiment

	N_{hyp}	$\Gamma n/\Gamma p$
BNL	$^{5}_{\Lambda}$He	.93±0.55
	$^{12}_{\Lambda}$C	1.33±1.12/0.81
KEK'95	$^{12}_{\Lambda}$C	1.87±0.91/1.59
KEK (Sat02)	$^{12}_{\Lambda}$C	0.87±0.09±0.21 (1N) 0.60±0.11±0.23 (1N+2N)
KEK (Kim03)	$^{12}_{\Lambda}$C	(0.45~0.51)±0.14 (1N)
E462 (Inclusive)	$^{5}_{\Lambda}$He	(0.66~0.69)±0.12 (1N)
E508 (Inclusive)	$^{12}_{\Lambda}$C	(0.49~0.55)±0.10 (1N)

HYP03 Conf.

Comparison with recent results of a_{nm}



Asymmetry : The Γ_n/Γ_p puzzle seems resolved. However, the decay asymmetry which is one of the two basic observables in weak interaction study remains to be understood.

Summary

1. I have mainly focused on ΓnΓp puzzle issue.
2. Since last HYP00, a series of experiments have been done at KEK-PS using SKS kaon spectrometer. The Γn/Γp ratios from inclusive nucleon spectra converge to significantly smaller ratios, ~0.5.
3. The extraction of Γn/Γp ratio was done simply using the nucleon number ratio, Nn/Np, of the inclusive spectra, but with the "1N(ΛN→NN) only" assumption. An inclusion of 2N process tends to decrease the ratio.
4. Pinning down Γn/Γp further will require understanding of 2N process and also of FSI better. Exclusive coincidence measurement is necessary for this purpose. (→ Next Dr. Outa's talk)
5. As long as Γn/Γp ratio concerned, the experimental and theoretical ratios now well agree to each other. However, αnm remains inconsistent between those of experiment and theory.

KEK-PS E462/508 collaboration

KEK, RIKEN, Seoul Univ., GSI,
Tohoku Univ., Osaka Univ., Univ. Tokyo
Osaka Elec. Comm. Univ.^{G} , Tokyo Inst. Tech.

S. Ajimura, K. Aoki, A. Banu, H. Bhang, T. Fukuda,
O. Hashimoto, J. I. Hwang, S. Kameoka, B. H. Kang,
E. H. Kim, J. H. Kim, M. J. Kim, T. Maruta, Y. Miura,
Y. Miyake, T. Nagae, M. Nakamura, S. N. Nakamura,
H. Noumi, S. Okada, Y. Okatasu, H. Outa, H. Park,
P. K. Saha, Y. Sato, M. Sekimoto, T. Takahashi,
H. Tamura, K. Tanida, A. Toyoda, K.Tsukada,
T. Watanabe, H. J. Yim

More results and Puzzles coming.

Stay tuned!

Extra slides

Status

•The neutron spectra from NMWD of He and C measured accurately with only a few % of statistical error.

- Γ_n/Γ_p ratios from Singles spectrum (with 1N assumption);

obtained the ratio significantly less than unity from recent weak decay experiments,

Γn/Γp(5ΛHe) : (0.66~0.69) ± 0.12. (E462)
Γn/Γp(12ΛC) : (0.49~0.55) ± 0.10. (E508)
: (0.45~0.51) ± 0.15. (E307/E369)

\- Derived directly comparing n and p spectra model independent way.

- Asymmetry ; The Γn/Γp puzzle seems resolved. However, the decay asymmetry which is one of the two basic observables in weak interaction study remains to be understood.
- Ambiguity ; There still remains some ambiguity due to the FSI and 2N process in the inclusive singles analysis.

- Coincidence easurements
- $^{5}_{\Lambda}$He → E462
- $^{12}_{\Lambda}$C → E508

Summary

1.

2. The Γ_n/Γ_p values derived from the proton spectrum of C, Si and Fe are close to or somewhat smaller than unity. But the error bar was quite large.

   Difficulties in the measurements of Γ_n/Γ_p ;

   i) FSI → Light mass system prefered. (E462)

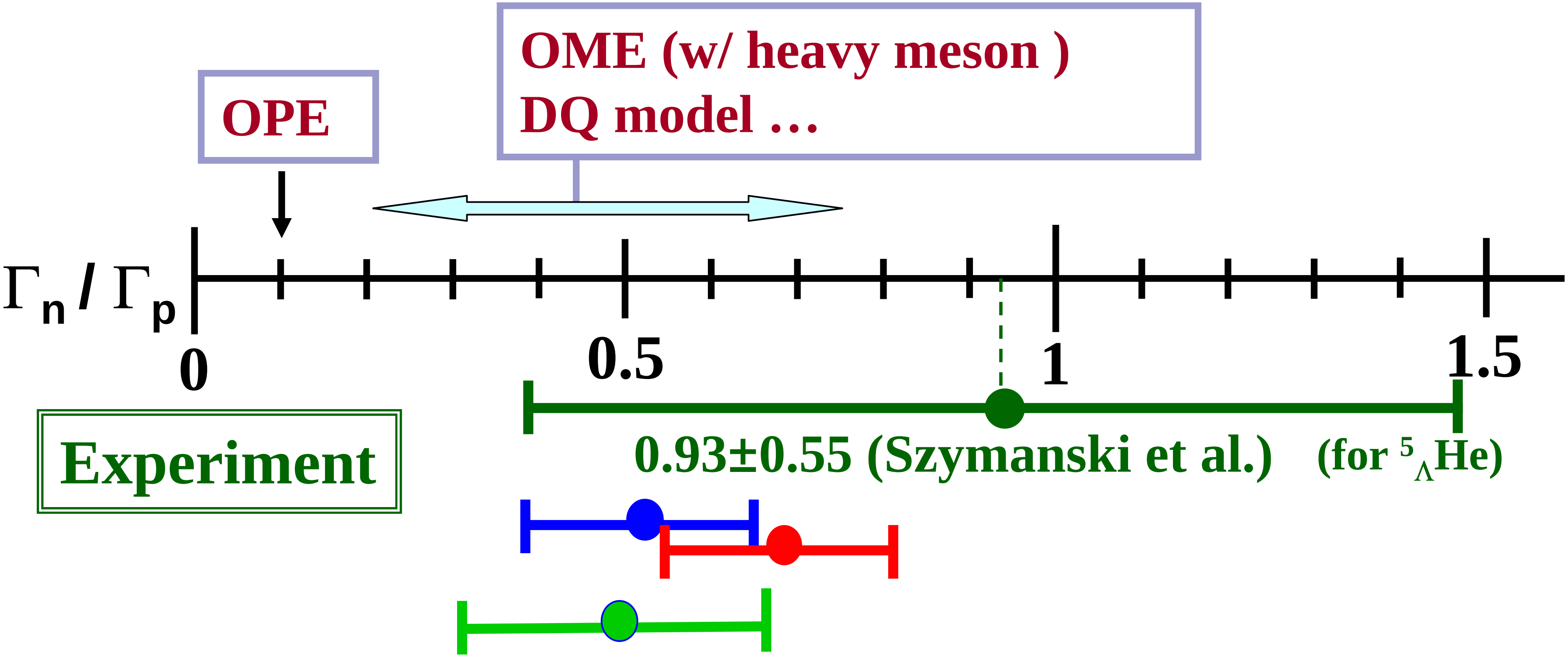
   ii) High Eth → n measurement. (E369)

3. The neutron spectrum
   - for 12ΛC with a greatly improved statistics and S/B ratio.
   - for a heavy Λ hypernucleus like 89ΛY is the first measured one.

4, Γn/Γp ratio
- the first experimental value significantly less than unity,

  ΓnΓp = (0.45~0.51)±0.14
- Obtained directly comparing the neutron and proton spectra without relying on a model calculation of FSI except for the estimation of the secondary cross over ratio into the high E region.

Γn/Γp from Singles Spectrum



OPE

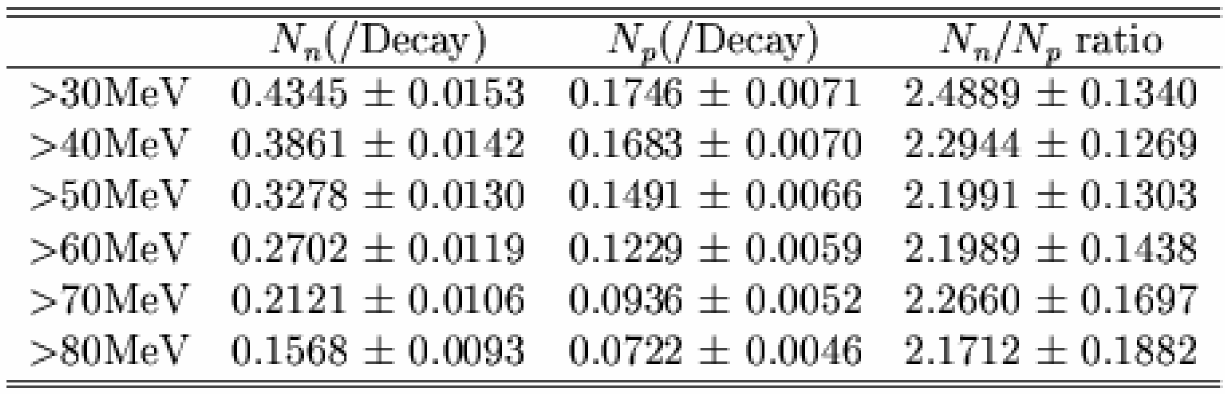
OME (w/ heavy meson)
DQ model …

Experiment

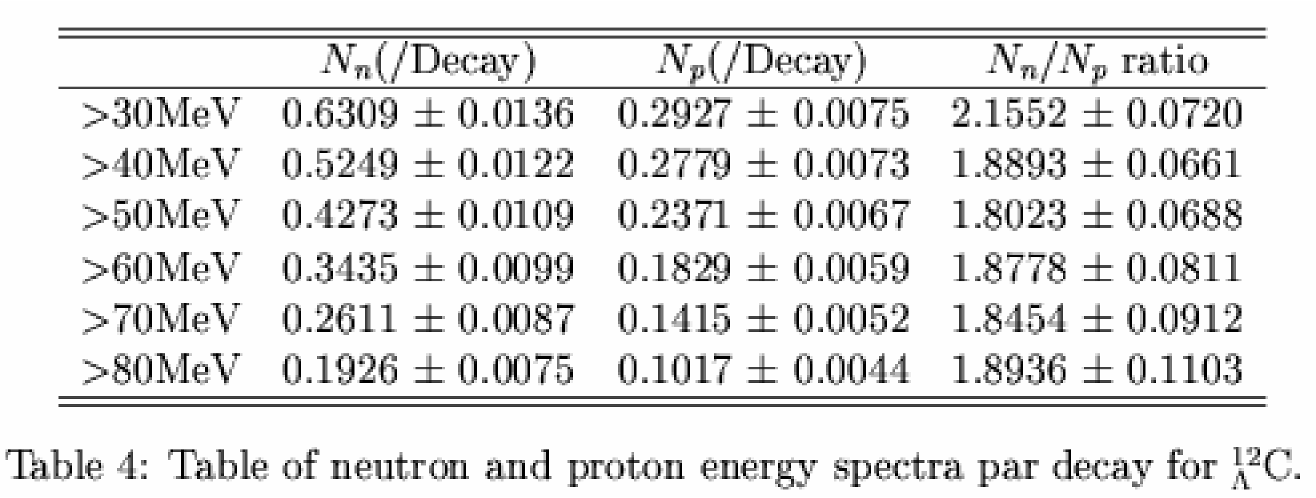
0.93±0.55 (Szymanski et al.) **(for $^{5}_{\Lambda}$He)**

$^{5}_{\Lambda}$He : (0.66~0.69)±0.12 (E462)
$^{12}_{\Lambda}$C : (0.49~0.55)±0.10 (E508)
: (0.45~0.51)±0.15 (E307/E369)

HY	source	α_{nm}	N_n >50	N_p >50	N_n/N_p	Γ_n/Γ_p	N_{nn}	N_{np}	N_{nn}/N_{np}	Γ_n/Γ_p
		Singles					Coincidence			
5He E462	Okada		0.341±.014	0.148±.007	2.20 ±.13 ±.15	(.66~.69) ±0.12	28	90		.47±.13 (<-.8)
	Kang		0.332±.013	0.150±.007	2.22±.13	Almost same as above	30	90		0.44+-0.11
	Maruta	.07±.08±.008/.0								
12C E508	E307/369		0.69	0.40	1.73±.22	(.45~.51) ±.15				
	Okada		.427	.237	1.80±.07±.12	(.49~.55) ±.10	33	117		.463±.11 (<-.8)
	Mijung		.441	.212	2.08±.09	(.66~.75) ±.10	36	101		.59±.13 (.59±.13)
	Maruta	-.24 ±.26±.08/.0								



	N_n(/Decay)	N_p(/Decay)	N_n/N_p ratio
>30MeV	0.4345 ± 0.0153	0.1746 ± 0.0071	2.4889 ± 0.1340
>40MeV	0.3861 ± 0.0142	0.1683 ± 0.0070	2.2944 ± 0.1269
>50MeV	0.3278 ± 0.0130	0.1491 ± 0.0066	2.1991 ± 0.1303
>60MeV	0.2702 ± 0.0119	0.1229 ± 0.0059	2.1989 ± 0.1438
>70MeV	0.2121 ± 0.0106	0.0936 ± 0.0052	2.2660 ± 0.1697
>80MeV	0.1568 ± 0.0093	0.0722 ± 0.0046	2.1712 ± 0.1882



	N_n(/Decay)	N_p(/Decay)	N_n/N_p ratio
>30MeV	0.6309 ± 0.0136	0.2927 ± 0.0075	2.1552 ± 0.0720
>40MeV	0.5249 ± 0.0122	0.2779 ± 0.0073	1.8893 ± 0.0661
>50MeV	0.4273 ± 0.0109	0.2371 ± 0.0067	1.8023 ± 0.0688
>60MeV	0.3435 ± 0.0099	0.1829 ± 0.0059	1.8778 ± 0.0811
>70MeV	0.2611 ± 0.0087	0.1415 ± 0.0052	1.8454 ± 0.0912
>80MeV	0.1926 ± 0.0075	0.1017 ± 0.0044	1.8936 ± 0.1103

Table 4: Table of neutron and proton energy spectra par decay for ${}^{12}_{\Lambda}$C.

The most recent results

1) Γ_p (E307)

- Measured the **Np/nm.**

  $N_p(E_p>40\ \mathrm{MeV})/nm \simeq 0.4$

- Compared with the INC (Ramos et al.)

  Best fit

  $\rightarrow \Gamma_n/\Gamma_p = 0.87 \pm 0.09 \pm 0.21$ **w/o** Γ_{2N}

  $\Gamma_n/\Gamma_p = 0.60 \pm^{0.11}_{0.09} \pm^{0.23}_{0.21}$ **w** Γ_{2N}

  where systematic error due to the FSI model is not included.

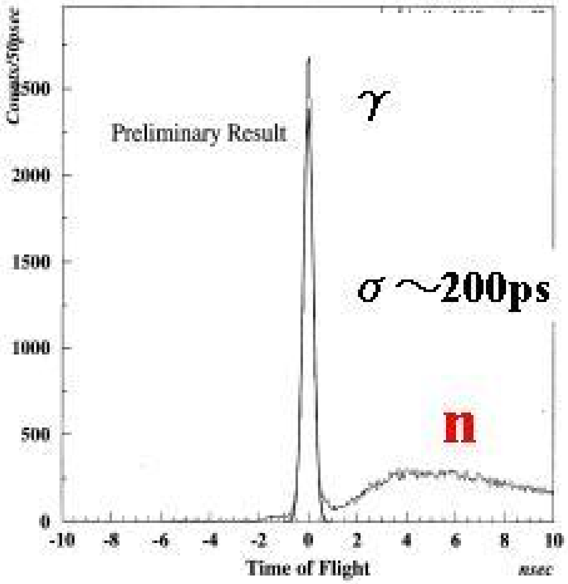
3. Neutron measurement：E369

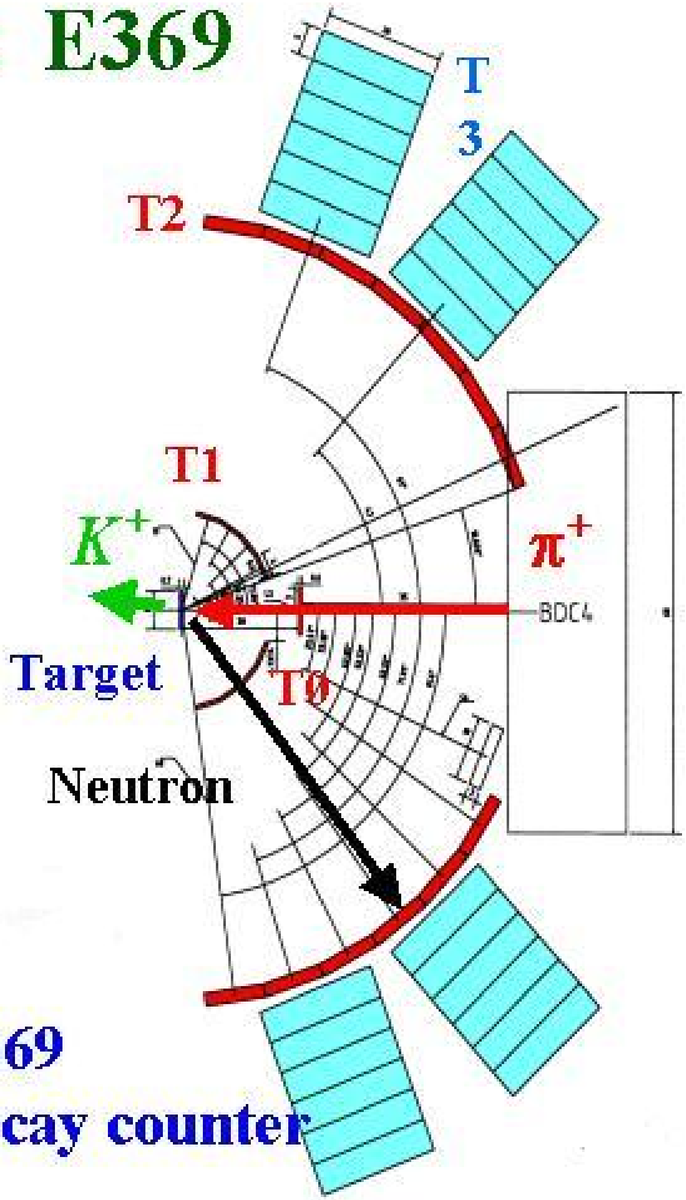
Experimental target: ^{12}C, ^{51}V and ^{89}Y

Observable:

- **Lifetime**
- **Branching ratios of charged particle**
- **Proton and neutron energy spectra**

n / γ separation by TOF method





E369
Decay counter

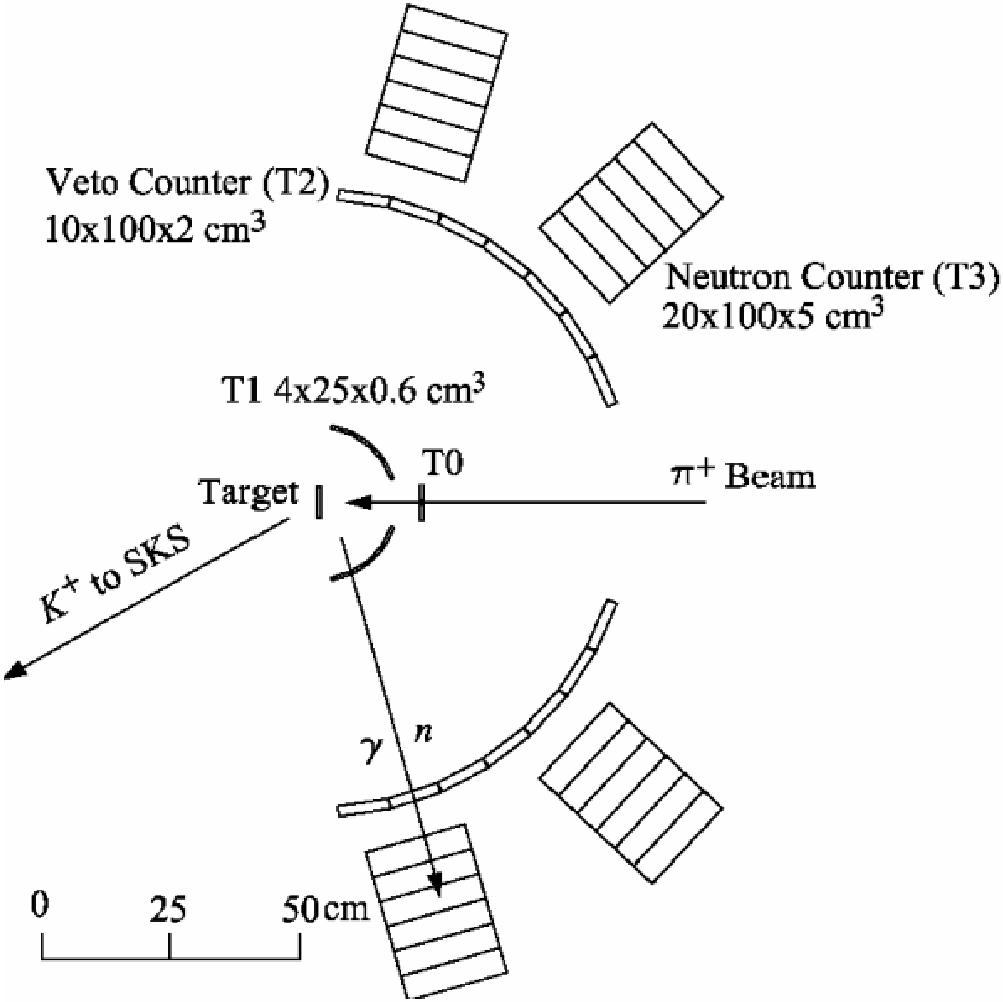
E369 Experiment/Setup

1. T0 ; before tatget

   T1, T2 ; After target

   T3 ; Neutron Counters (30cm)
2. Target thick ; 1.74 g/cm2
3. T3 acceptance ; 0.114

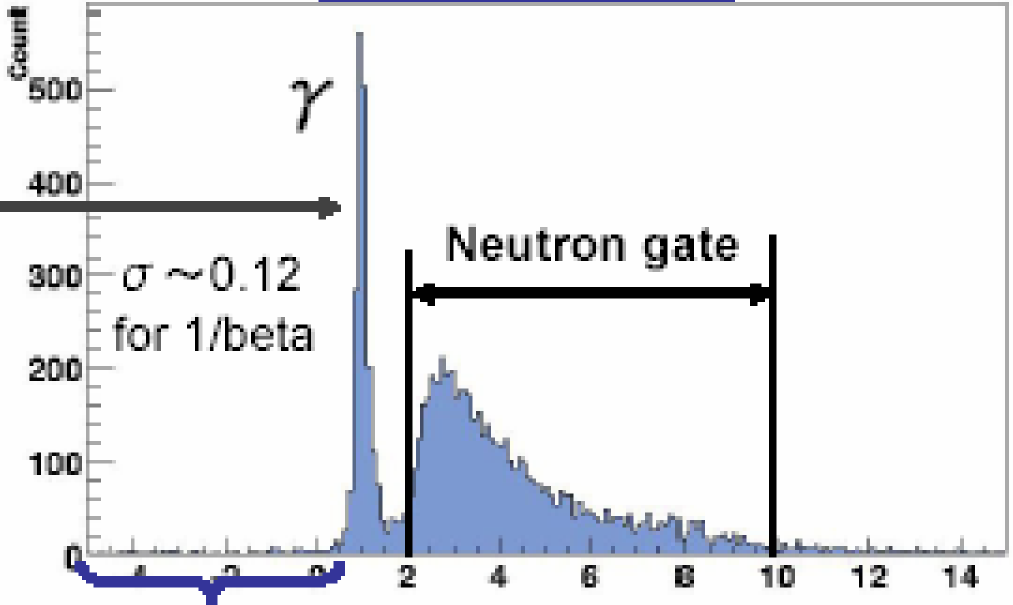
	A (cm2)	Thick (cm)	D (cm)	Seg.
T0	12x12	0.6	30	3
T1	48x25	0.6	15	8
T2	140x100	2.0	60	14
T3	80x100	30.0	68	4x6



Neutral particle identification

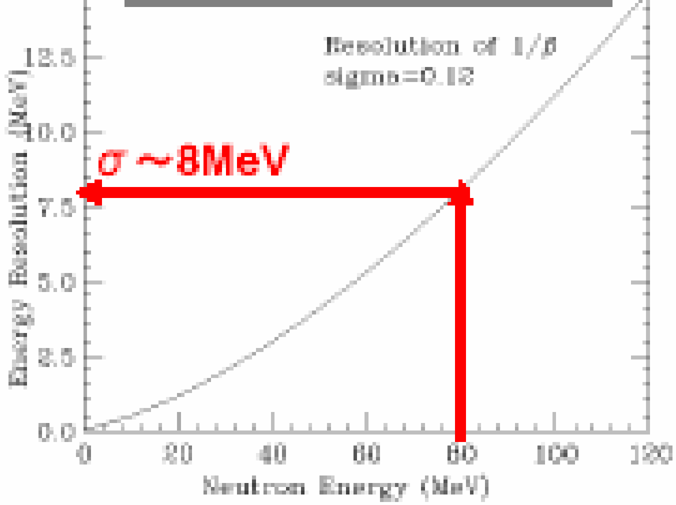
- ✓ Good γ n separation
- ✓ Good S/N ratio (~30)
- ✓ High statistics
  (~ 5000neutrons)

1 / β spectra



σ ~0.12
for 1/beta

Resolution
for neutron counter
σ ~8MeV
(around 80MeV)
width of γ peak



σ ~8MeV

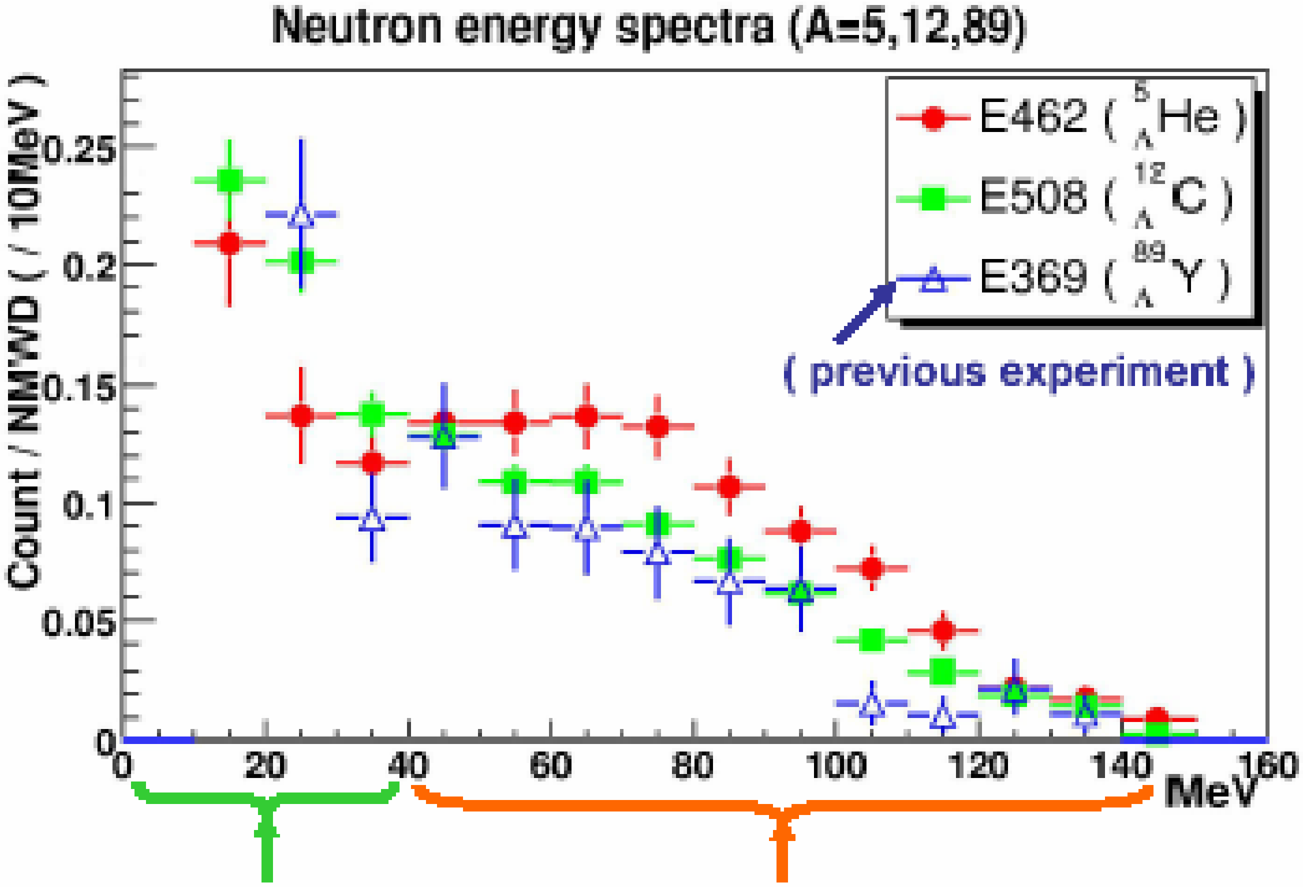
gated $^{12}{}_{\Lambda}C$ ground state

Constant
background
→ very small

decay mode 2γ

$\Lambda \to n\pi^0$ $\Lambda \to p\pi^-$	$\Lambda n \to nn$ $\Lambda p \to pn$

Mass number dependence of neutron energy spectra (A=5,12,89)



(previous experiment)

As the mass number become lager, the number of neutron become lager in the low energy part, and smaller in the high energy part.

Summary

1. Measured Lifetimes (Total width) are almost saturated at 12 C region to a value about 80% of the free lifetime. → Γnm

2. The Γ_n/Γ_p values derived from the proton spectrum of C, Si and Fe are close to or somewhat smaller than unity. But the error bar was quite large.
   Difficulties in the measurements of $\mathbf{\Gamma_n/\Gamma_p}$;
   i) FSI → Light mass system prefered. (E462)
   ii) High Eth → n measurement. (E369)

- The neutron spectrum:
  - for 12ΛC with a greatly improved statistics and S/B ratio.
  - for a heavy Λ hypernucleus like 89ΛY is the first measured one.

- Γn/Γp ratio
  - the first experimental value significantly less than unity,
    ΓnΓp = 0.45±0.14
  - Obtained directly comparing the neutron and proton spectra without relying on a model calculation of FSI except for the estimation of the secondary cross over ratio into the high E region.

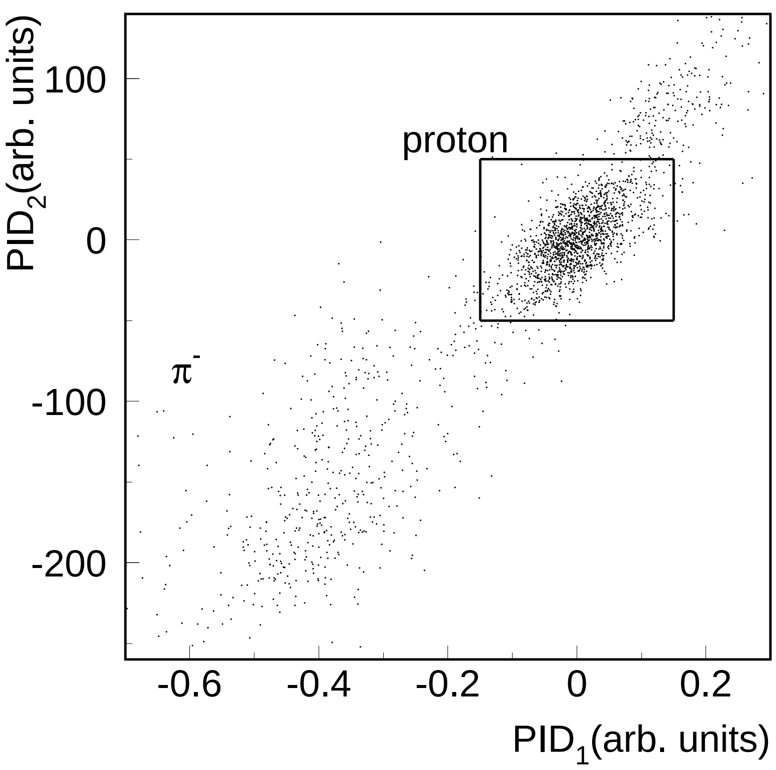
E307

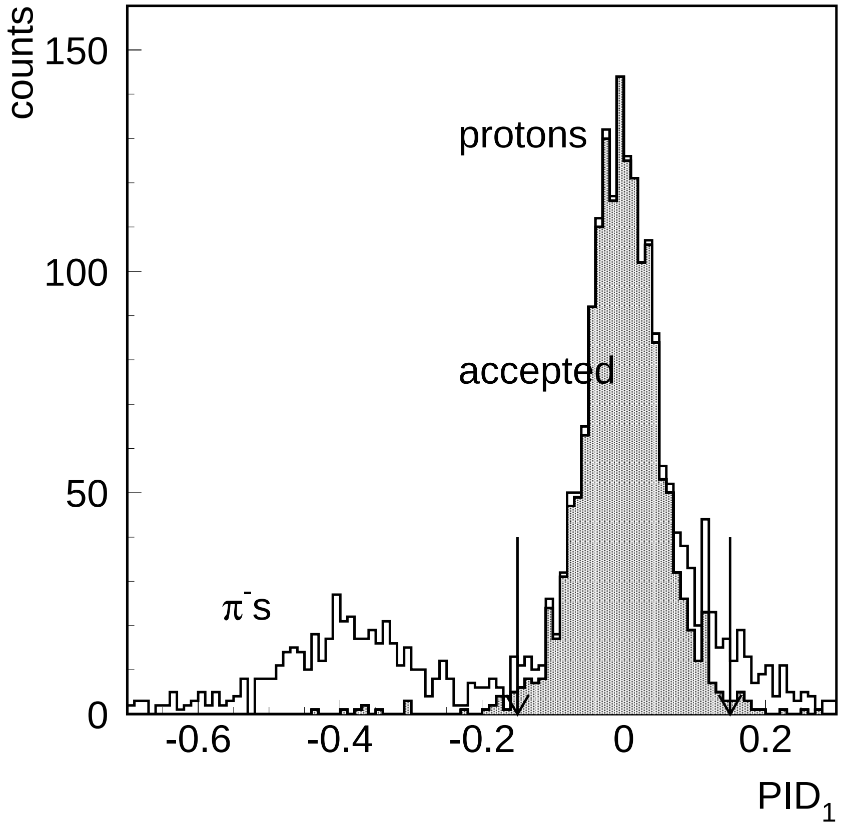
- C decay width status 의 테이블을 complete하게 만들것

Widths(Γ_Λ)	${}^{12}_{\Lambda}C$
Γ_t	1.25±0.18 [1] 1.14±0.08 [2]
Γ_{π^-}	0.14±0.07±0.025 [3] 0.113±0.013±0.005 [4]
Γ_{π^0}	0.217±0.073±0.011 [5]
Γ_m	0.33±0.075±0.012
Γ_n/Γ_p	
Γ_p	$0.31\pm0.07\pm^{0.11}_{0.04}$ [3] **0.43**±0.08 ±0.11* [6]
Γ_n	**0.38**±0.06 ±0.05 [1N]
Γ_{nm}	0.89±0.15±0.03 [3] 0.81±0.11±0.013
Γ_n/Γ_p	

1. R. Grace et al., PRL 55 (1985)
2. H. Bhang et al., PRL 81 (1998) 4323,
   H. Park et al., PRC 61 (2000) 054004
3. H. Noumi et al., PRC 52 (1995) 2936
4. Y. Sato et al., Nuc. Phys. A691 (2001) 189
5. Sakakuchi et al., PRC 43 (1991) 73
6.

Particle Identification





Discussion

1. Measured Lifetimes (Total width) are almost saturated at 12 C region to a value about 80% of the free lifetime.

2. The Γ_n/Γ_p values obtained for C, Si and Fe are close to or somewhat smaller than unity. But the error bar is still large.

3. Difficulties in the measurements of $\mathbf{\Gamma_n/\Gamma_p}$;
    - i) FSI → Light mass system prefered. (E462)
    - ii) High Eth → n measurement. (E369)

α dependence ;

- α value **depends on the model** calculation of FSI.
- In order to see the sensitivity on α, we can extract a value from the INC calculation of Ramos et al. ; α =0.11 which is 50% bigger value.
- With this 50 % higher α value, the Γn /Γp value is 0.51 compared to 0.45 with the α = 0.076. This weaker sensitivity on the model calculation is due the fact that the INC value is used only for the correction of the secondary effect, namely for the cross over recoil nucleons.

Discussion

- The neutron spectrum:
  - for ${}^{12}{}_{\Lambda}C$ with a greatly improved statistics and S/B ratio.
  - for a heavy Λ hypernucleus like ${}^{89}\Lambda Y$ is the first measured one.

- Γ_n/Γ_p ratio
  - the first experimental value significantly less than unity,

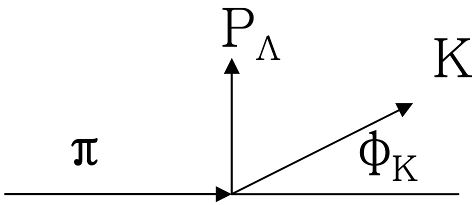
    $$\Gamma_n\Gamma_p = (0.45\sim0.51)\pm0.15$$

  - Obtained directly comparing the neutron and proton spectra without relying on a model calculation of FSI except for the estimation of the secondary cross over ratio into the high E region.

- **Asymmetry** : Now the experimental and theoretical values for ΓΓ are in good agreement. The GG puzzle seems resolved. However, the decay asymmetry which is one of the two basic observables in weak interaction study remains to be understood. There also remains some ambiguity due to the 2N process.

Asymmetry

- When the hypernucleus is polarized,
  the weak decay particles have an asymmetric angular distribution.
  Namely,

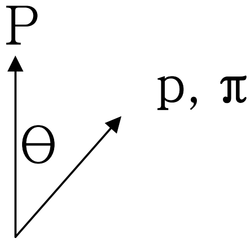


$$N(\Theta) = N_o(1+P\alpha\cos\Theta)$$
$$= N_o(1+A\cos\Theta),$$

where P ; polarization of the hypernucleus,

A ; Asymmetry of the decay ang. dist.

α ; Asymmetry parameter.

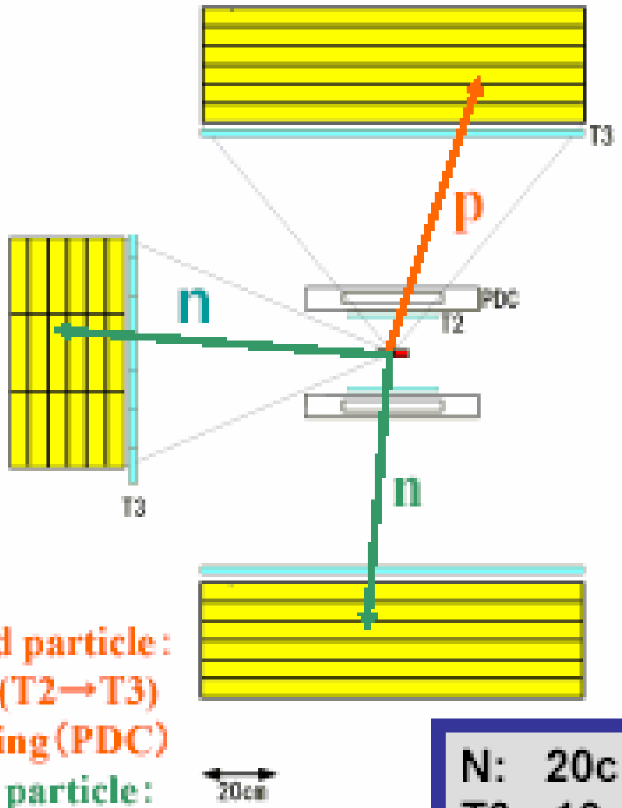


Setup (E462)

(KEK-PS K6 beamline & SKS)

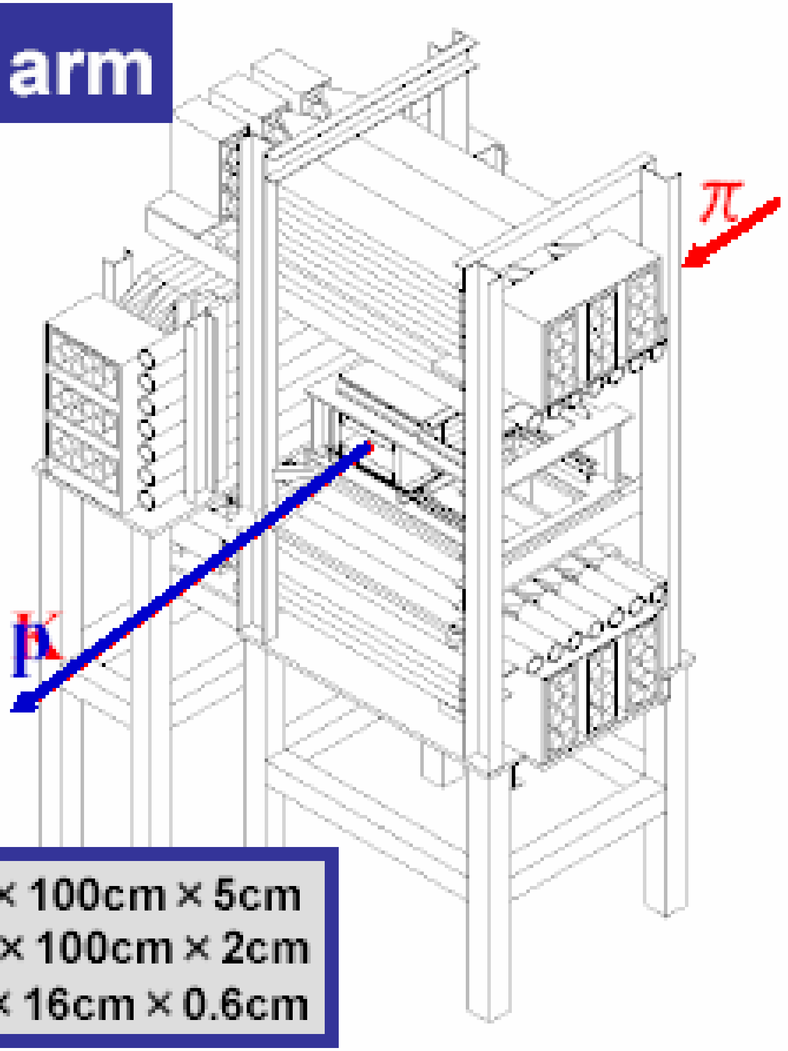
Decay arm

Solid angle: 26%
9(T)+9(B)+8(S)%



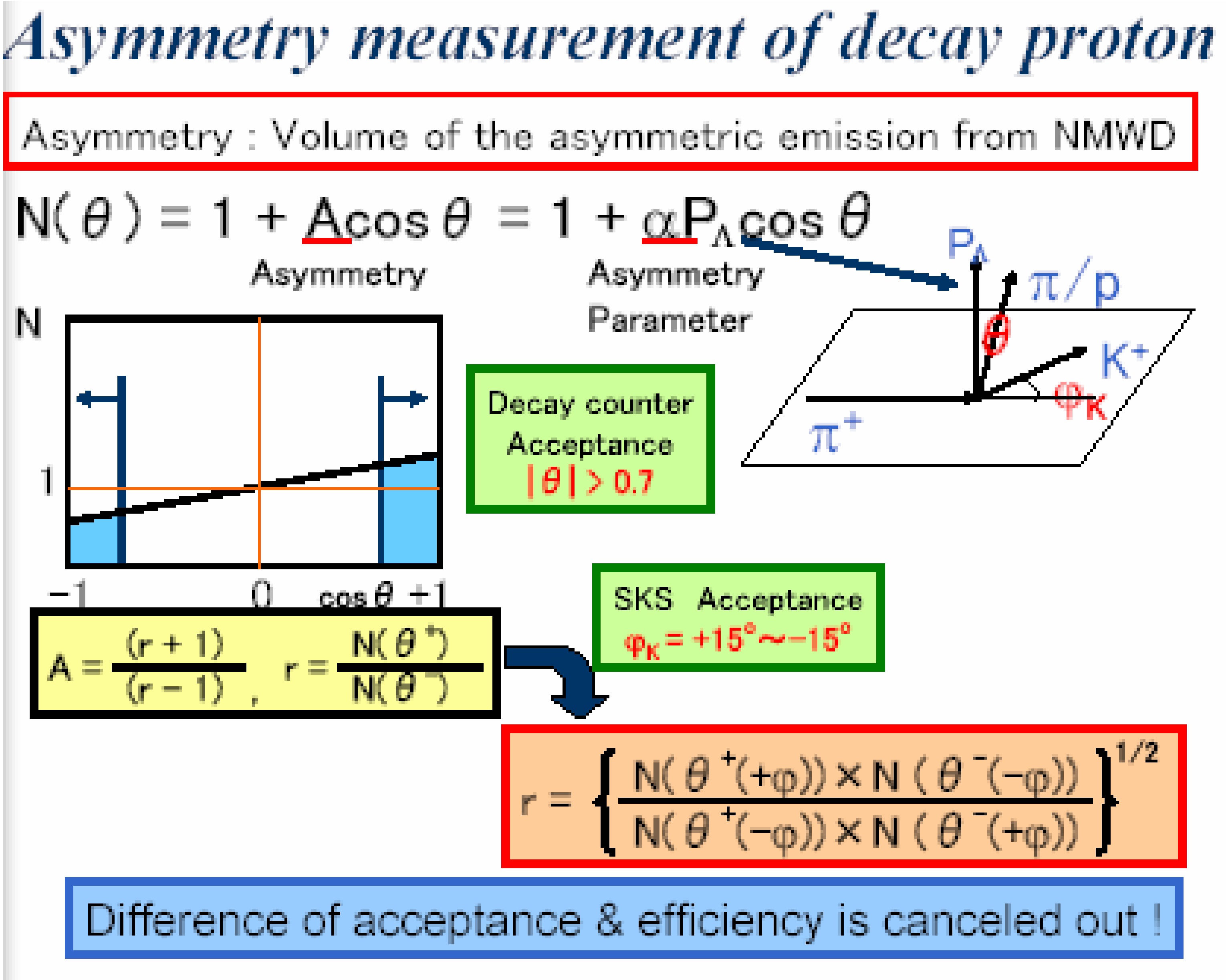
Charged particle:
- TOF (T2→T3)
- tracking (PDC)

Neutral particle:
- TOF (target→NT)
- T2/T3 VETO



N: 20cm × 100cm × 5cm
T3: 10cm × 100cm × 2cm
T2: 4cm × 16cm × 0.6cm

4. Asymmetry



Asymmetry measurement of decay proton

Asymmetry : Volume of the asymmetric emission from NMWD

$$N(\theta) = 1 + \underline{A}\cos\theta = 1 + \underline{\alpha}P_\Lambda\cos\theta$$

Asymmetry

Asymmetry Parameter

Decay counter Acceptance
$|\theta| > 0.7$

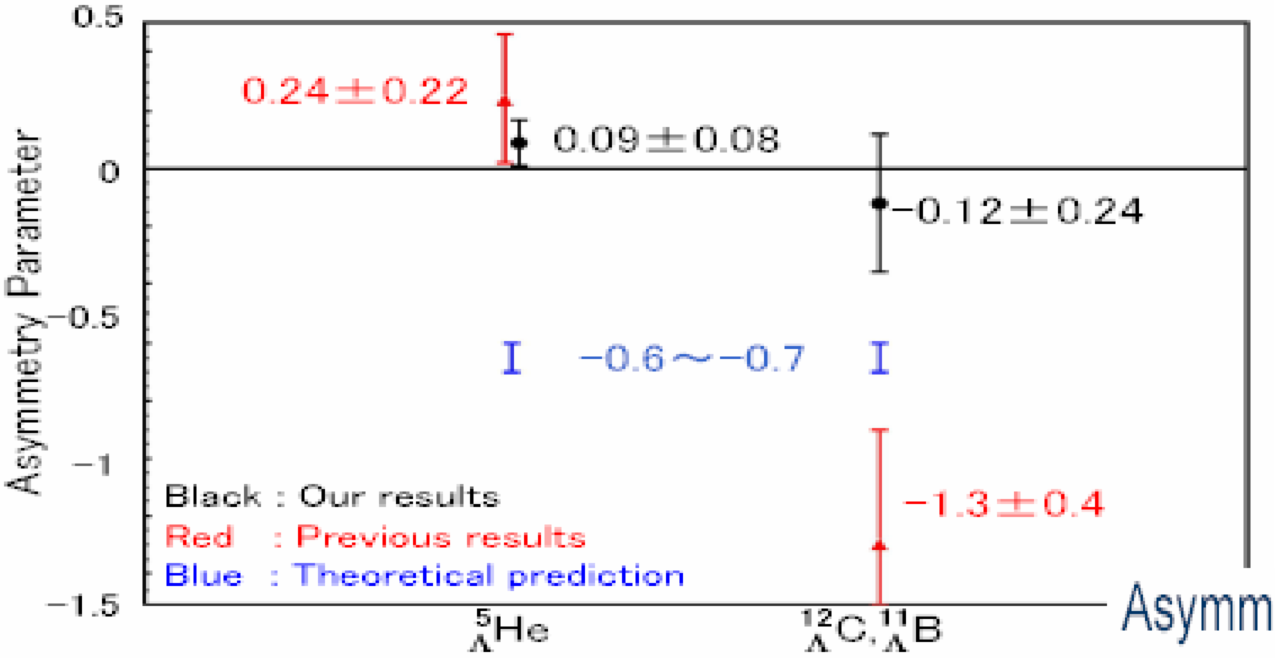
$$A = \frac{(r+1)}{(r-1)}, \quad r = \frac{N(\theta^+)}{N(\theta^-)}$$

SKS Acceptance
$\varphi_K = +15^\circ \sim -15^\circ$

$$r = \left\{ \frac{N(\theta^+(+\varphi)) \times N(\theta^-(-\varphi))}{N(\theta^+(-\varphi)) \times N(\theta^-(+\varphi))} \right\}^{1/2}$$

Difference of acceptance & efficiency is canceled out !

Comparison with recent results



Asymmetry parameter of NMWD

– s-shell($^{5}_{\Lambda}$He : E462) → 0.09±0.08

(E278 : 0.24±0.22)

– p-shell($^{12}_{\Lambda}$C, $^{11}_{\Lambda}$B : E508) → -0.12±0.24

↕ Large discrepancy

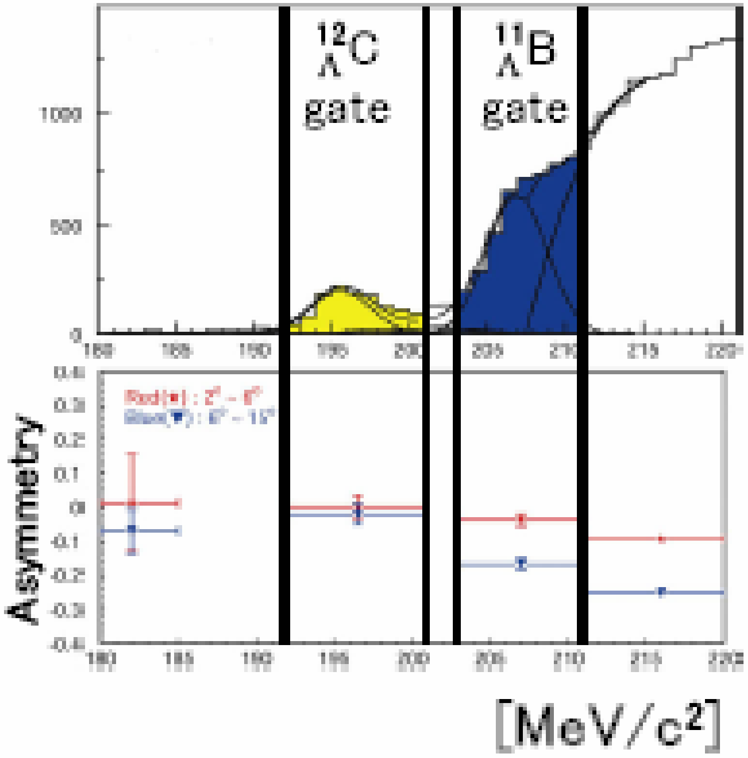
(E160 : -1.3±0.4)

Theoretical prediction (s/p-shell hypernuclei) → -0.6 ~-0.7

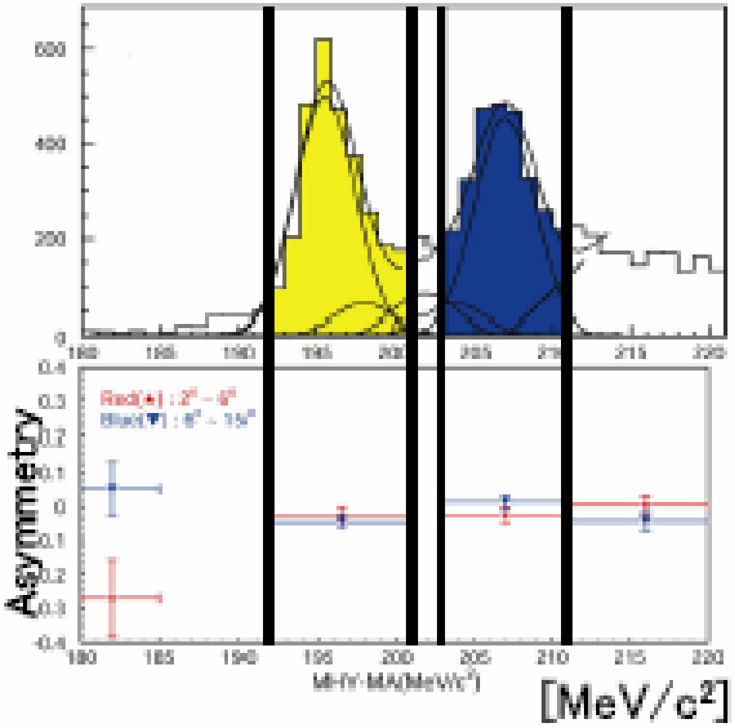
Asymmetry of p-shell hypernuclei

Estimation of the contamination
from other energy levels .

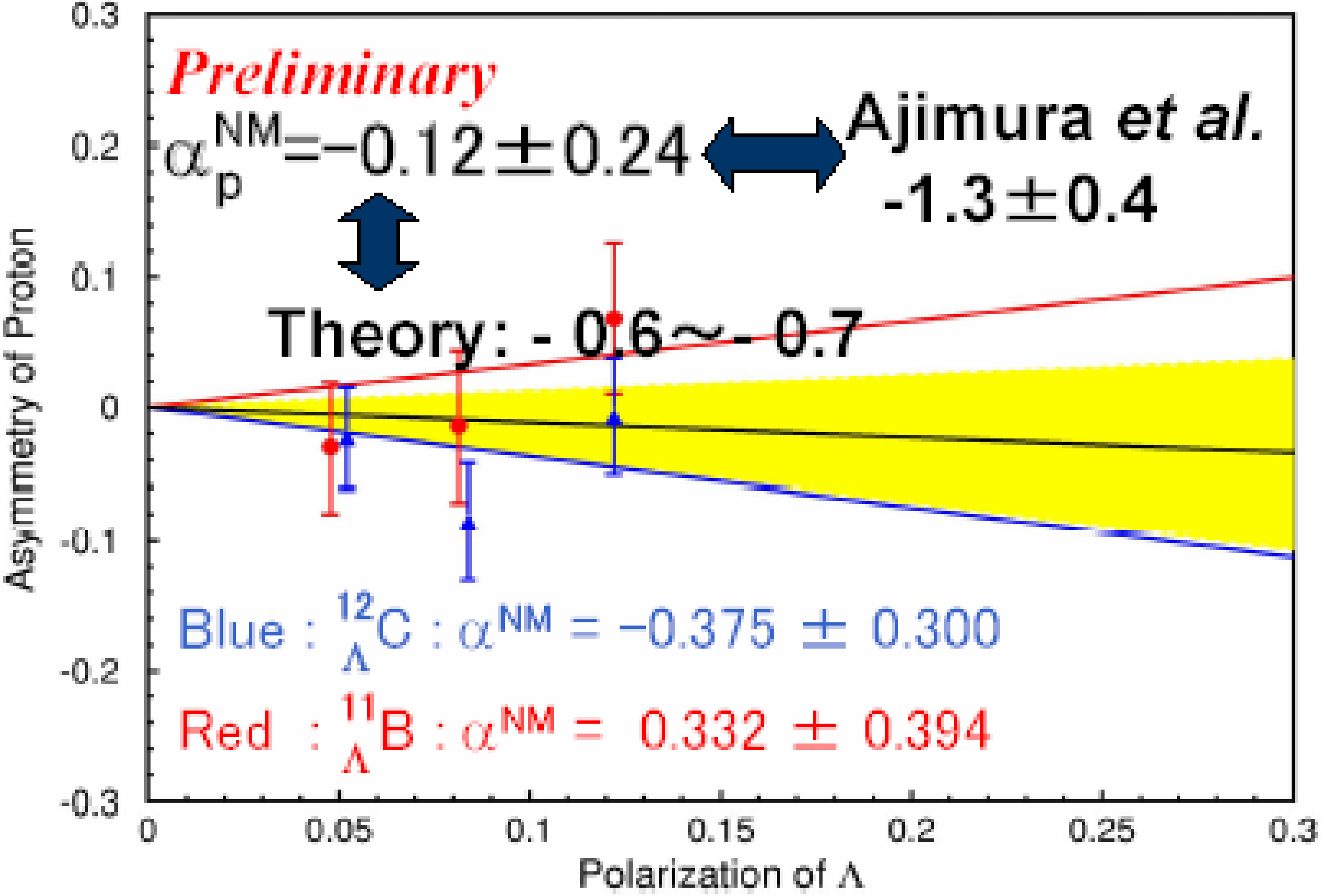
Pion coincidence



Proton coincidence



Asymmetry parameter of ${}^{12}_{\Lambda}C, {}^{11}_{\Lambda}B$



Preliminary

$\alpha_p^{NM} = -0.12 \pm 0.24$ ⟷ Ajimura *et al.* -1.3 ± 0.4

Theory: - 0.6～- 0.7

Blue : ${}^{12}_{\Lambda}C$: $\alpha^{NM} = -0.375 \pm 0.300$

Red : ${}^{11}_{\Lambda}B$: $\alpha^{NM} = 0.332 \pm 0.394$

Γn/Γp ratio

Model Independent Analysis

- Now we have both neutron and proton spectrua.
  It is desirable to estimate the Γ_n/Γ_p ratio directly from
  the experimental data.
- Consider NMWD 1N process only ; $r_n + r_p = 1$,
- Yields ;

$$Y_n = N_{nm}(2 - r_p)\Omega_n \varepsilon_n f_n \qquad 2 - r_p = 2\,r_n + r_p$$

$$Y_p = N_{nm} r_p \Omega_p \varepsilon_p f_p$$

Where Y ; Yields above E_{th} (~ 40 MeV)

r_p ; The fraction of the p channel out of the NMWD

$r_p + r_n = 1$ if 1N process only.

f_n, f_p ; FSI factors

- The neutron (proton) number per NMWD for full solid angle
  and $\varepsilon = 1$.

$$N_n = \frac{Y_n}{N_{nm}\Omega_n \varepsilon_n} = (2 - r_p) f_n$$

$$N_n = \frac{Y_n}{N_{nm}\Omega_p \varepsilon_p} = f_p r_p$$

- Since we have
  > the high threshold energy
  > Isospin independence of Strong Int.
  > Isospin symmetric propagation medium ; ${}^{12}_{\Lambda}C$

--> Assume $f_n = f_p = f$.

- Assume $f_n = f_p = f$.

$$\frac{N_n}{N_p} = \frac{2-r_p}{r_p} = \frac{0.69}{0.40} = 1.73$$

$$\frac{\Gamma_n}{\Gamma_p} = \frac{r_n}{r_p} = 0.36 \quad \ll 1$$

Much small than 1.

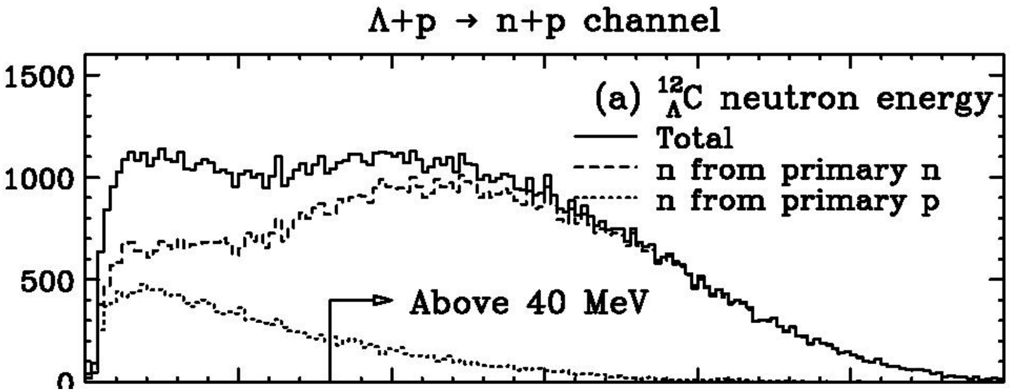
- However the effects of the cross over Secondary Events exist.

$$N_n = (2-r_p)f + r_p g$$
$$N_p = (2-r_p)g + r_p f$$

Therefore

$$\frac{N_n}{N_p} = \frac{2-r_p+r_p\beta}{(2-r_p)\beta+r_p} = \alpha$$

Where $\beta = \frac{g}{f} \simeq 0.076$



-

$$\therefore r_p = 0.688$$

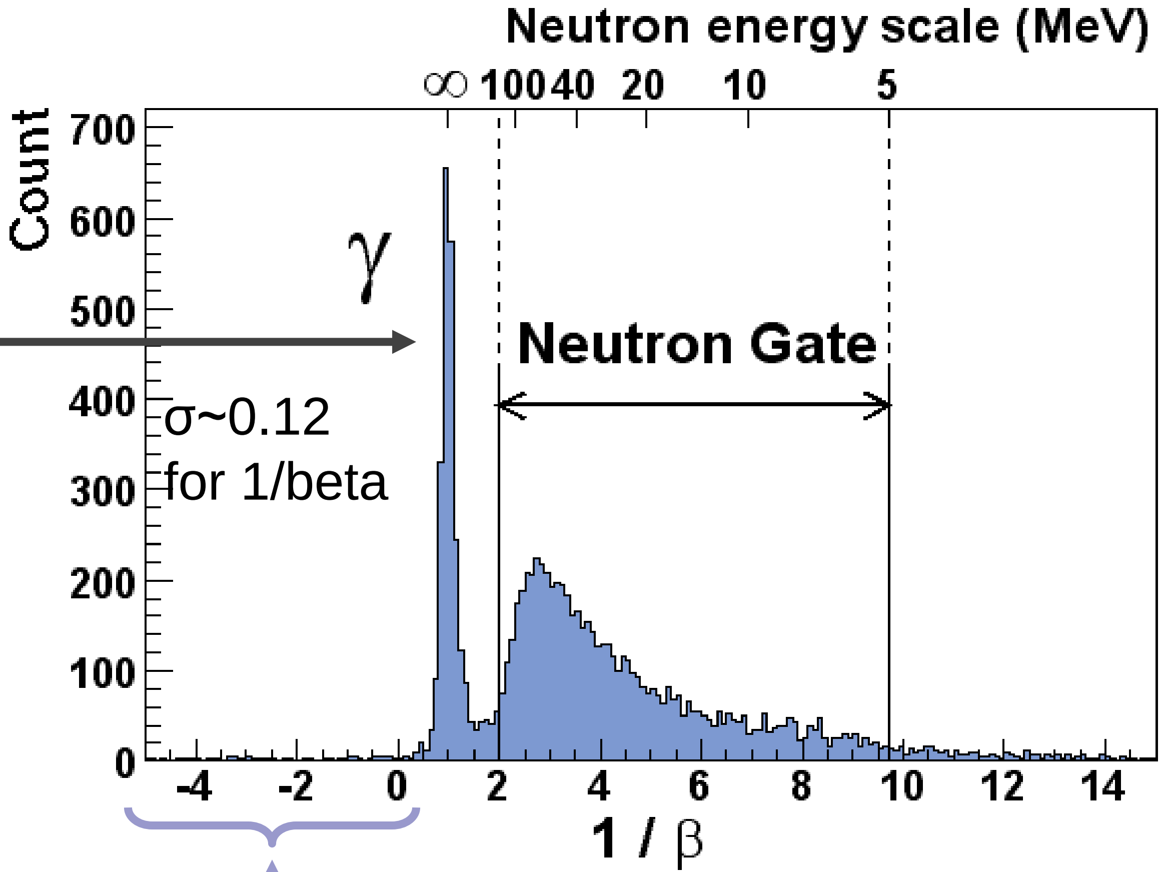
$$\frac{\Gamma_n}{\Gamma_p} = \frac{1-r_p}{r_p} = 0.45$$

(0.51 with β=0.11, 50% higher value)

A Γ_n/Γ_p significantly smaller than 1.0 is obtained without relying on INC instead obtained simply assuming $|f_n = f_p$.

Neutral particle identification

Resolution
for neutron counter
σ~**8MeV**



σ~0.12
for 1/beta

gated $^{12}{}_{\Lambda}C$ ground state

- ✓ **Good γ n separation**
- ✓ **Good S/N ratio (~30)**
- ✓ **High statistics (~5000neutrons)**

Constant background
→ very small

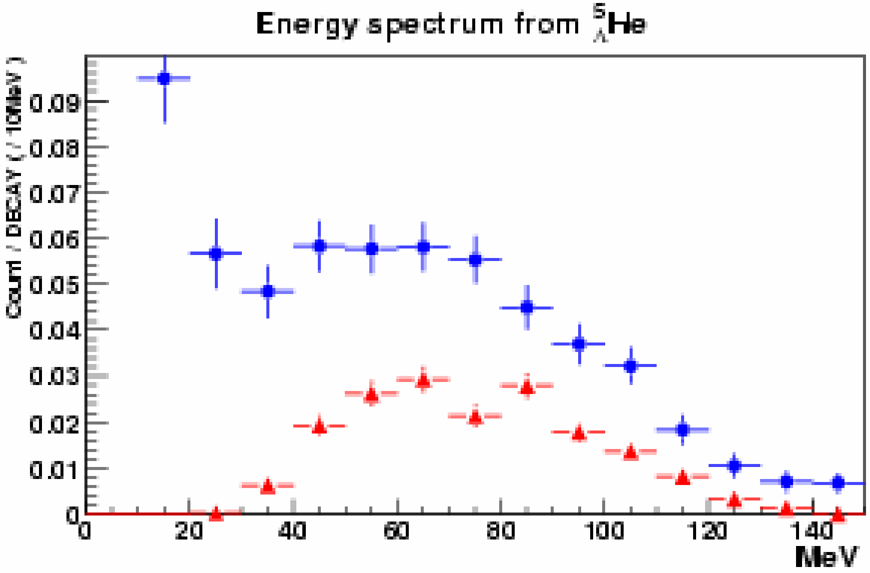


Figure 3: Nucleon energy spectra from $^{5}_{\Lambda}$He

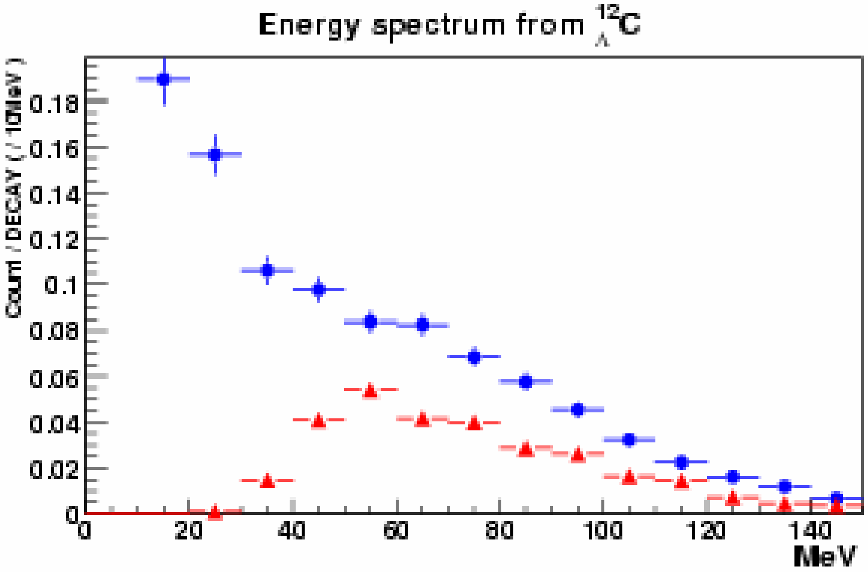


Figure 4: Nucleon energy spectra from $^{12}_{\Lambda}$C

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7. Department of Physics, Hampton University.

E307 Experiment

1. Measured mass dependence of lifetimes of Λ hypernucleus with a high accuracy, ~(6-7) %.

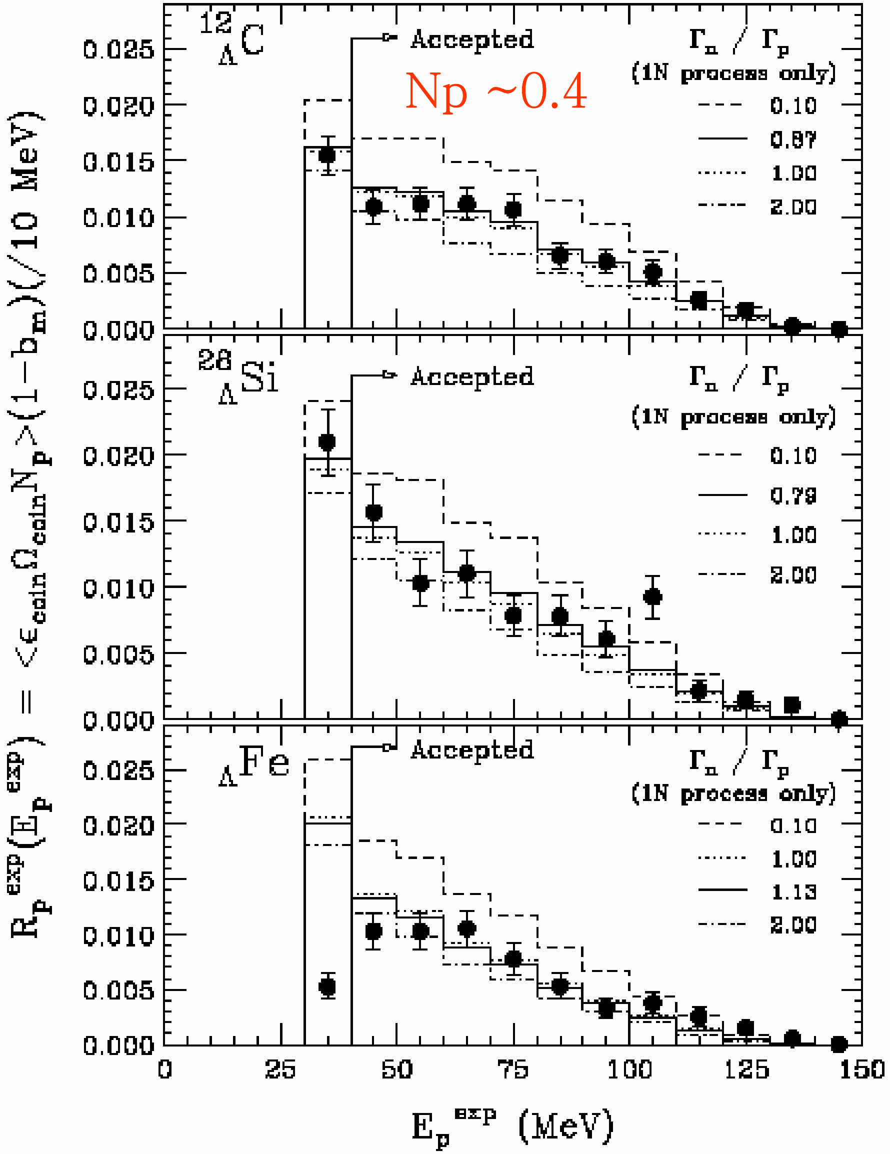
2. Comparing to INC calc.

$$\frac{\Gamma_n}{\Gamma_p} = \begin{pmatrix} 1.17 \pm 0.09 \pm 0.20\,(1N) \\ 0.96 \pm 0.10 \pm 0.22\,(2N) \end{pmatrix} \rightarrow \begin{pmatrix} 0.87 \pm 0.09 \pm 0.21\,(1N) \\ 0.60 \pm 0.11 \pm 0.23\,(2N) \end{pmatrix}$$

3. The ratios are less than unity but only within 1σ from unity. And the error bar is still quite large.

4. The integrated proton number per NMWD above 40 MeV is 0.4.

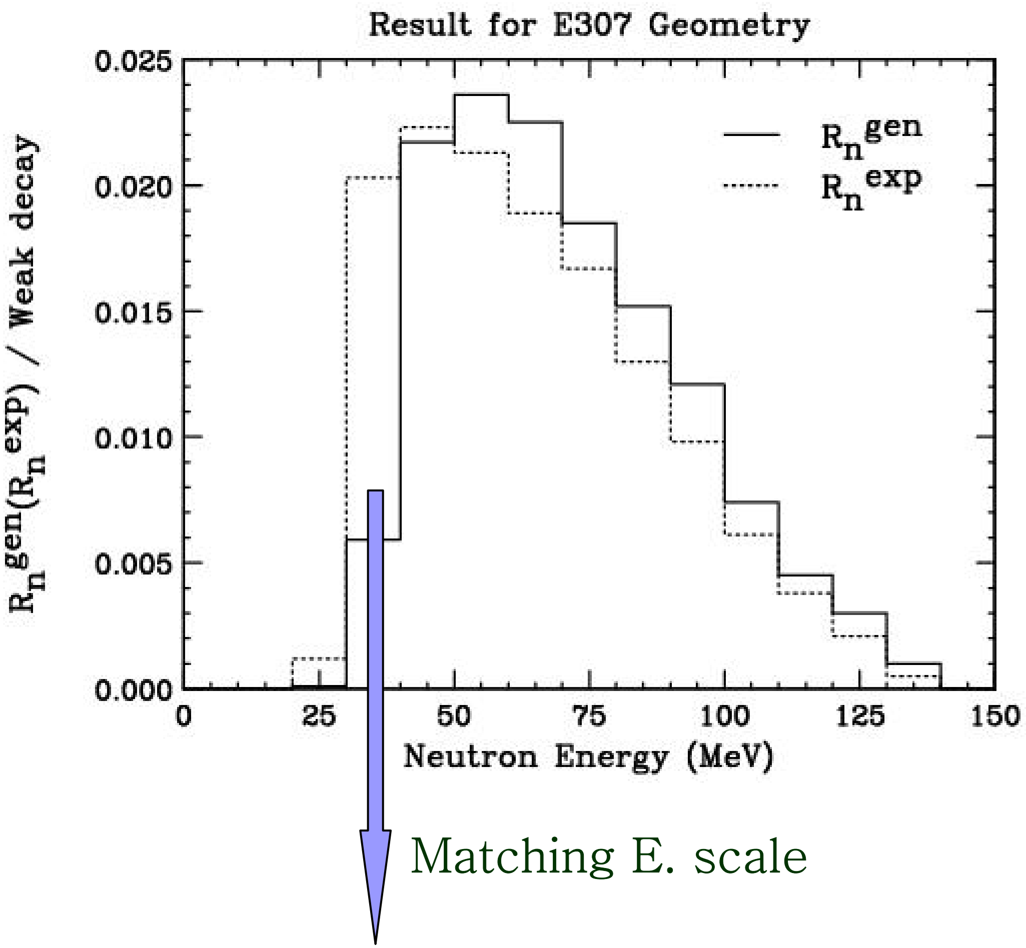
5. Difficulties to determine Γn/Γp ;
   - i) FSI →Light mass sys. (E462)
   - ii) High E th → n meas. (E369)



Np ~0.4

HYP03 Conf.

Energy scale matching



Matching E. scale

N_n ; 0.80 → 0.69

Now we can directly compare this # to that of proton, N_p

- Since we have

  - the high threshold energy
  - isospin independence of strong interaction
  - isospin symmetric propagation medium

- Assume fn = fp = f.

$$N_n/N_p = (2-r_p)/r_p = 0.69/0.40 = 1.73$$

$$\Gamma_n/\Gamma_p = r_n/r_p = 0.36 \ll 1$$

which is much smaller than unity.

- However, the effects of the cross over secondary events exist.

$$N_n = (2-r_p)f + r_p g$$

$$N_p = (2-r_p)g + r_p f$$

Theory

	N_{hyp}	Γn/Γp
sas02	$^{5}_{\Lambda}$He	0.70
Ito02	$^{5}_{\Lambda}$He	0.39
Gar03	$^{5}_{\Lambda}$He	0.46
Ose01	$^{12}_{\Lambda}$C	0.53
Ito03	$^{12}_{\Lambda}$C	0.57
Gar03	$^{12}_{\Lambda}$C	0.34

Experiment

	N_{hyp}	Γn/Γp
BNL	$^{5}_{\Lambda}$He	1.33±0.5
	$^{12}_{\Lambda}$C	1.33±1.12/0.81
KEK'95	$^{12}_{\Lambda}$C	1.87±0.91/1.59
KEK (Sat02)	$^{12}_{\Lambda}$C	0.87±0.09±0.21 (1N) 0.60±0.11±0.23 (1N+2N)
KEK (Kim03)	$^{12}_{\Lambda}$C	(0.45~0.51)±0.14 (1N)

- The neutron spectrum: with greatly improved statistics and S/B ratio.
- Γn/Γp ratio ; − the first experimental value significantly less than unity,

  ΓnΓp = (0.45~0.51) ±0.15

  − Obtained directly comparing n and p spectra model independent way.
- Asymmetry ; The Γ_n/Γ_p puzzle seems resolved. However, the decay asymmetry which is one of the two basic observables in weak interaction study remains to be understood.
- Ambiguity ; There still remains some ambiguity due to the FSI and 2N process.

1. Baryonic Weak Interation

- has bee studied **Mainly through parity violation phenomena** in the nuclear and hadronic interaction **via the meson exch. diag.**

  --> Successful
- They are limited only to **the parity violation component** of the NN weak interaction.
- In the nuclear environment

  --> **low momentum components only.**
- However, in order **to understand the four baryon weak int.** we need to understand

  *** Parity conserving**

  *** the strangeness changing**

  *** higher momentum**

  components.

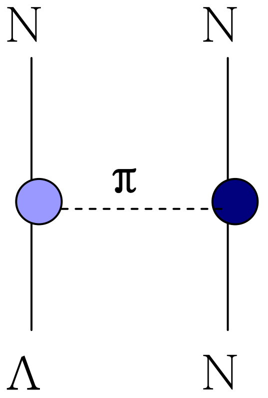
  → **NMWD provides such study ground.**

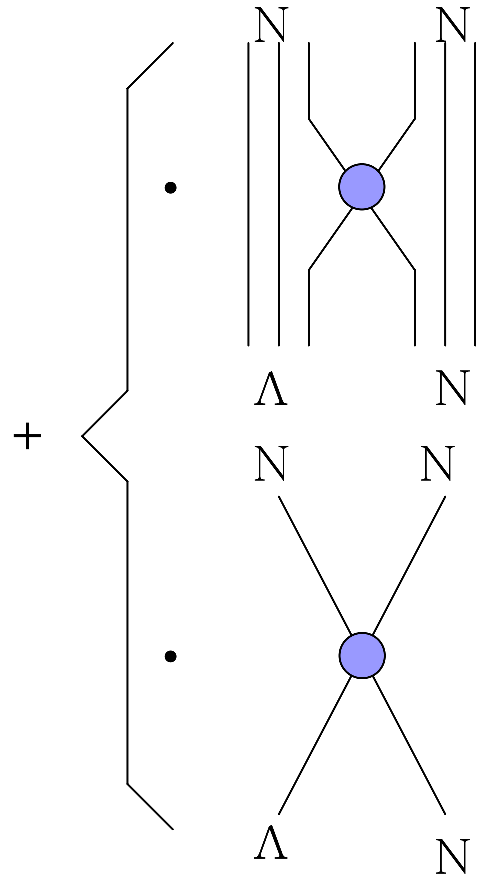
Γn/Γp puzzle

2) Hybrid Model

OPE + Short Range Model

- Direct Quark Int.
- Phen. Point Int. etc.





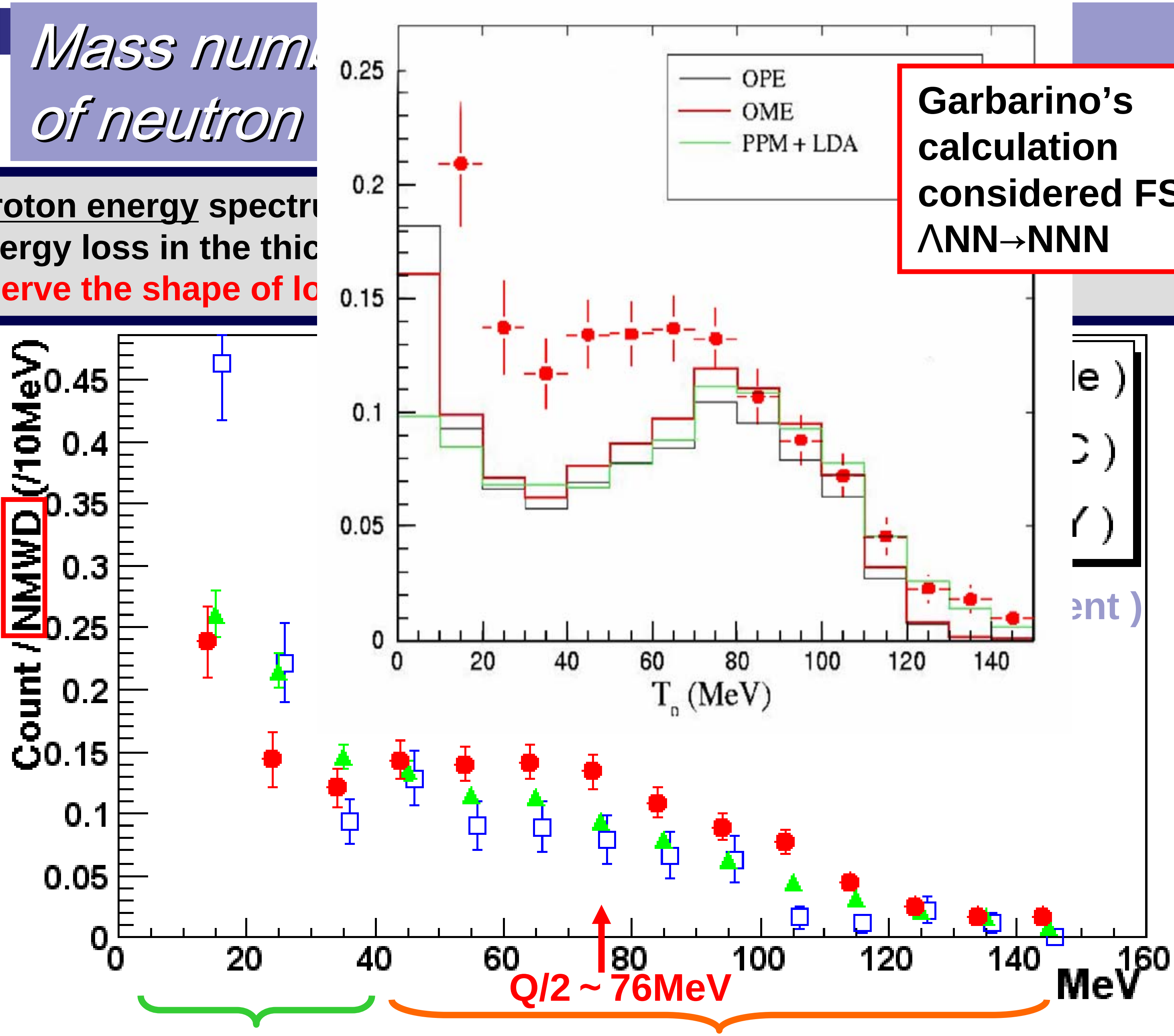
	OPE	OPE+ DQ	EXP(BNL)	EXP(KEK)
Γ_{NM} ($^{4}_{\Lambda}$He)	0.154	0.253	0.20±0.05	0.20±0.05
Γ_n/Γ_p($^{4}_{\Lambda}$He)	0.061	0.178	0.25±0.13	0.20±0.05
Γ_{NM} ($^{5}_{\Lambda}$He)	0.154	0.627	0.41±0.14	
Γ_n/Γ_p($^{5}_{\Lambda}$He)	0.061	0.489	0.93±0.55	

Though the ratios among experiments are consistent, the error bars involved are too large to distinguish different models.

Improvement of the experimental accuracy seemed very urgent. In this regards, the two experiments, KEK-PS E307 and E369, on the decay of Λ hypernucleus has been implemented at KEK.

Mass num
of neutron

<u>The proton energy spectr</u>
the energy loss in the thic
to observe the shape of lo

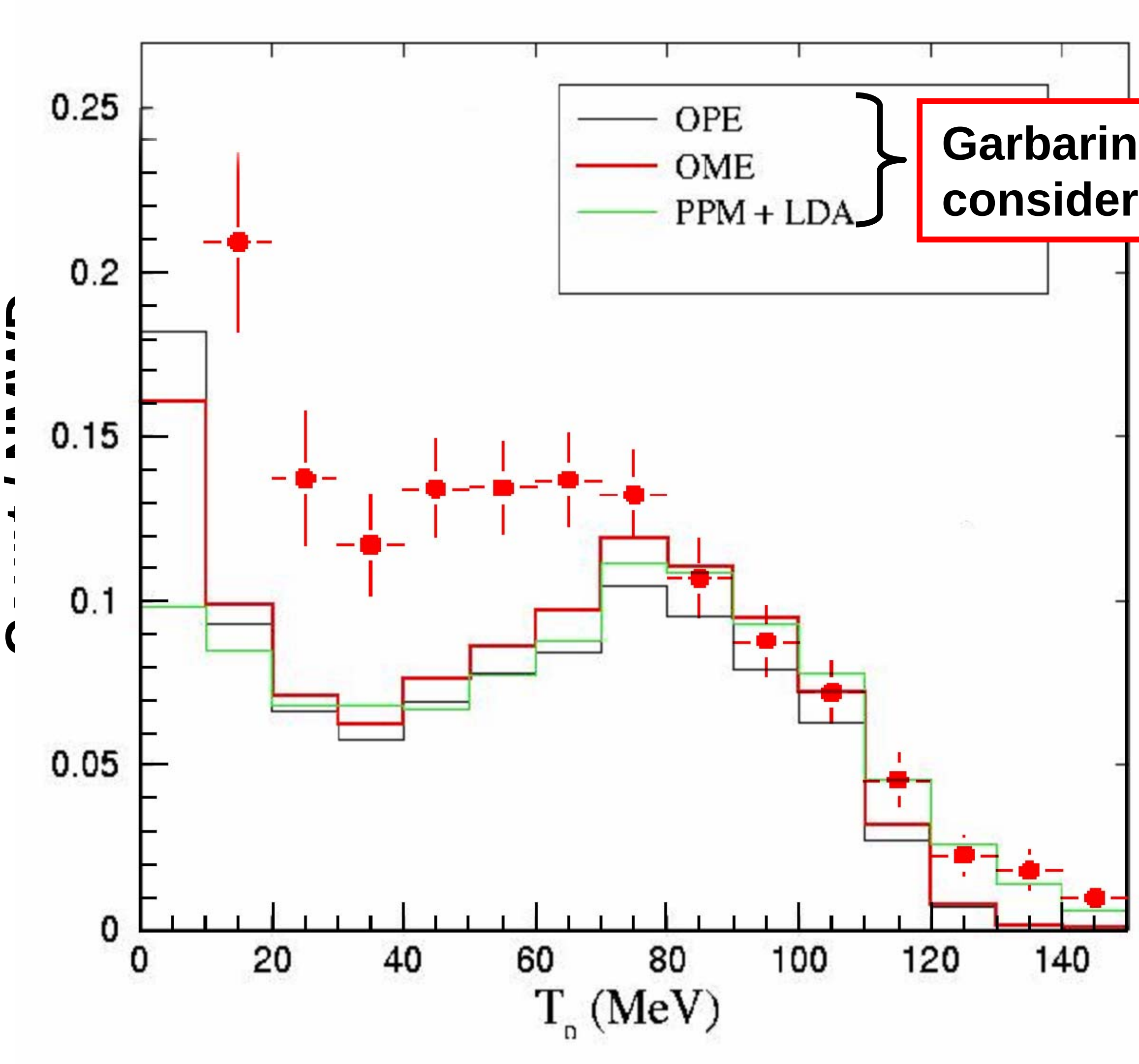


Garbarino's calculation considered FSI & ΛNN→NNN

Q/2 ~ 76MeV

As the mass number become lager, the number of neutron become lager in the low energy part, and smaller in the high energy part.

Neutron energy spectra of $^{5}{}_{\Lambda}$He



Garbarino's calculation considered FSI & ΛNN→NNN

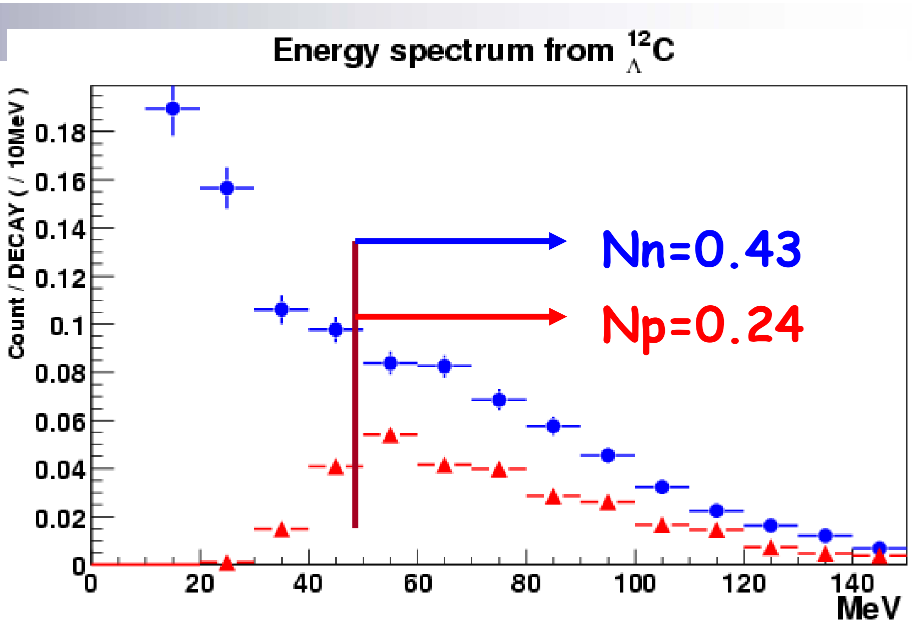
No peaking at half of Q-value (76MeV) even $^{5}{}_{\Lambda}$He

76MeV

suggested larger contribution of ΛNN→NNN or FSI than his theory.

Energy Scale

In E462 and E508, we now have **Nn and Np obtained from same target measurement and with same energy threshold** for both n and p, which is much improved situation than those of E307/E369.



In both of $^{5}{}_{\Lambda}$He and $^{12}{}_{\Lambda}$C, **the target vertex resolutions were high enough** that we could recover **the original emitted energy of the proton** from the degradation.

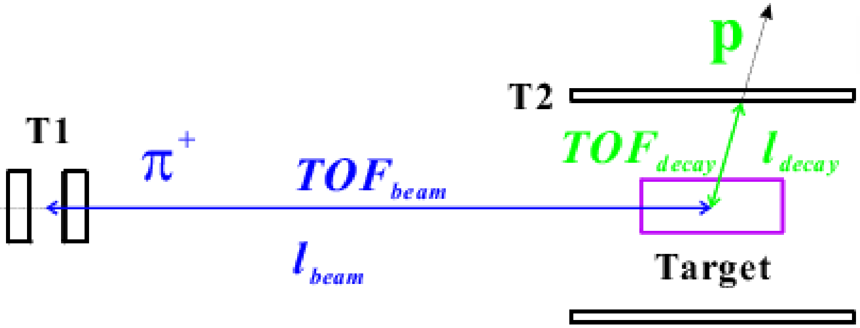
$\therefore$ **No need for Energy Scale Matching** of n/p in E462/E508.

The same energy scales make the **direct comparison of the integrated yields of n and p spectra possible** with less systematic error than that of E307/E369.

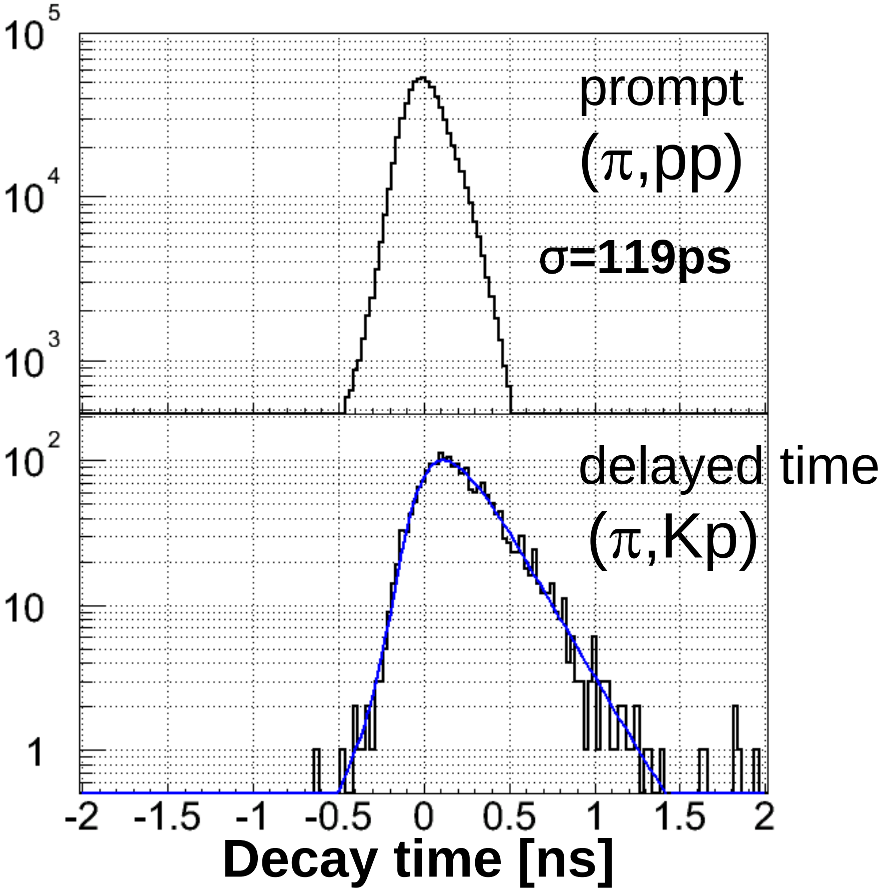
Lifetime analysis

$$\Delta t = t_{T2} - \mathrm{TOF}_p - \mathrm{TOF}_\pi - t_{T1}$$

$$= t_{T2} - \frac{l_p}{\beta_p c} - \frac{l_\pi}{\beta_\pi c} - t_{T1}$$



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



preliminary

τ = 212 ± 6 ps

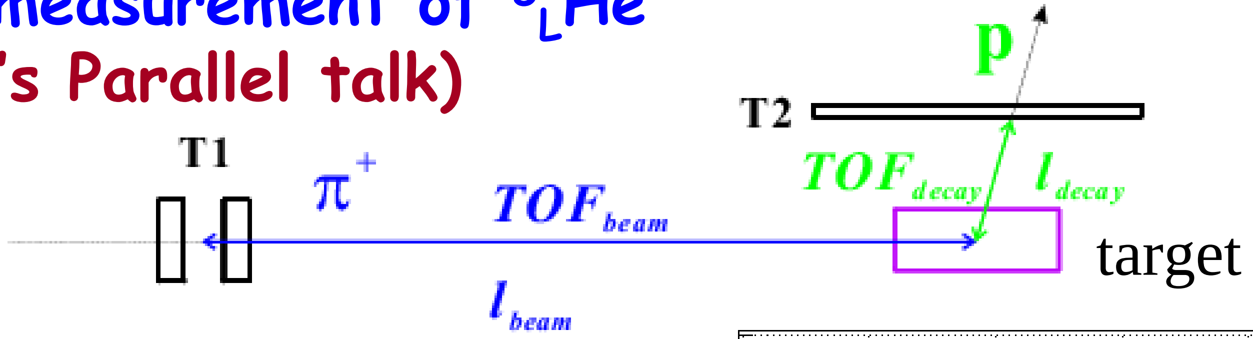
(statistical only)

cf. <KEK-E307>

τ = 230±15 ps

(Park *et al.*)

Lifetime measurement of $^{5}_{\Lambda}$He
(Kameoka's Parallel talk)



$$\Delta t = t_{T2} - TOF_p - TOF_\pi - t_{T1}$$

$$= t_{T2} - \frac{l_p}{\beta_p c} - \frac{l_\pi}{\beta_\pi c} - t_{T1}$$

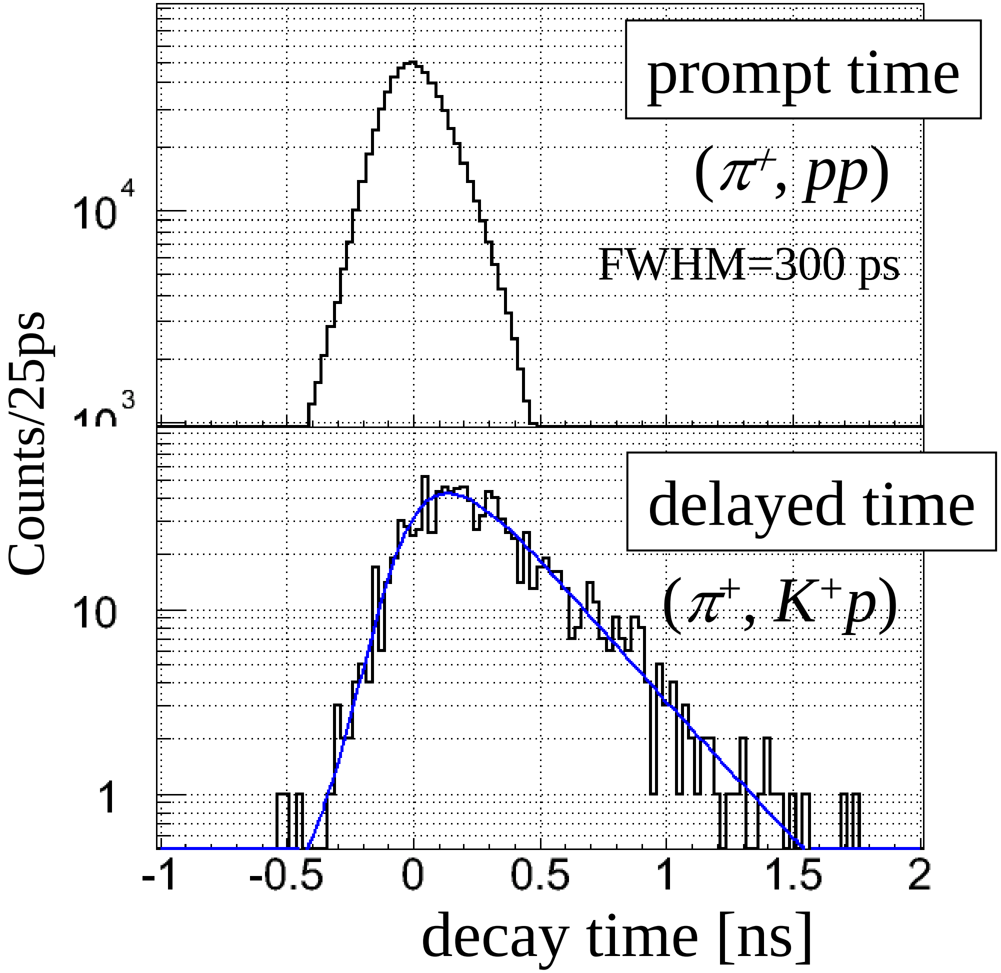
Present experiment

$\tau = \mathbf{278}\,^{+11}_{-10}$ ps

(statistical error only)

cf. Szymanski *et al.*(1991)

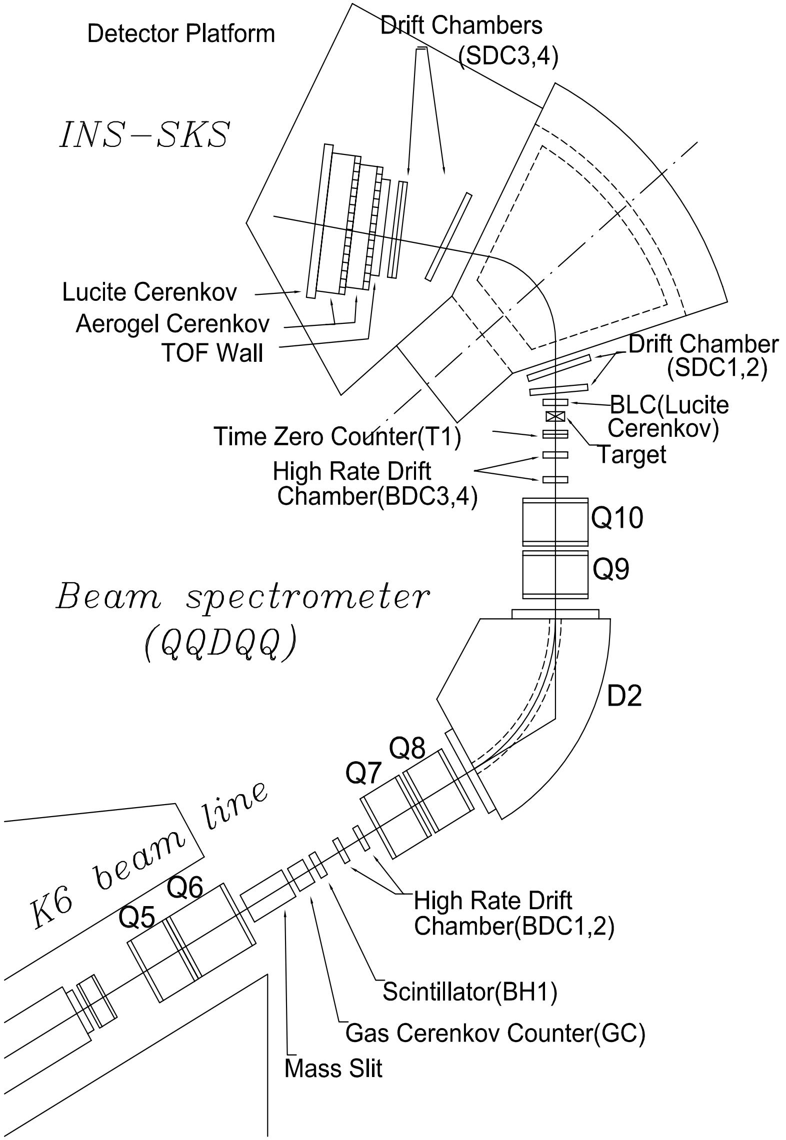
$\tau = 256 \pm 20$ ps



E307 Experiment/Setup

1. Objectives
   1) τ for $^{12}_{\Lambda}\mathrm{C}$, $^{28}_{\Lambda}\mathrm{Si}$ and $_{\Lambda}\mathrm{Fe}$
   2) Proton energy spectrum
   3) Γp, $\Gamma \pi -$

2. Set up
   1) (π^+, K^+) reaction
   2) Large solid angle, ~100msr, SKS
   3) Decay spectrometer



One of the main goals of E307 was to reduce the exp. error of Gn/Gp.

p spectrum was compared to that of INC. The comparison was necessary since the measured spectrum cover only a limited portion of all the emitted nucleons, namely, a partial information of p (HE p only) and nothing of n.

In fact, the INC calc. originally we used was corrected with an errotum later. Accordingly we had to revise our Γ_n/Γ_p result as

$$\frac{\Gamma_n}{\Gamma_p} = \begin{pmatrix} 1.17 & \pm\ 0.09 & \pm\ 0.20 & (1N) \\ 0.96 & \pm\ 0.10 & \pm\ 0.22 & (2N) \end{pmatrix}, \text{PRL 89 (2002)}$$

$$\rightarrow \begin{pmatrix} 0.87 & \pm\ 0.09 & \pm\ 0.21 & (1N) \\ 0.60 & \pm\ 0.11 & \pm\ 0.23 & (2N) \end{pmatrix}, \text{PRC (submitted)}$$

∴ Best way would be to derive the ratio directly from experimental data.

For it, we need to measure

1. the neutron spectrum → E369
2. with low E threshold
3. the light system which have less FSI. → E462

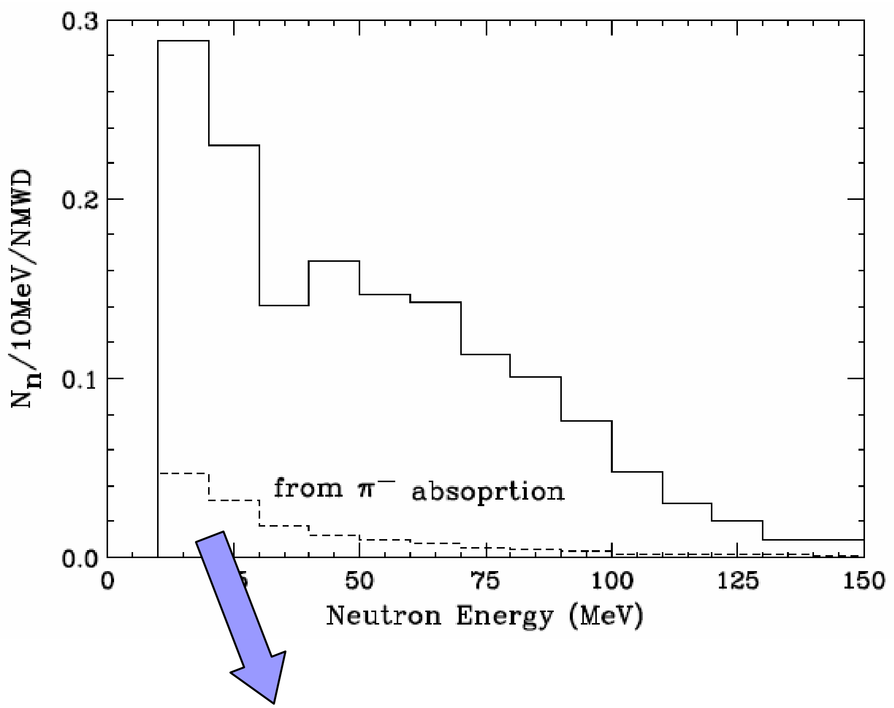
In fact, the latter ratio is due to the revision of INC result with an errotum later. Accordingly **we had to revise our Γ_n/Γ_p result** as

∴Best way would be **to derive the ratio directly from experimental data.**

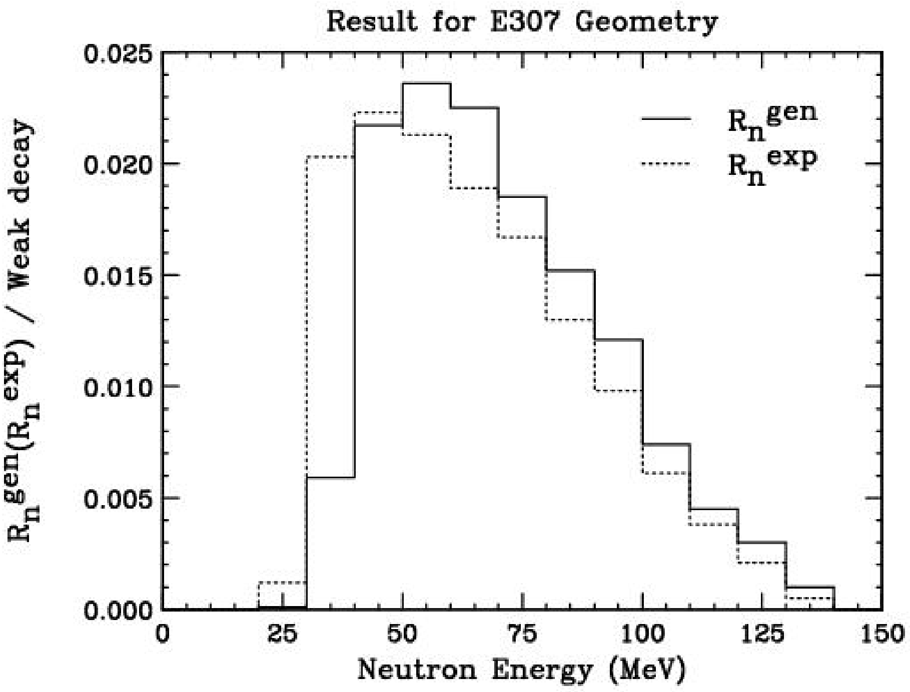
For it, we need to measure

1. **the neutron spectrum** → **E369**
2. **with low E threshold**
3. **the light system which have less FSI.** → **E462**

Comparison of Proton and Neutron Spectra



π^- absorption background subtraction



Energy threshold matching

FSI and 2N induced NMWD

- Need to confirm the small $\Gamma n/ \Gamma p$.
- 2N induced NMWD has not been identified yet, though theoretical calculation claim its significant contribution.
- E462 : Exclusive Coincidence measurement of the decay of ${}^{5}{}_{\Lambda}$He to identify this. However, it showed an unexpectedly large LE component in the decay particle spectrum. 2N/fsi are mixed.
- E508 : Need an additional target in p−shell to separate them.
  → **Coin. Meas. of the decay of** ${}^{12}{}_{\Lambda}$C
- Asymmetry issue: Large inconsistency among α_{nm} for C.

Aims of E462 and E508

To measure

the decay particle spectra from ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C

both n & p in coincidence

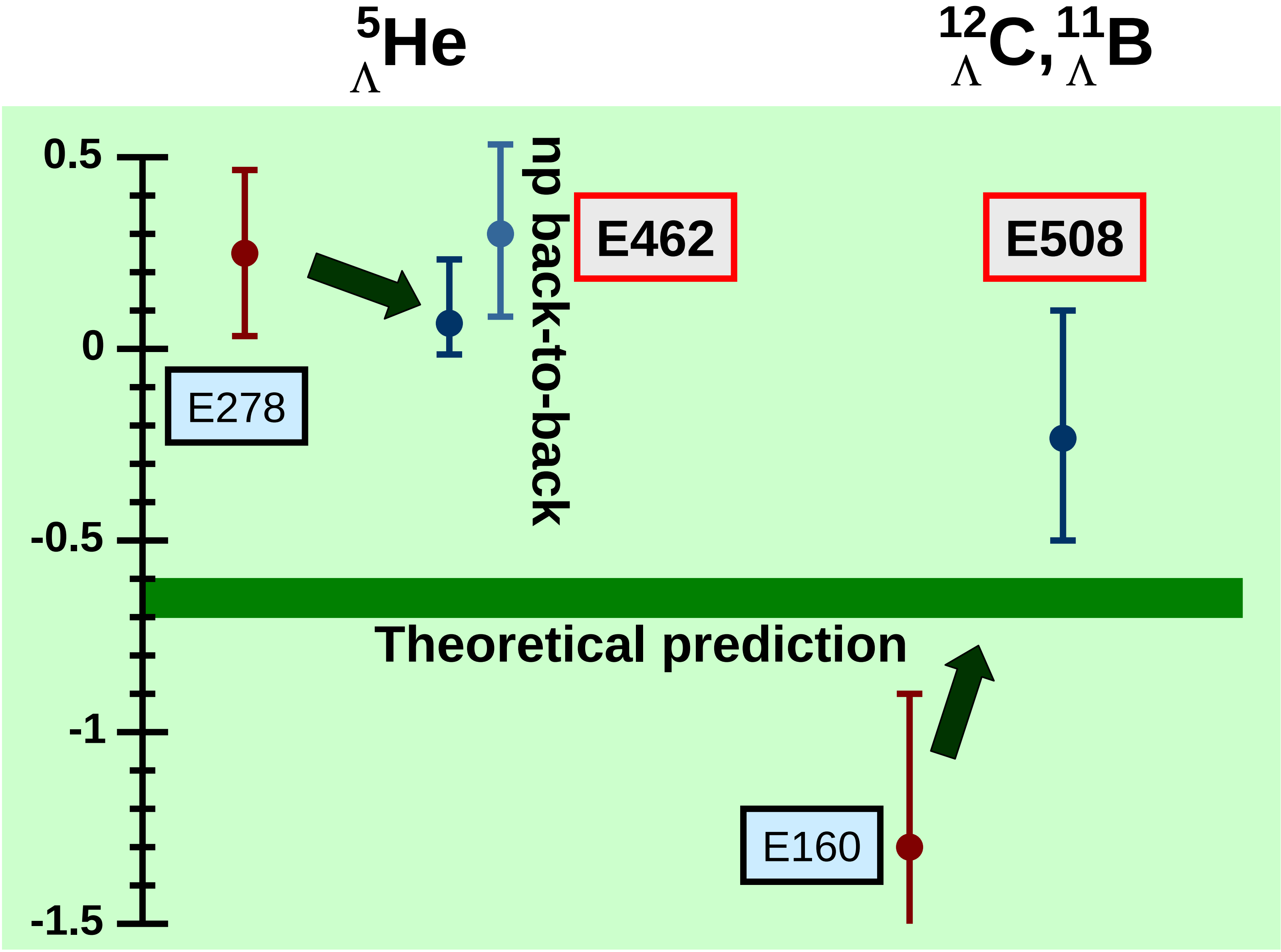
with high statistics.

To resolve

the current issues of NMWD such as

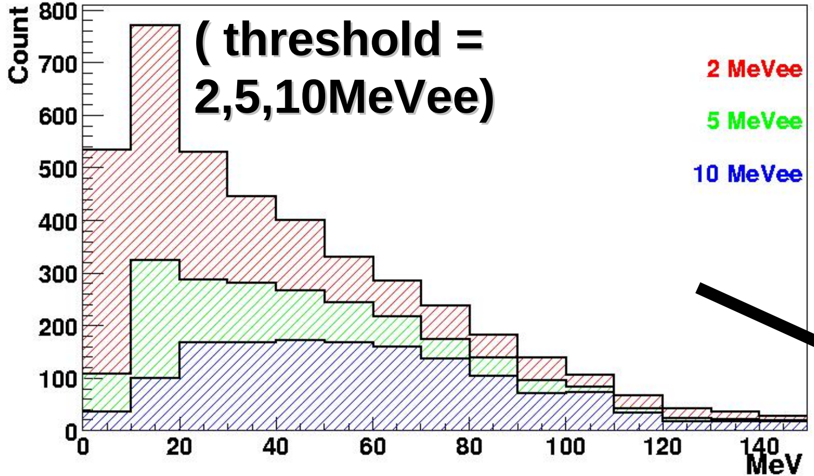
- Γ_n, Γ_p, Γ_π,
- Γ_n/Γ_p
- α_{nm} ; asymmetry parameter

Comparison with recent results

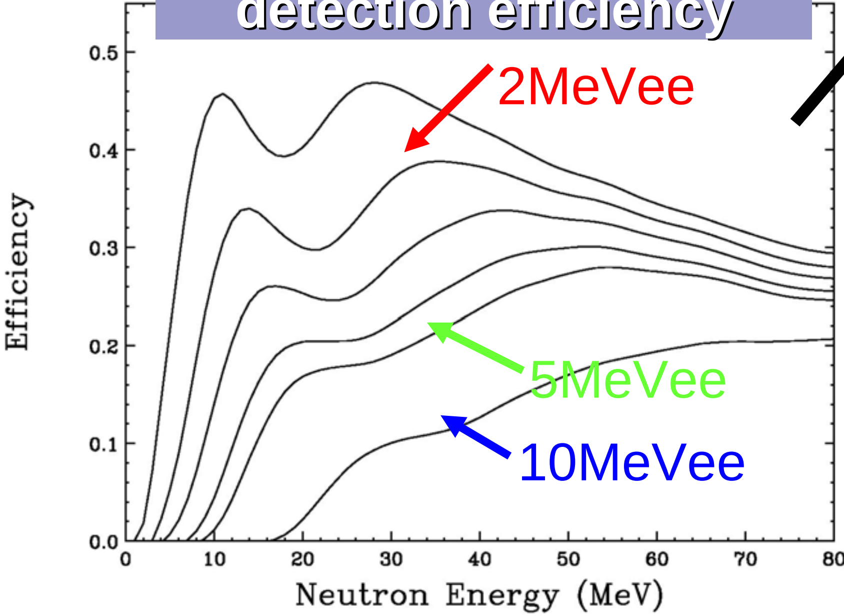


Neutron efficiency correction

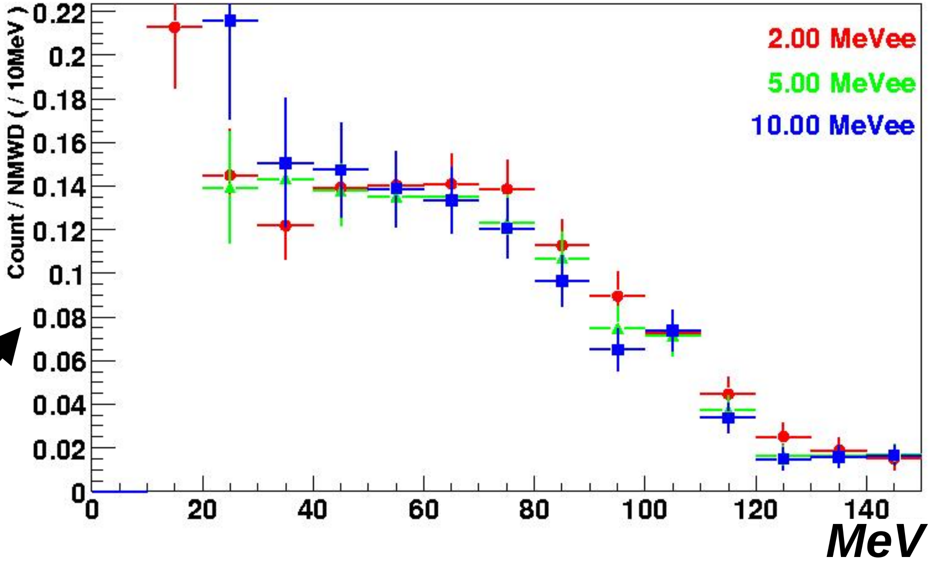
Raw neutron spectra


(threshold = 2,5,10MeVee)

Simulated neutron detection efficiency



Corrected spectra



Threshold control is worked well.