The Contribution of the Three-Body Process in the Nonmesonic Weak Decay of Λ Hypernuclei

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For KEK-PS E508 Collaboration

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I. The Weak Decay Modes of Λ Hypernuclei.
II. Γ_n/Γ_p ratio puzzle and 3-body NMWD process.
III. The Partial Decay widths of NMWD; Γ_{2N}, Γ_n, Γ_p

I. The Decay Modes of Λ Hypernuclei

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

- Γ_m
  - $\Gamma_{\pi^-}(\Lambda \rightarrow p\pi^-)$
  - $\Gamma_{\pi^o}(\Lambda \rightarrow n\pi^o)$

  } Mesonic, q~ 100 MeV/c

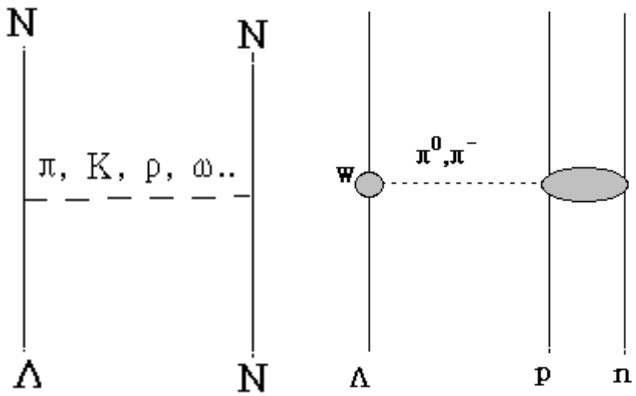
- Γ_{nm}
  - $\Gamma_p(\Lambda p \rightarrow np)$
  - $\Gamma_n(\Lambda n \rightarrow nn)$ — (1N)
  - $\Gamma_{2N}(\Lambda NN \rightarrow nNN)$ — (2N)

  } Nonmesonic, q~ 400 MeV/c

Γ_n/Γ_p puzzle

3-Body Process;

Predicted theoretically



(2N-NMWD)

The Status of NMWD Study of Λ hypernuclei

I. Fundamental Motivation ; to study the elem. B-B Weak Interaction ;

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

- Γ_n/Γ_p and Ay have been mainly studied so far.

II. Outstanding Issues ;

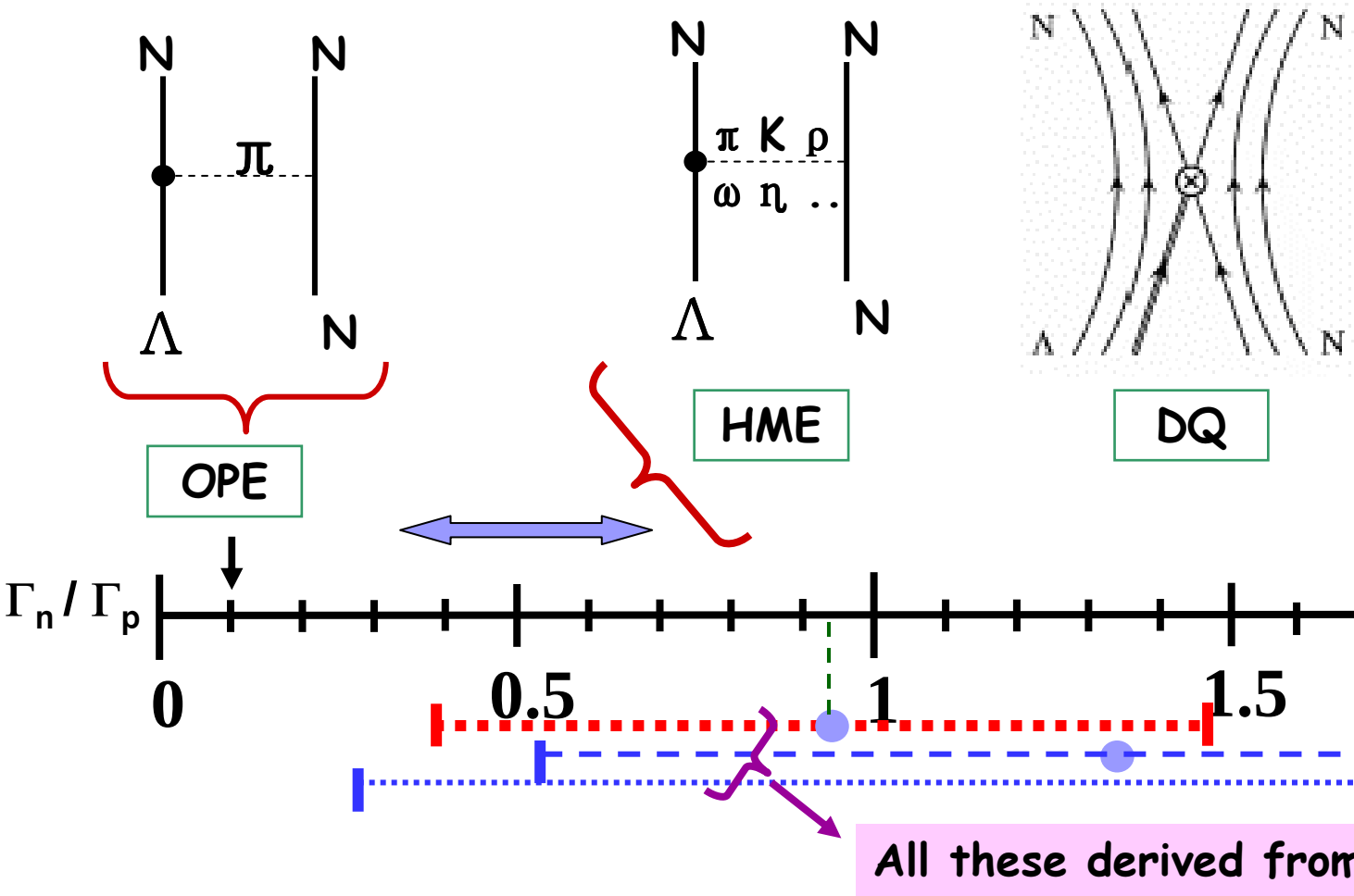
- Decay widths; Γ_n, $\Gamma_p \leftrightarrow \Gamma_{2N}$ (3-body process)
- Asymmetry;
- $\Delta I=1/2$ rule in NMWD ;

Γ_n/Γ_p puzzle and the previous searches

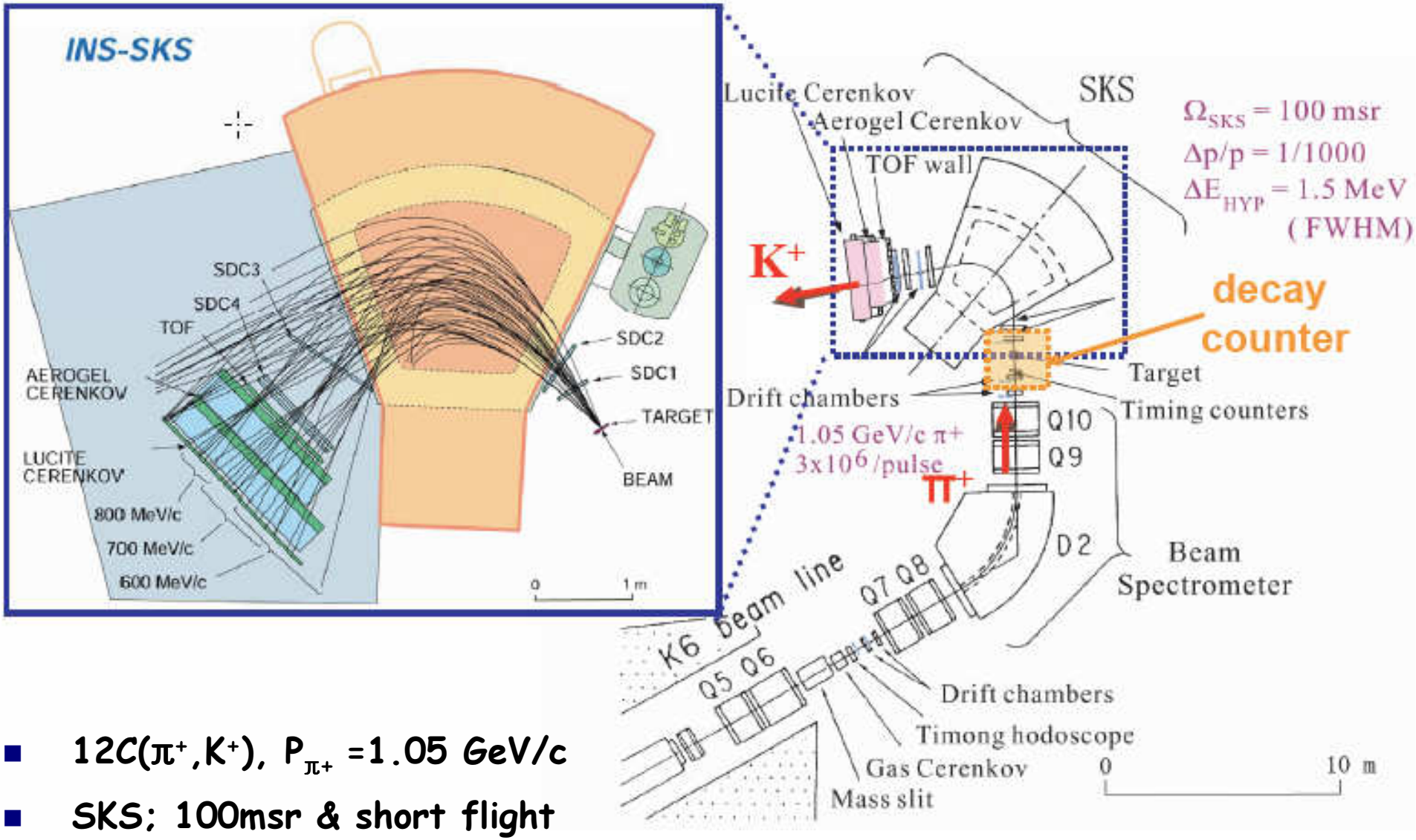
1. Γ_n/Γ_p Puzzle :

$\Gamma_n/\Gamma_p^{exp} \leftrightarrow \Gamma_n/\Gamma_p^{th(OPE)}$

~ 1 ~0.1



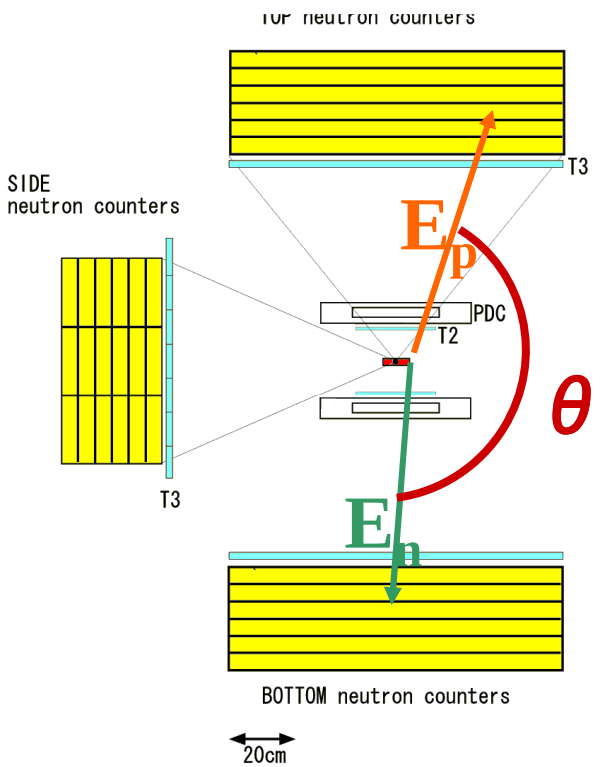
E508 & KEK-PS K6 beamline and SKS

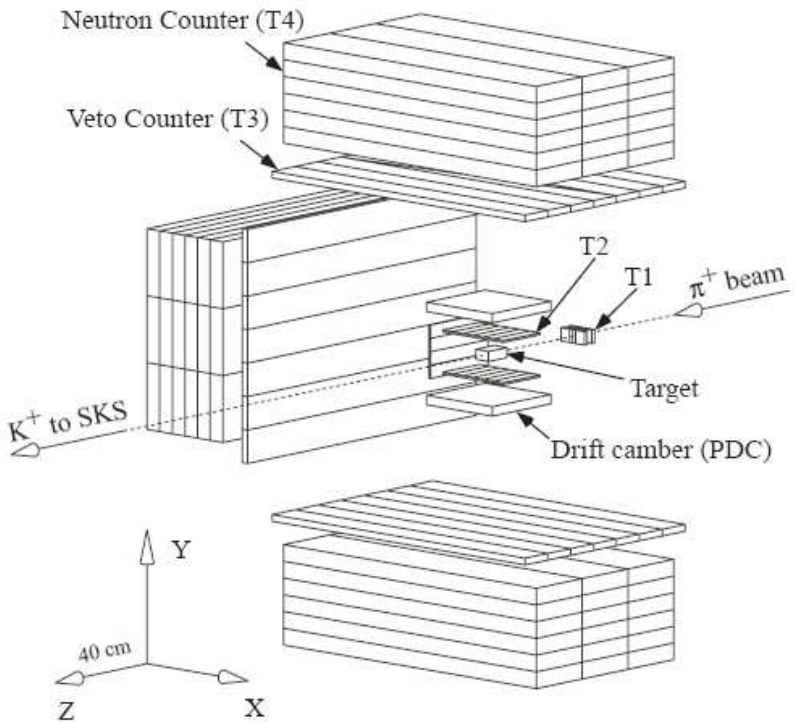


- $^{12}C(\pi^+,K^+)$, $P_{\pi+}$ =1.05 GeV/c
- SKS; 100msr & short flight path

Coincidence Measurement (KEK-PS E462/E508)

- Measured all decay particles





- Pair yields, Y_{np} and $Y_{pn}(\Theta)$ meas.
  $\{Y_{nn}(\Theta), Y_{np}(\Theta)\}/N_{nm} \equiv \{N_{nn}(\Theta), N_{np}(\Theta)\}$

- Can distinguish back-to-back(bb) and non-bb kinematic events.

- Require back-to-back ($\cos\Theta < -0.7$) condition.
  → can supress FSI and 3-b decay events.

Test of Modified DEMONS Program for n Efficiency

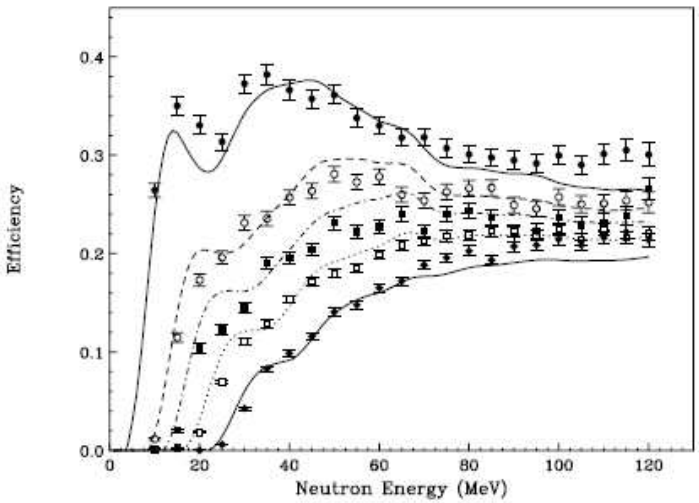


Figure 4.12: The neutron detection efficiencies as a function of the neutron energy calculated by the DEMONS code (lines) [55], which are compared with that of existing experimental data (point with error bar) [56]. The thresholds are 2.80, 5.58, 7.89, 11.15 and 15.75 MeVee from top.

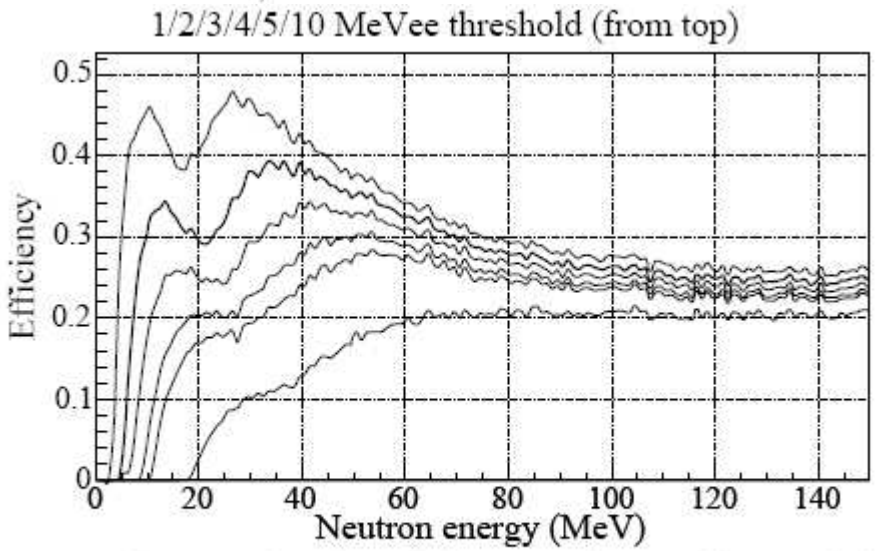
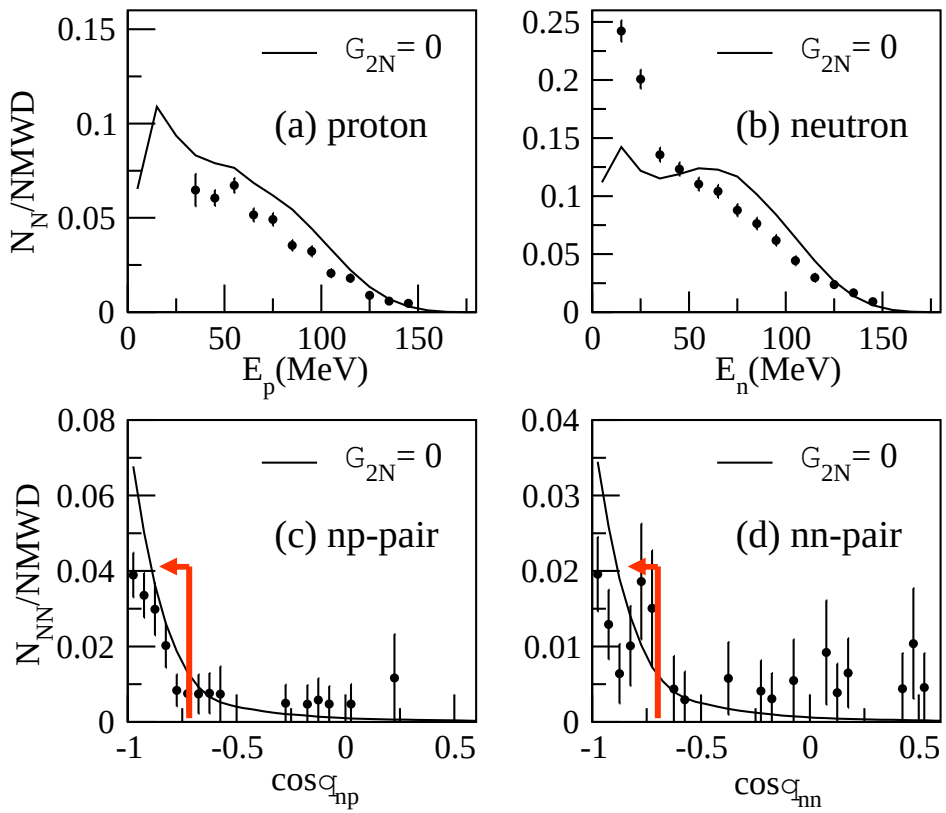


Figure 4.13: The energy dependence of the neutron detection efficiency calculated by the DEMONS code for the present setup. The thresholds are 1, 2, 3, 4, 5 and 10 MeVee from top.

Coincidence Yields (NN correlations)



- Detection efficiency corrected.
- Normalized to unit NMWD.
- back-to-back(bb) ; $\cos\Theta < -0.7$
- FSI/3-B broaden the angular corr.

N_{nn}/N_{np} (bb) → Γ_n/Γ_p

$\Gamma_n/\Gamma_p = 0.51 \pm 0.13 \pm 0.05$

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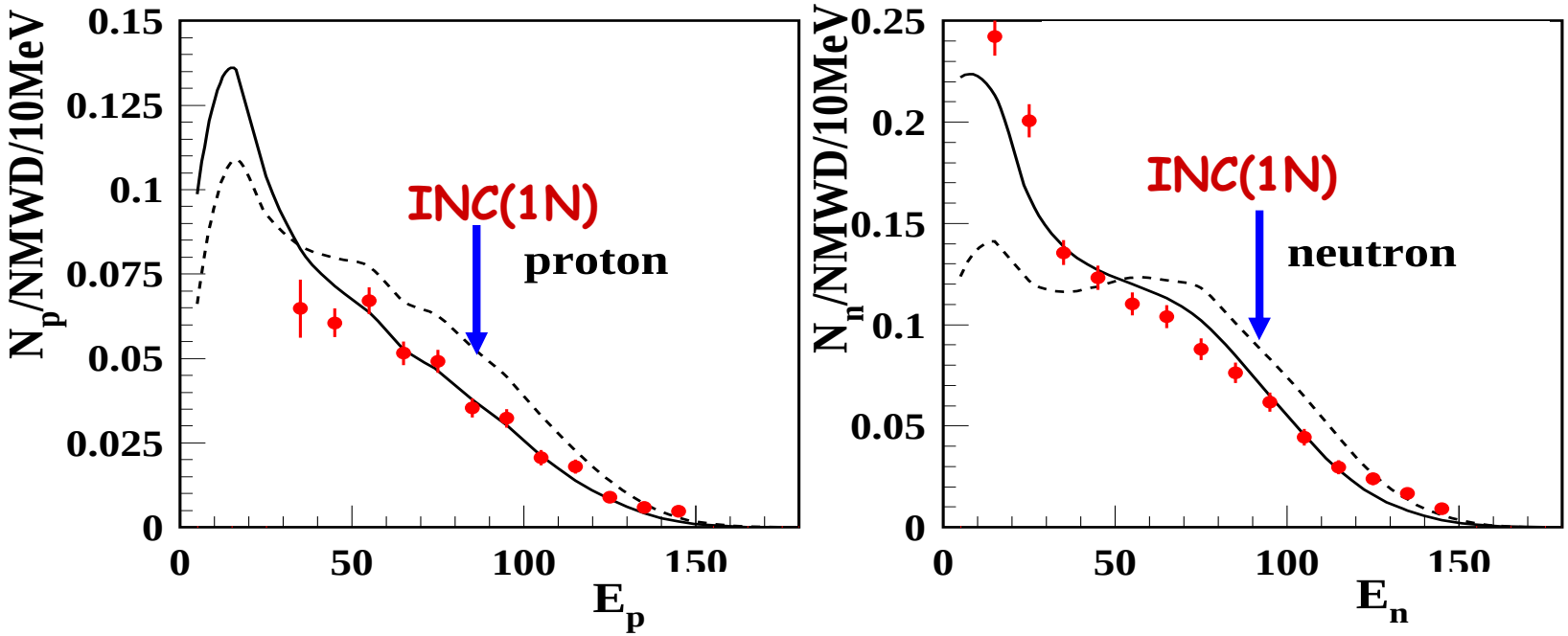
1. Well agreed with Th. Ratios.
2. Γ_n/Γ_p puzzle finally solved.
3. Why the exp. Γ_n/Γ_p ratios have been so high?

Quenching of Singles Yield



1. Quenching in both p and n spectra from that of INC(1N).
2. What would be the mechanism for the nucleon Quenching?

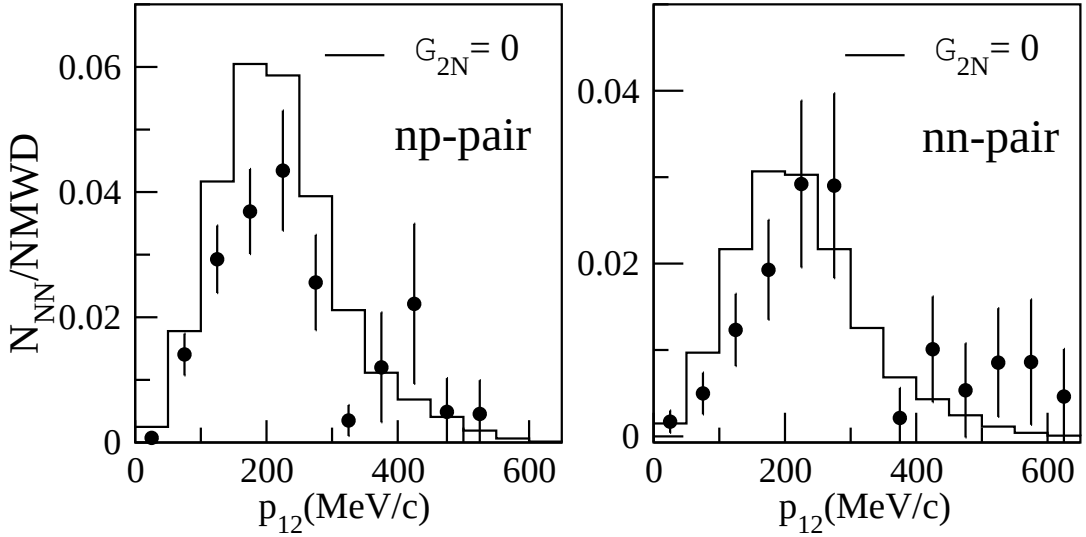
   → FSI & 3-Body process.

   → Both reduce the energy of emitted nucleons.

   → Quenching

Momentum sum distribution.

- Missing momentum dist.
  - $|p_1+p_2| \equiv p_{12}$



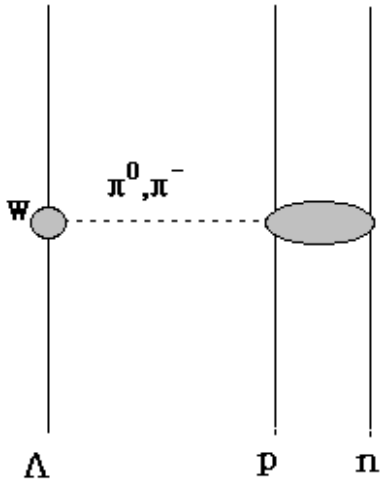
Two groups?

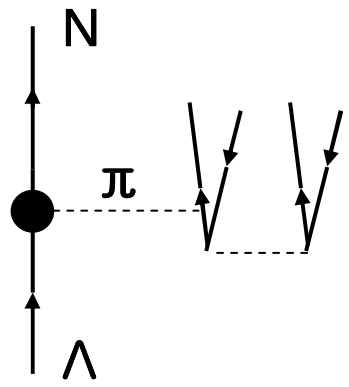
- low mom(~200 MeV/c); Essentially same as the bb kinematics events.
- high mom(~500 MeV/c); Non-bb kinematics events and

indicate a third party either via FSI or 3-B int. process.

Theo. Prediction of 3-body process (Γ_{2N}) of NMWD.

- Model for 2N-NMWD; ΛNN → nNN
  - Alberico-Ericson for Nuc. matter ('91), and
  - Ramos-Oset extended to finite nuclei ('94).
  - Recently Bauer and Garbarino; extensive calc. including complete set of mesons and NN pairs.
- Γ_{2N} = 0.25 – 0.27 Γ_{Λ} ($^{12}{}_{\Lambda}C$)





Previous INC calculation and Quenching

Table 1. The normalized nucleon pair numbers, N_{np} and N_{nn}, to the NMWD of ${}^{12}_{A}C$ in each kinematics region, back-to-back ($\cos\theta \leq -0.7$;bb) and non-back-to-back ($-0.7 \leq cos\theta \leq 0.6$;nbb), are shown and compared to those of present INC(INC_{1N} and INC_{1N+2N}) and the previous INC [?]. N_{NN} is the sum, $N_{np} + N_{nn}$.

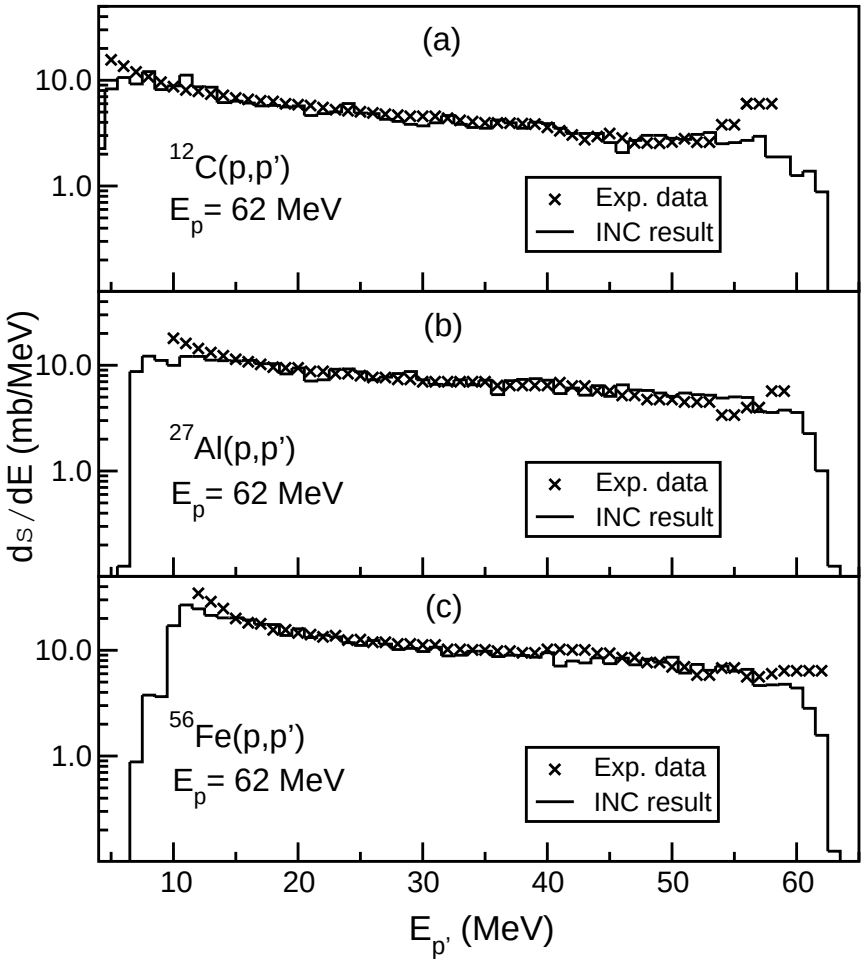
	E508	INC_{1N}	INC_{1N+2N}	INC_{prev}
$N_{np}(bb)$	0.138±0.014	0.231	0.157	0.35
$N_{nn}(bb)$	0.083±0.014	0.118	0.104	0.15
$N_{NN}(bb)$	0.221±0.020	0.349	0.261	0.50
$N_{np}(nbb)$	0.059±0.018	0.089	0.069	0.52
$N_{nn}(nbb)$	0.059±0.017	0.046	0.040	0.18
$N_{NN}(nbb)$	0.118±0.027	0.135	0.109	0.70

Overproduction

INC (IntraNuclear Cascade) calculation

- A nucleus as a local density Fermi gas with Woods-Saxon density dist.
- FSI is simulated as a cascade free NN scattering along with Fermi blocking.
- Density geometry parameters are adopted from scattering data.
- These parameters are fixed for the decay INC calc.
- In principle, the INC does not have fitting parameters.

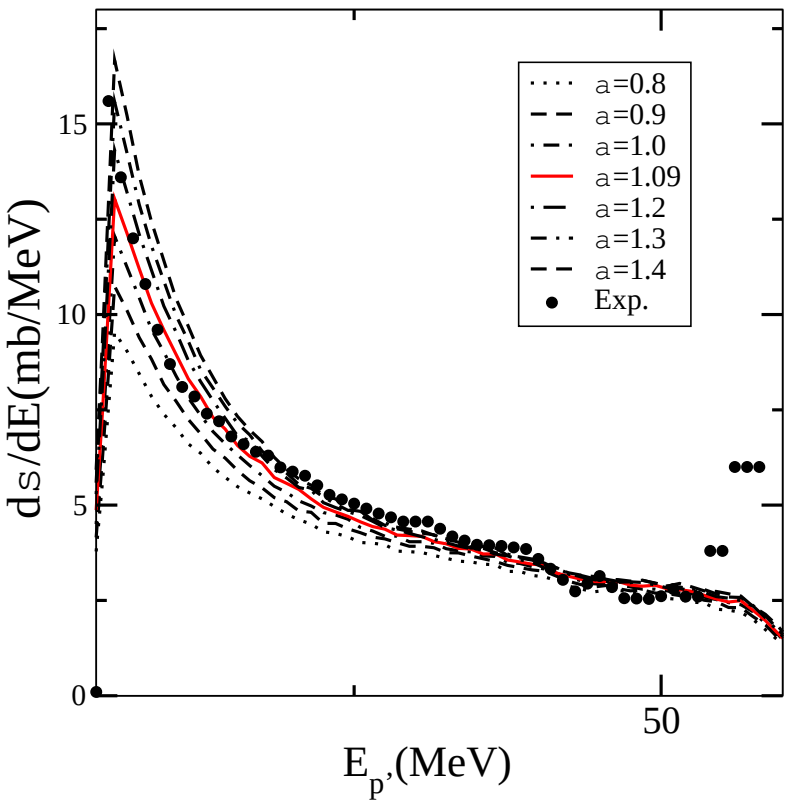
Mass Dependence

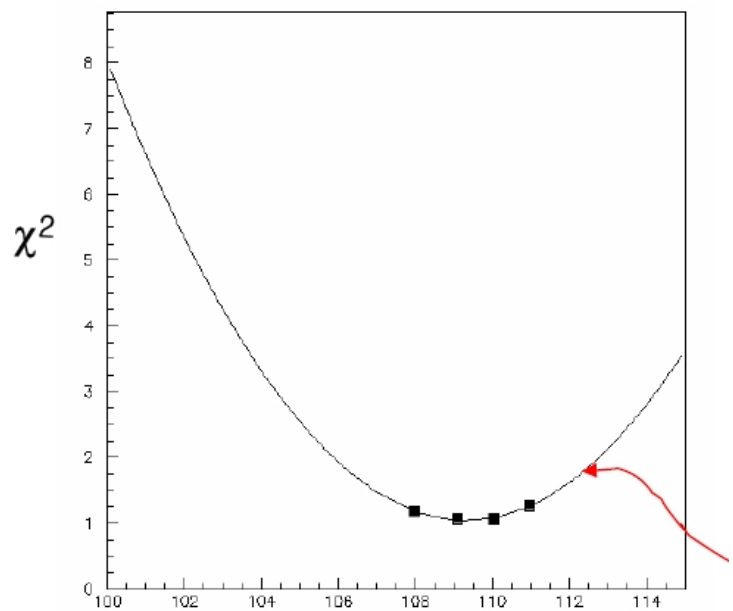


M. Kim, JKPS 46 ('05) 805

INC and a renormalization parameter

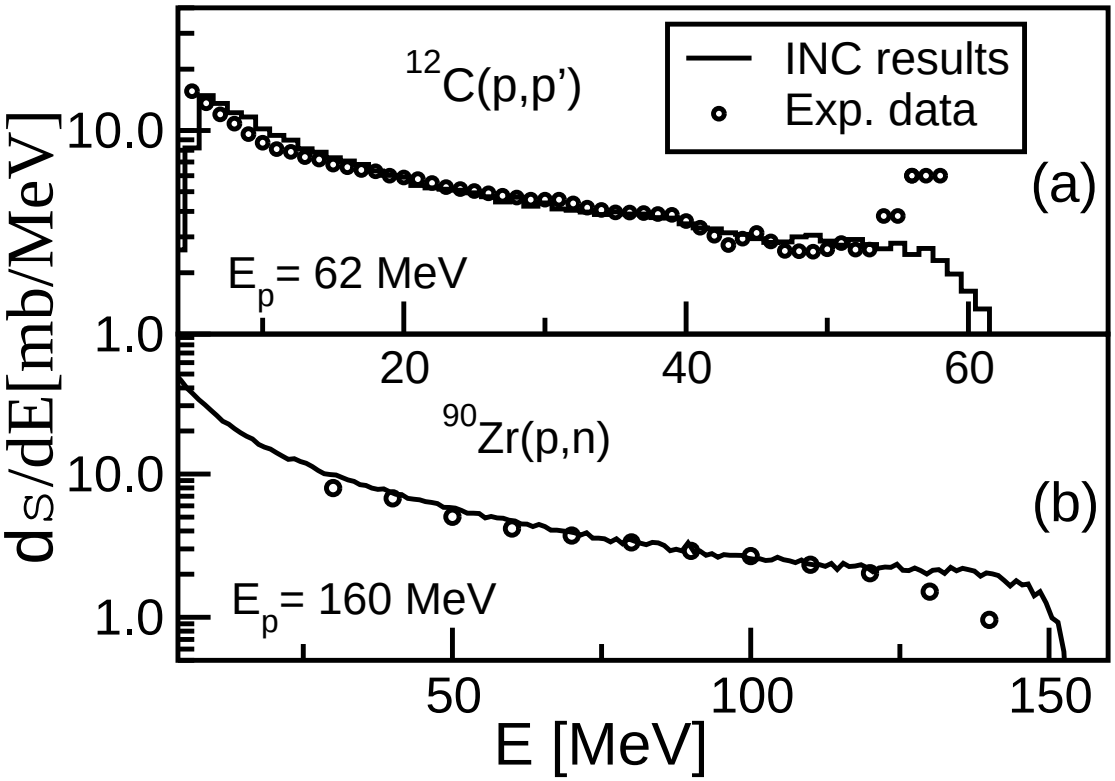
- In principle, INC model does not have fitting parameters.
- However, to reproduce FSI in NMWD, we used INC as a fitting function for scattering data by renormalizing the $\sigma_{NN} \rightarrow \alpha\sigma_{NN}$.
- Renormalization param., α=1.09+-0.04, defines the experimental FSI.
- Then INC carry this exp. FSI to the emitted nucleons in NMWD





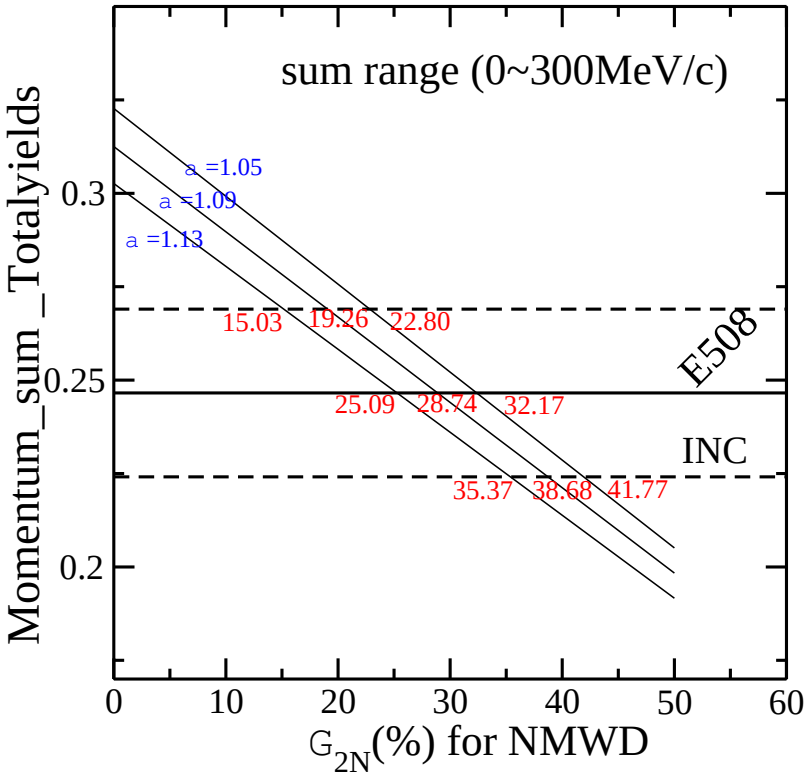
χ^2=0.08(α-109.3)^2+1.04

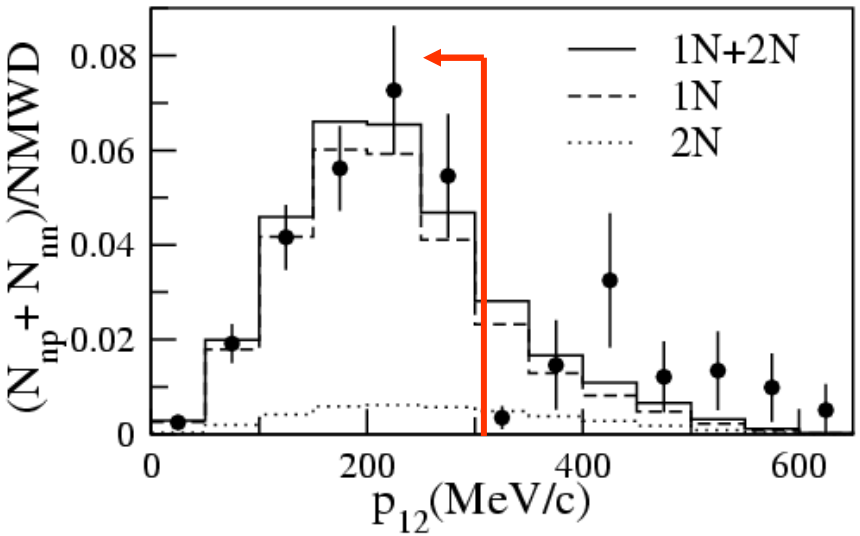
Reproduction



Three-Body Process (Γ_{2N}) and the quenching of yields

- **3-Body NMWD; Uniform phase space distribution**





- Total sum of the yields under 300MeV/c is reproduce with the branching ratio 2N-NMWD of 0.29.
- $b_{2N} \equiv \Gamma_{2N}/\Gamma_{nm}$ **=0.29± 0.13**

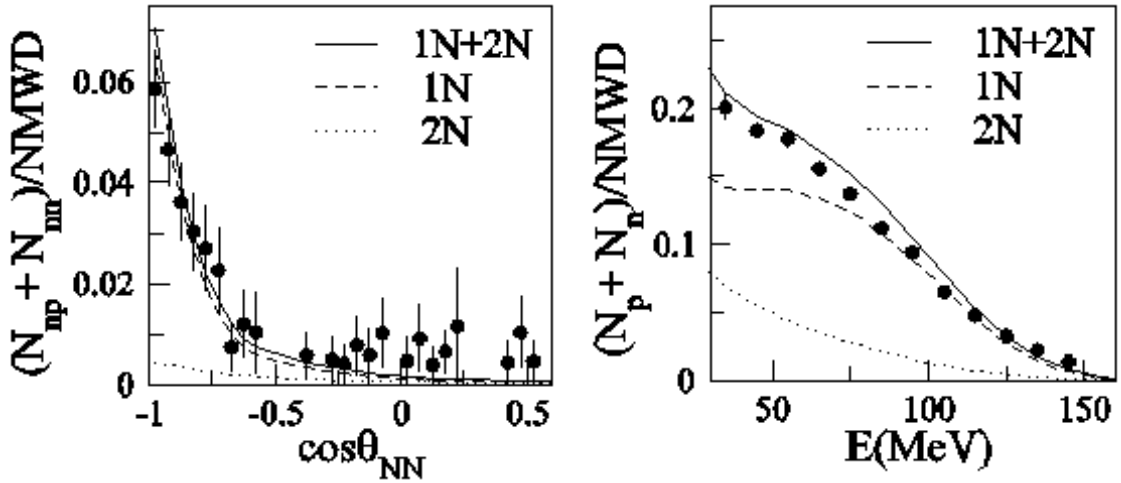


TABLE I: Branching ratios and decay widths of NMWD of ${}^{12}_{\Lambda}C$ are measured and compared with the current theoretical values. The bold letters are the present results determined along with Γ_{2N} in this work. The unit of the widths is Γ_Λ.

	Present Experiment	Theory Bauer[9]	Jido[19]	Itonaga[20]
Γ_n/Γ_p	0.51±0.13±0.05 [4]	0.327	0.53	0.503
Γ_{nm}	0.95±0.04 [16–18]	0.876		
b_{2N}	**0.29 ± 0.13**	0.288		
Γ_{2N}	**0.27 ± 0.13**	0.252		
Γ_{1N}	**0.68 ± 0.13**	0.624	0.769	0.660
Γ_n	**0.23 ± 0.08**	0.154	0.265	0.222
Γ_p	**0.45 ± 0.10**	0.470	0.504	0.438

- **Γ_{2N} agrees with the current theo. Prediction.**
- **Γ_n, Γ_p agree with those of the most extensive recent calculation.**
- **Errors are big, 20-45%.**

  → Experiment(J-PARC E18)

Summary

1. We have measured the branching ratio of 3-Body NMWD of $^{12}{}_{\Lambda}C$, 0.29±0.13, for the first time.
2. Combining with the Γ_{nm}, we obtained the widths Γ_n and Γ_p including 3-body NMWD.
3. These results are very well agreed with the current 3-body model predictions.
4. However, the errors are big, 20-45% → For accurate meas.

J-PARC E18 ; Γ_{2N} (3-body decay process), Γ_n ,Γ_p for $^{12}{}_{\Lambda}C$

KEK-PS E508 collaboration

KEK, RIKEN, Seoul N.Univ., GSI,
Tohoku Univ., Osaka Univ., Univ. Tokyo,
Osaka Elec. Comm. Univ., 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

Extra

Partial decay widths of NMWD

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Γ_n	**0.23 ± 0.08**	0.154	0.265	0.222
Γ_p	**0.45 ± 0.10**	0.470	0.504	0.438

- **Units ; Γ_Λ**
- **b_{2N} is derived from the quenching of yields of low missing momentum which is of bb kinematics events.**
- **Γ_{2N} agrees with the current theo. Prediction.**
- **Γ_n, Γ_p agree with those of the most extensive recent calculation.**
- **Errors are big, 20-50%. → Experiment(J-PARC E18) ; Extensive study including the non-bb events, namely those of the high missing momentum.**

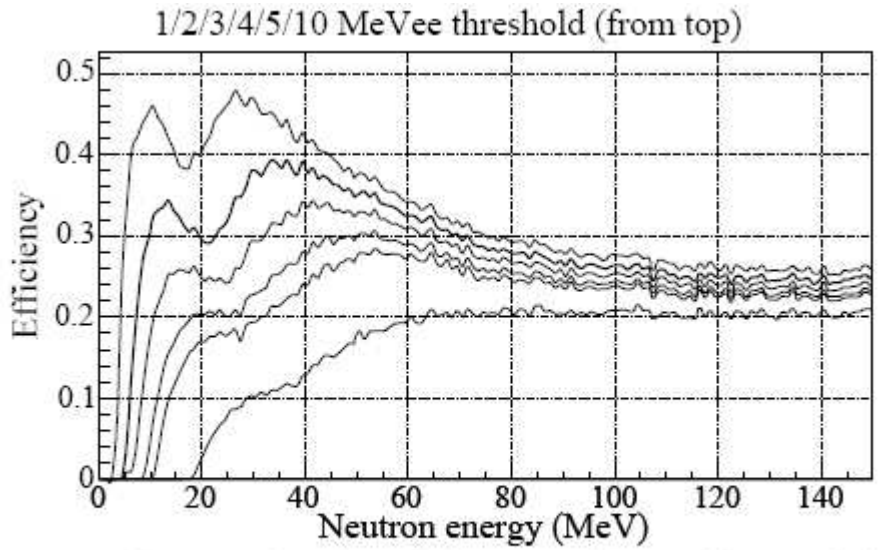


Figure 4.13: The energy dependence of the neutron detection efficiency calculated by the DEMONS code for the present setup. The thresholds are 1, 2, 3, 4, 5 and 10 MeVee from top.

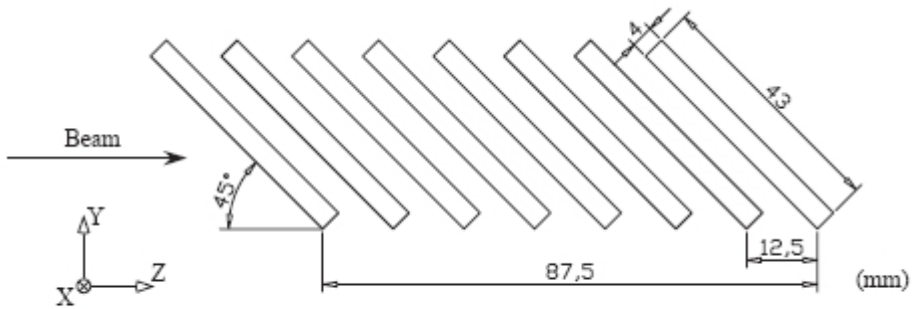


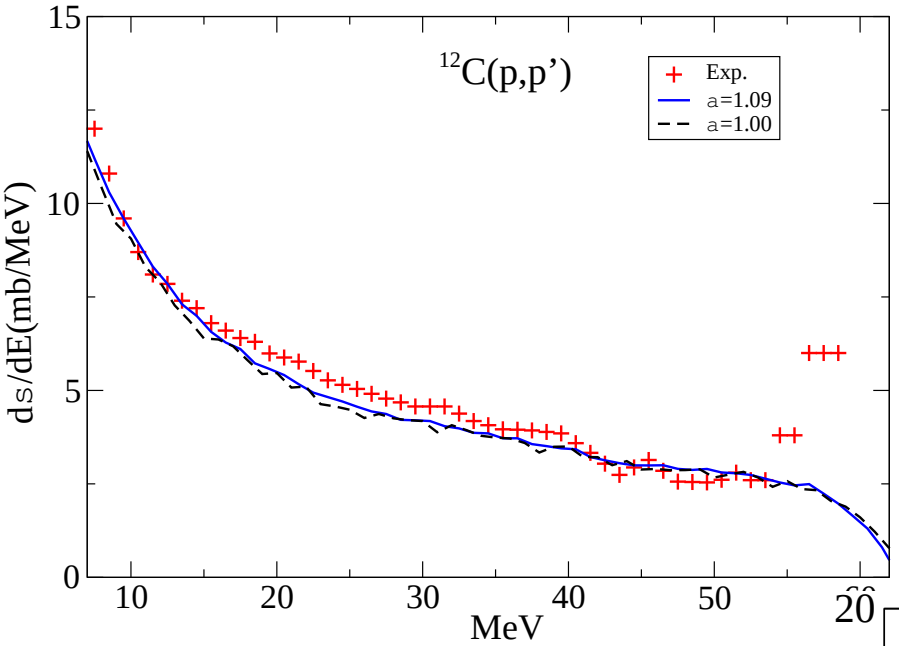
Figure 2.20: Configuration of the E508 target.

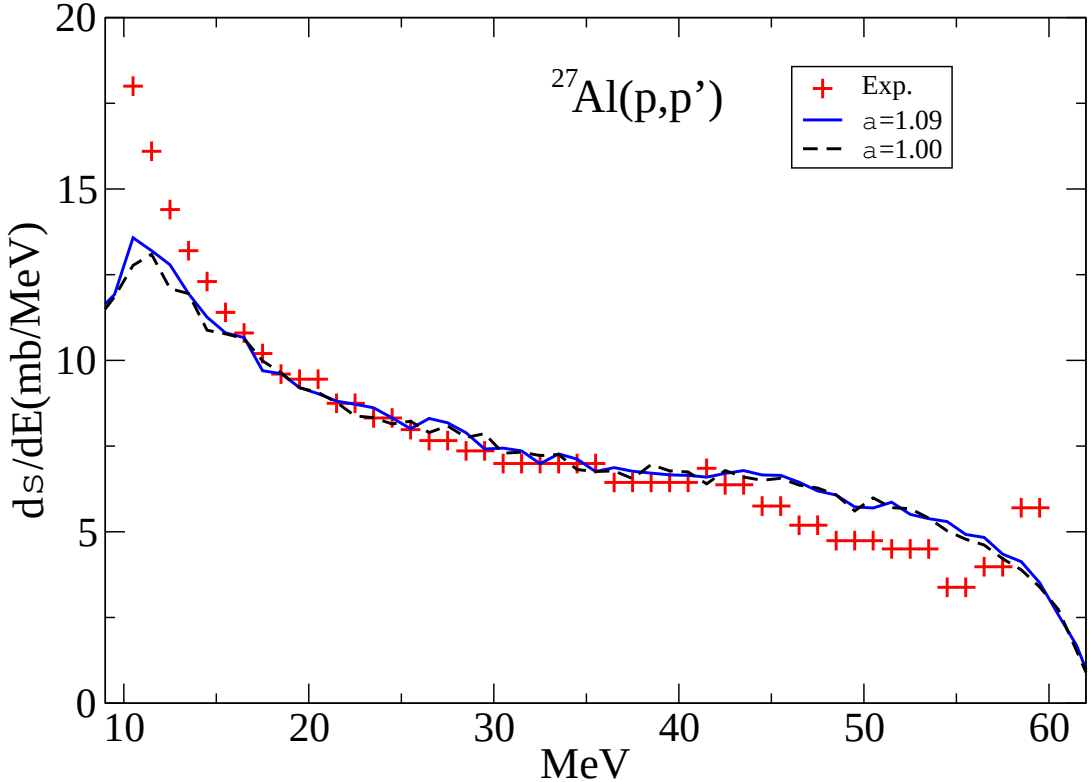
Korea-Japan Collaboration

- 1990~1991; Prof. Yamazaki and Prof. Nakai visited Korea and introduced N. Physics activity in Japan and the new KEK-PS program.
- 1992 ; started the KOSEF-JSPS international collaboration program and participated the E140a experiment of Prof. Hashimoto.
- 1993 ; proposed the lifetime measurement E307 in collaboration with Prof. Hashimoto. It was the lifetime and proton measurement of Λ hypernuclei and found the saturation of the total decay width at around carbon.
- E369 ; Neutron measurement; Breakthrough of the Γ_n/Γ_p puzzle.
- E462/E508; First coincidence measurement of NMWD and solved the Γ_n/Γ_p puzzle problem.
- 2006 ; JPARC P18; proposal for 3-body NMWD decay.
- 2007; Got 1st stage approval and we are now preparing for it.

- The collaboration was very successful, I consider.
- It was fun and enjoyable, so I would like to thank all the collaborators.
- I am quite sure it to be continued and further blossomed in J-PARC collaboration experiments.

Thank you very much.


^{12}C(p,p')
Exp.
a=1.09
a=1.00
ds/dE(mb/MeV)
MeV
0
5
10
15
10
20
30
40
50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Exp.
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a=1.00
ds/dE(mb/MeV)
MeV
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5
10
15
20
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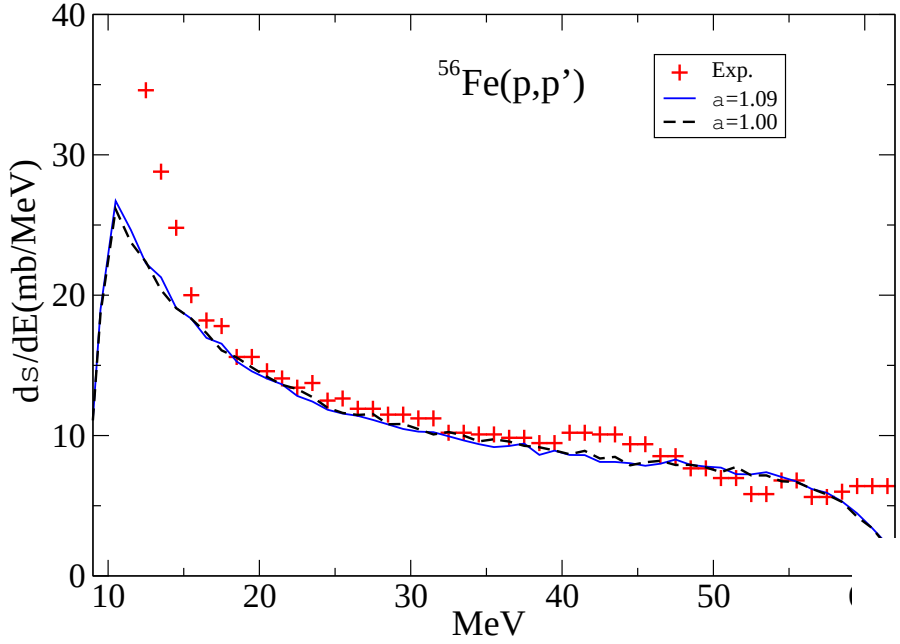
30
40
50
60


^{56}Fe(p,p')
Exp.
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dS/dE(mb/MeV)
MeV
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20
30
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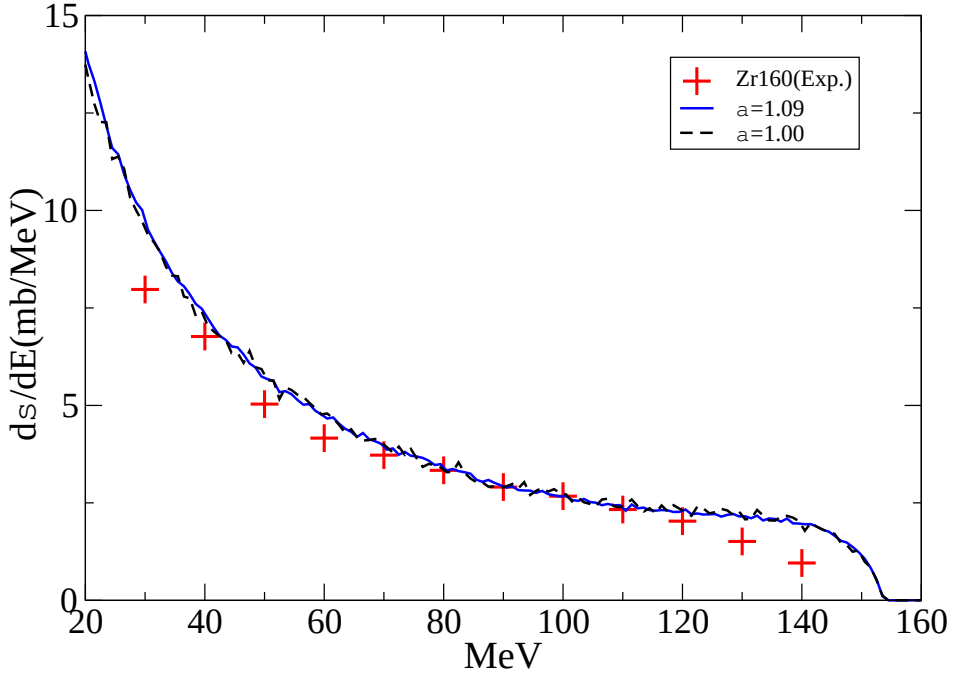
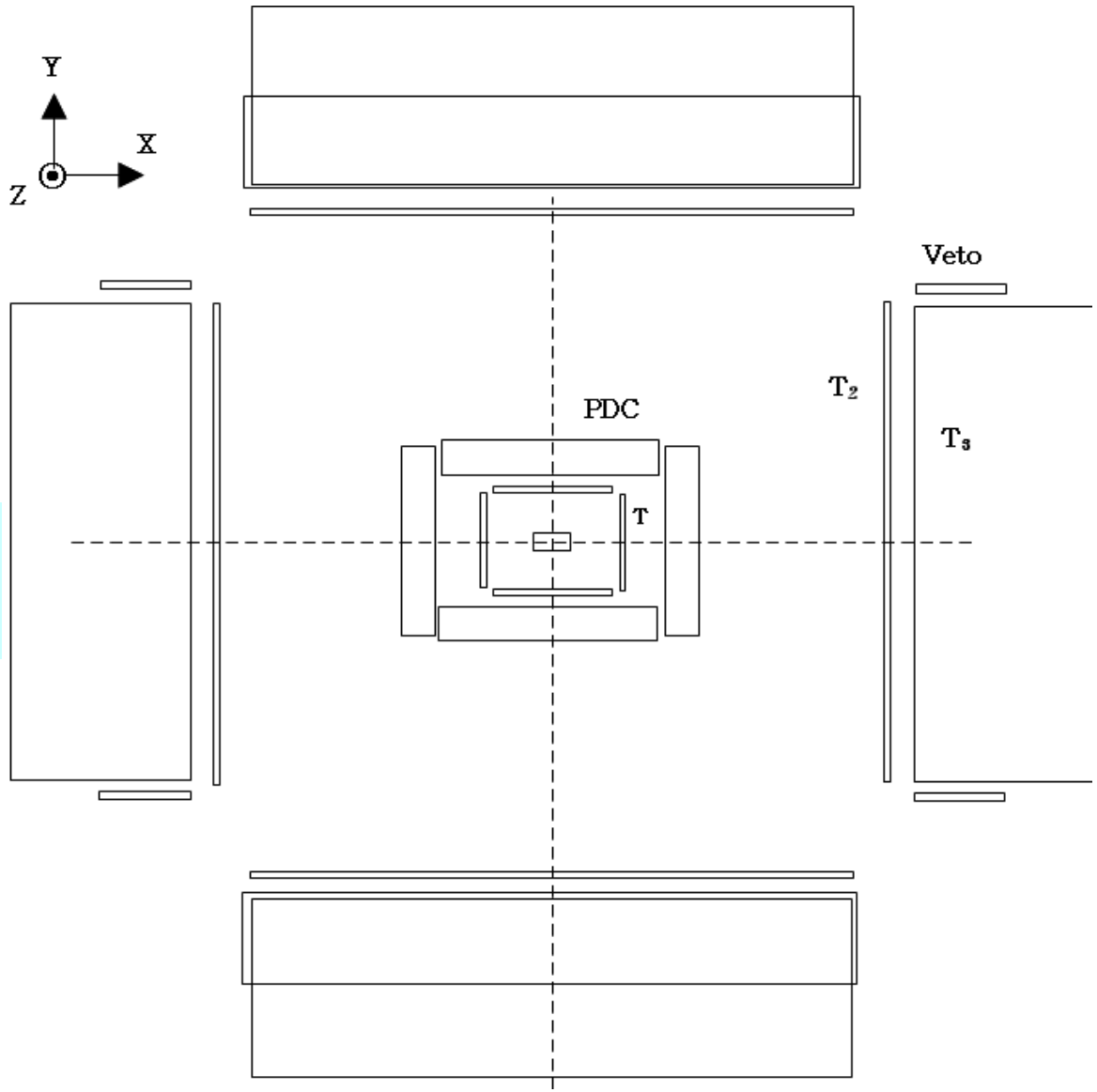
20
30
40
50

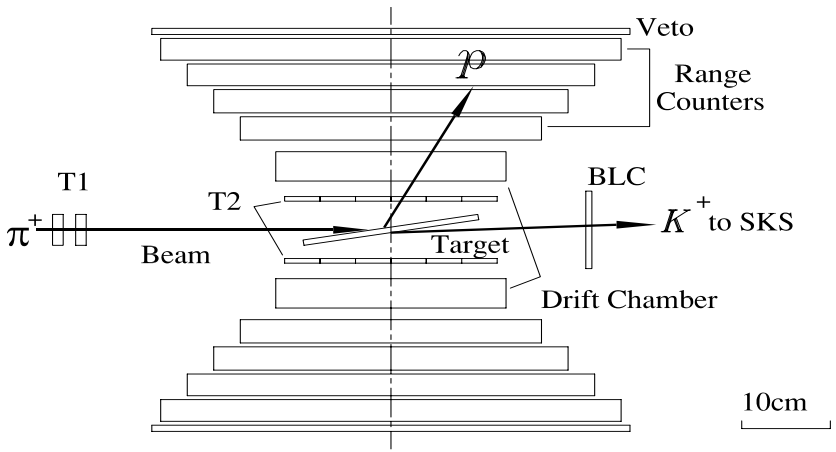

Zr160(Exp.)
a=1.09
a=1.00
dS/dE(mb/MeV)
MeV
0
5
10
15
20
40
60
80
100
120
140
160

Decay Counter Setup (J-PARC E18)

- Covers ~50% solid angle; 2(solid angle)x3(beam)



Lifetime and Proton Measurement (E307)

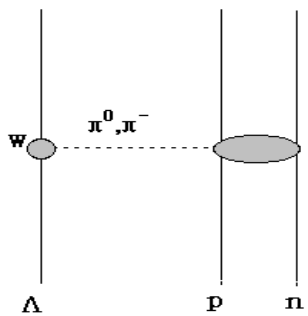


E307 decay counter setup

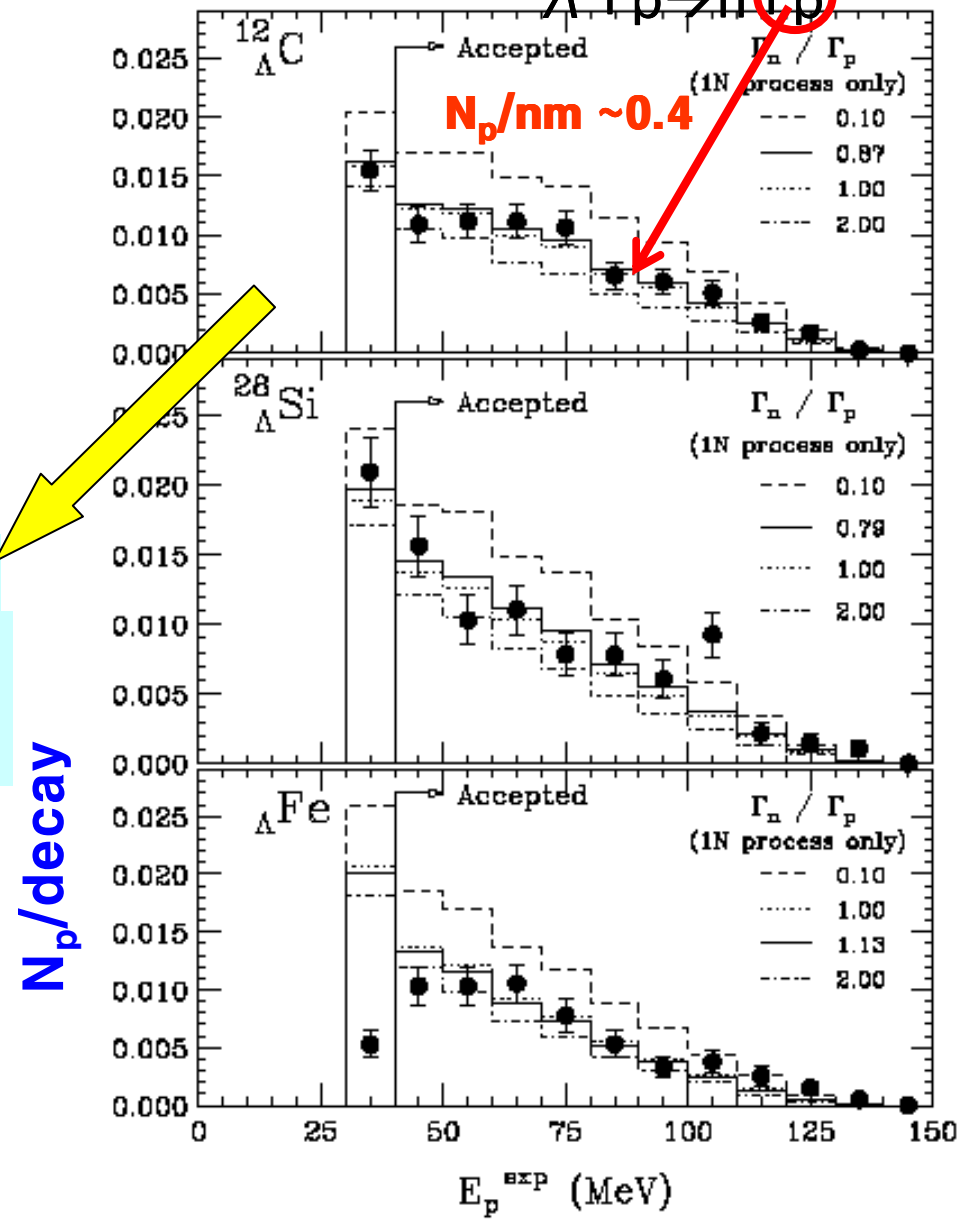
Comparison to INC results gave

$$\frac{\Gamma_n}{\Gamma_p} \rightarrow \begin{pmatrix} 0.87 \pm 0.09 \pm 0.21 \ \ (1N) \\ 0.60 \pm 0.11 \pm 0.23 \ \ (1N+2N) \end{pmatrix}$$

where 2N ; ΛNN → NNN.

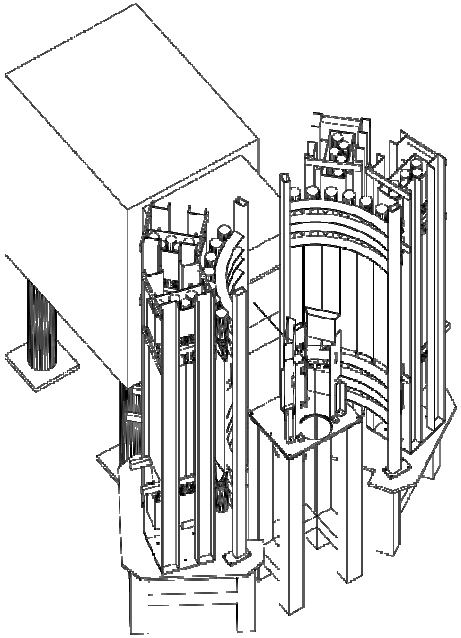


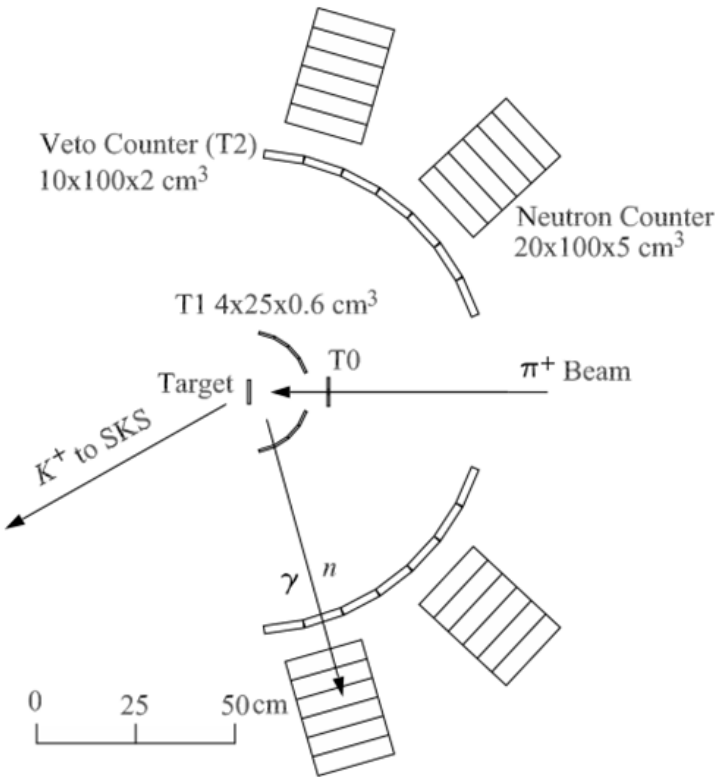
Λ+n→n+n
Λ+p→n+p

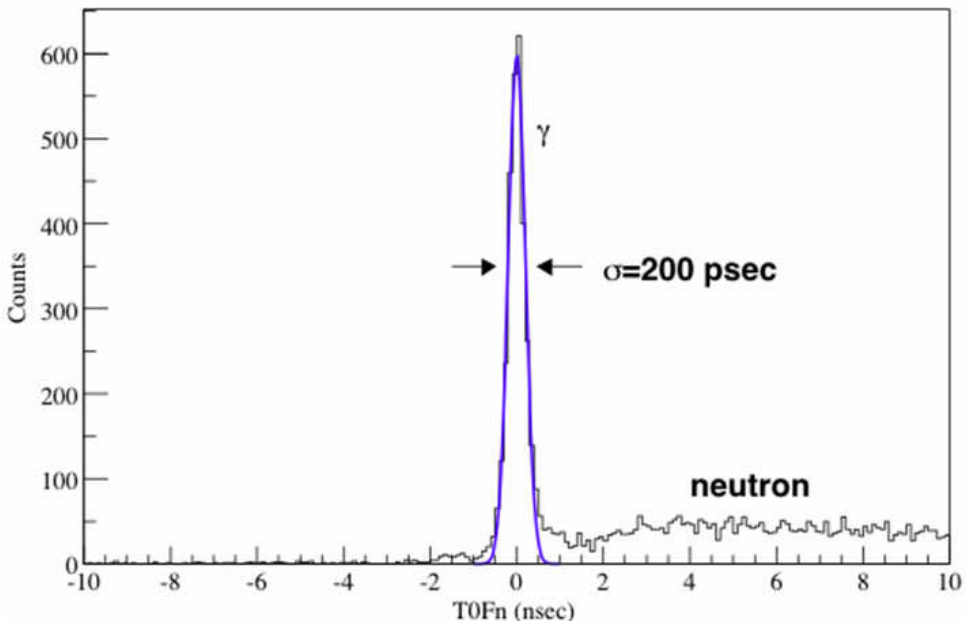


Neutron Measurement (E369)

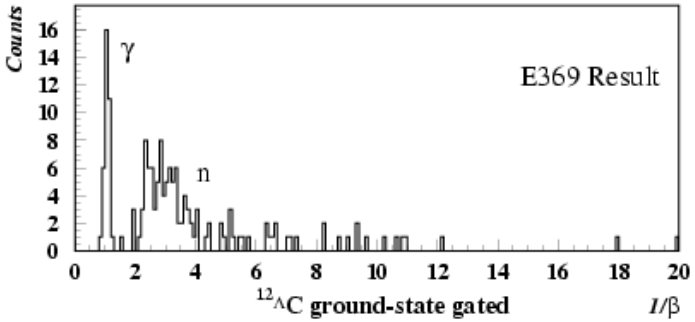
- Neutron spectra measured.
- Target; 12C, 51V and 89Y
- n-γ seperation by TOF

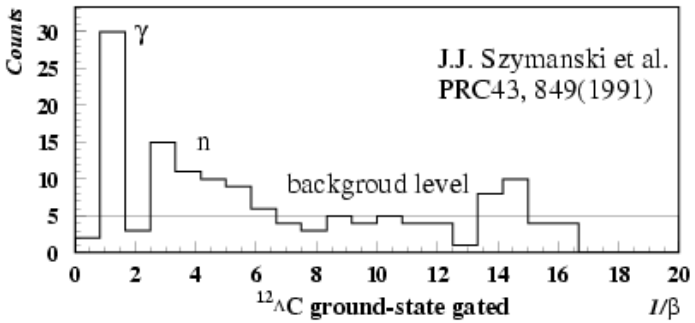


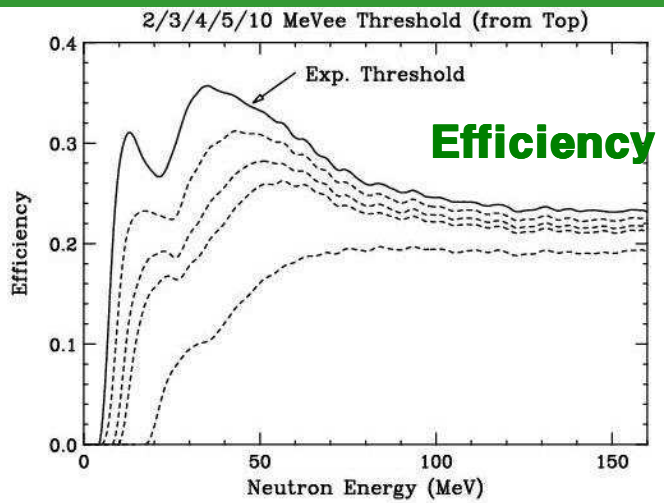


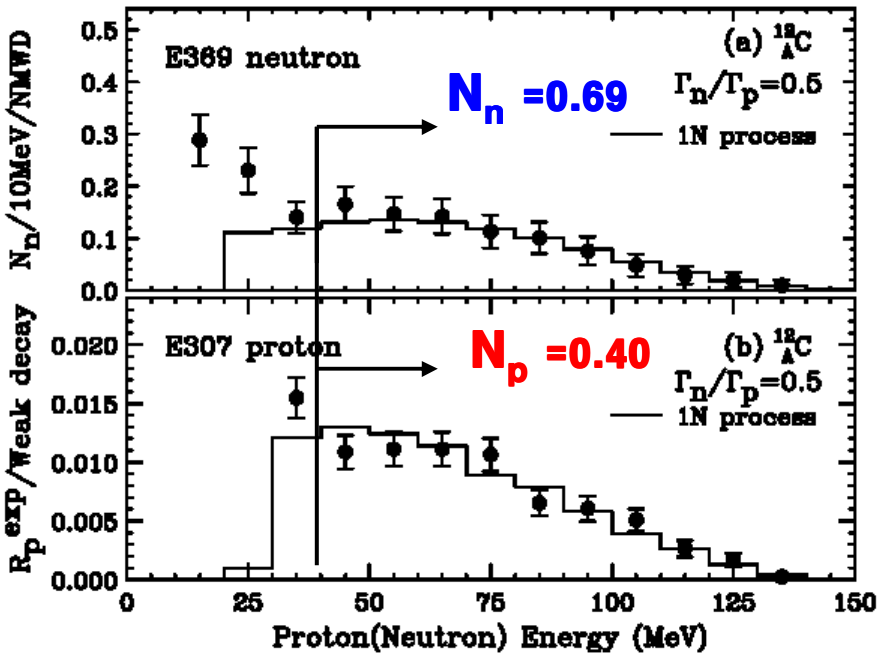


Neutron Spectrum (E369)









- N_n is compared with N_p.
- N_n (> 40 MeV) = 0.69 while N_p = 0.40 (E307)

HYP03 Conf.

Γ_n/Γ_p ratio

E307/E369 Experiment ;

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

- Obtained almost model independent way
- Large sys. error due to Γ_{nm} is cancelled
- First exp result to show a significantly smaller ratio than unity.

However, some ambiguities still exist due to

- final state int.
- 2N induced NMWD.

→

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

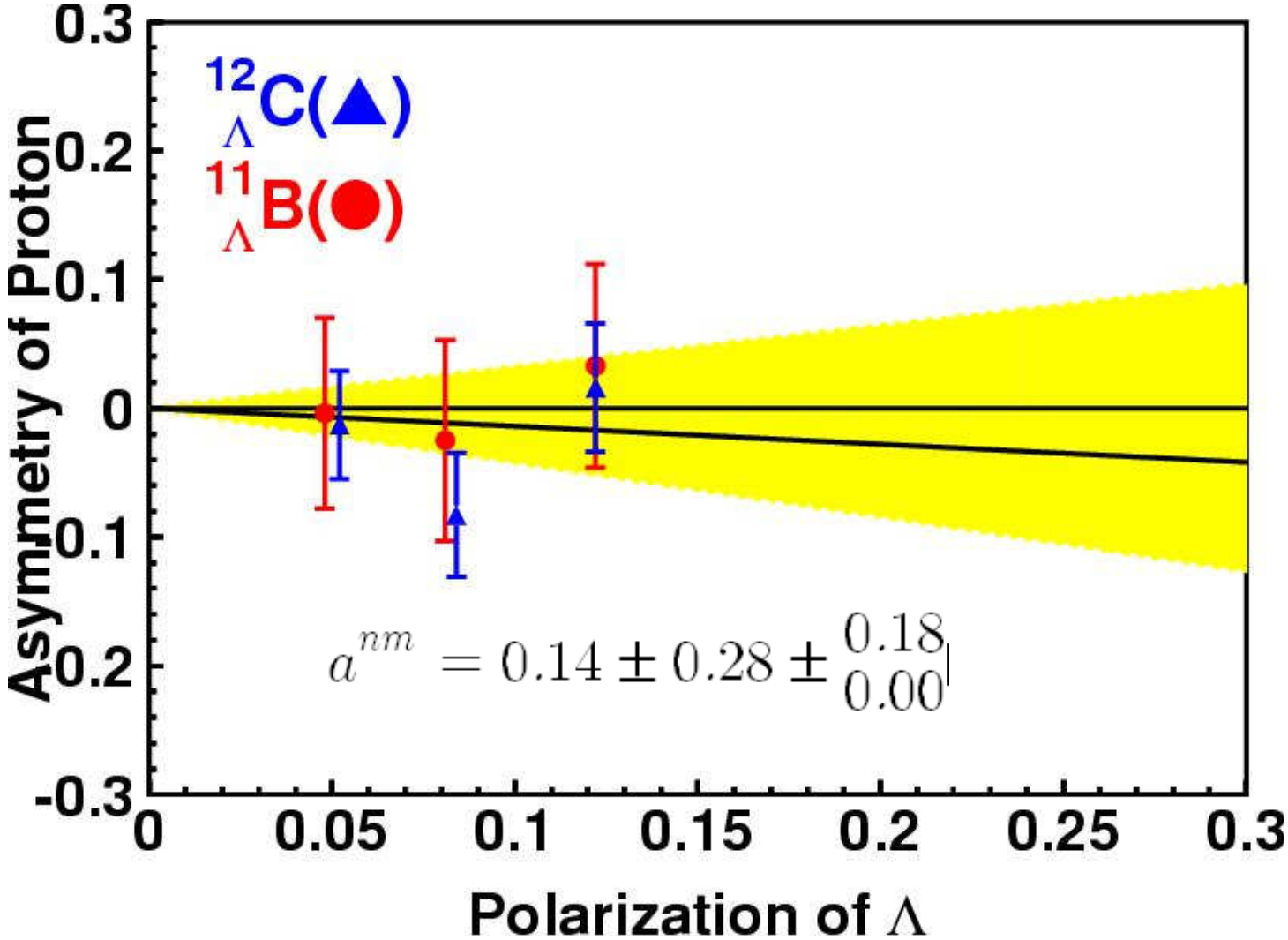
Asymmetry issue:

Serious inconsistency among α_{nm} for C.

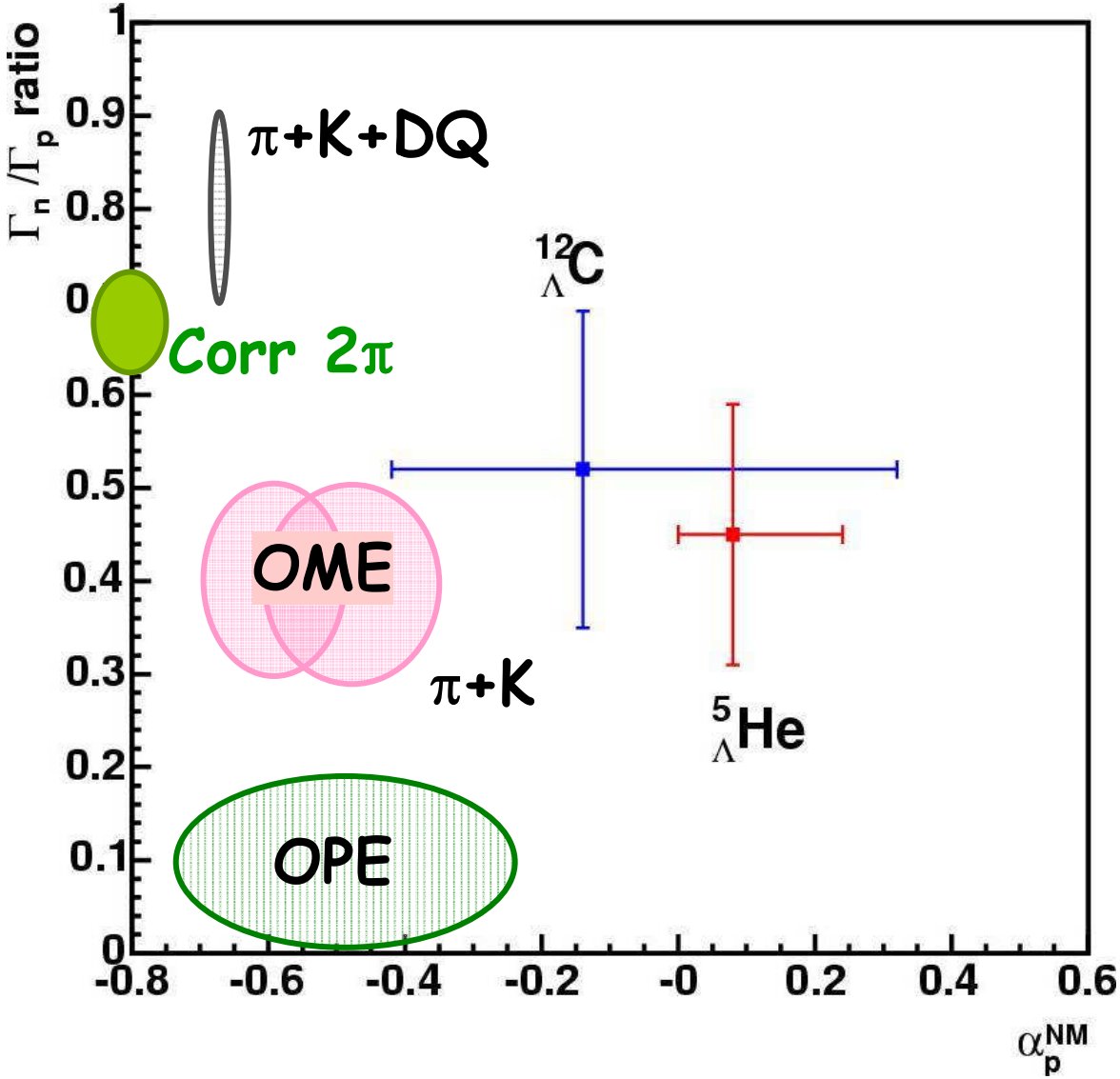
Korea- Japan Collaboration

- In retrospect, for me the collaboration was quite successful and

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

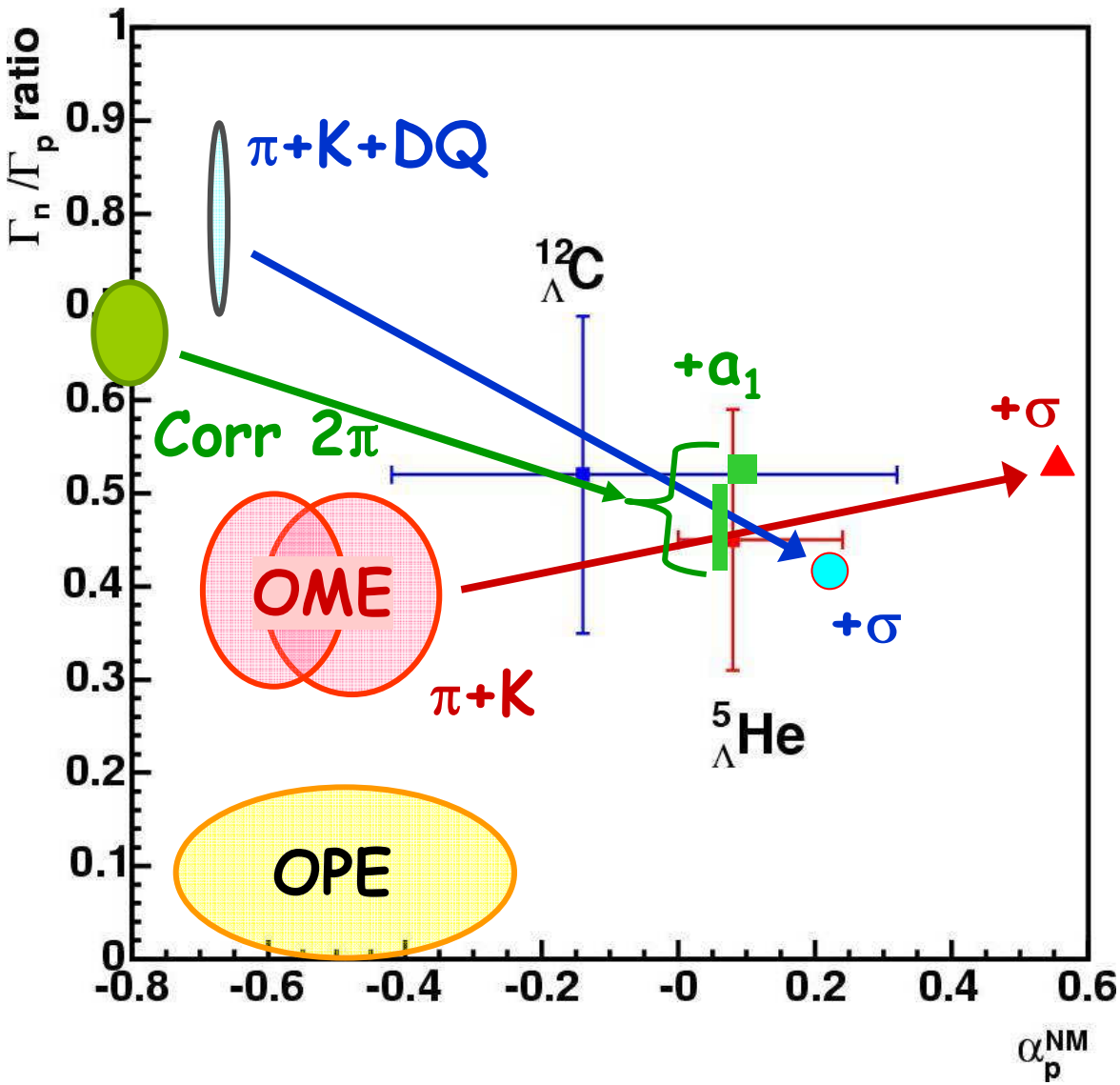


Status of Γ_n/Γ_p and α_p^{nm}



- Models explain Γ_n/Γ_p, but not a_p^{nm} !!
- Serious inconsistency between theo. and exp. α^{nm} values.

Most recent status of Γ_n/Γ_p and α_p^{nm}



- +σ meson; Sasaki et al., PRC 71 035502 ('05)
- +a_1 meson; Itonaga et al PRC 77 044605 ('08)

Summarising on the decay widths of NMWD

1. NN Correlation data show two groups of missing momentum, low and high mom groups. The HM group tells the existence of many-body process.
2. FSI calculation strongly indicates that the reason behind the Γ_n/Γ_p puzzle was the quenching of the nucleon yields in NMWD.
3. The degree of the quenching is well explained simply by adopting the uniform phase space distribution of the 3-body process, but of the significant fraction of NMWD.
4. In order to extract the most fundamental decay observables, Γ_n, Γ_p accurately, one has to determine Γ_{2N} first. → J-PARC (E18).
5. The Γ2N is

Status of NMWD of Λ hypernuclei

Urgent problems to be solved ;

- **$\Delta I=1/2$ rule (I: $^{4}_{\Lambda}He$)** → **J-PARC E22**
- **3-body process of Weak Decay;**

  Is there really such processes?

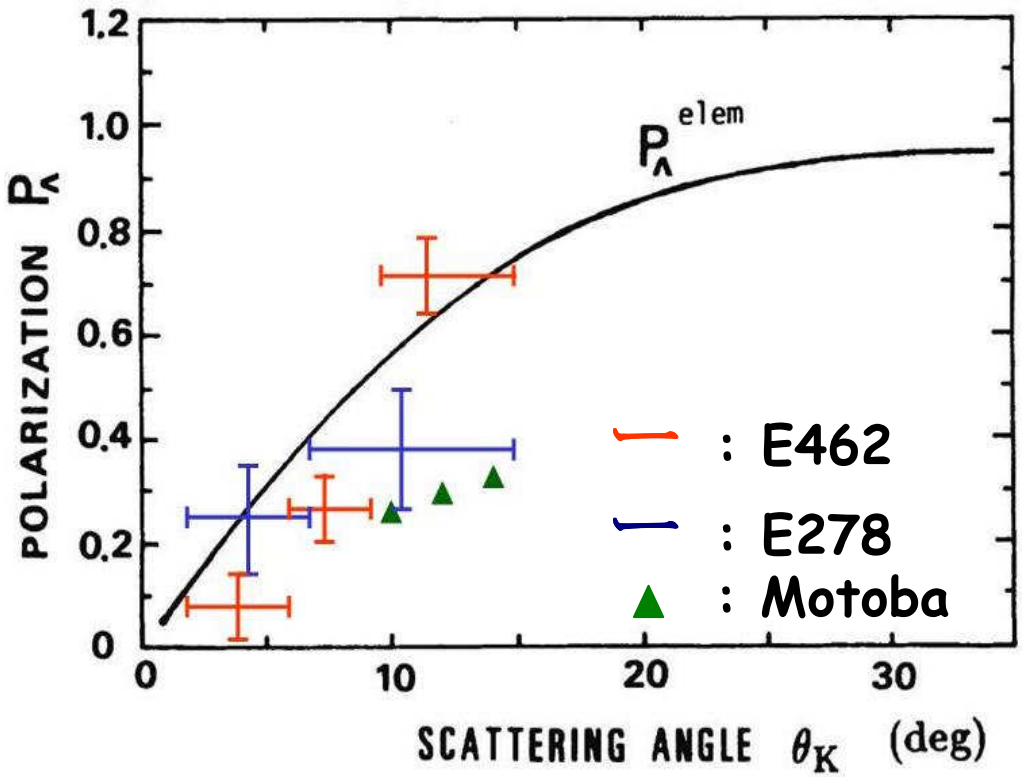
  How much contribution?

  Why 3-body effect is so strong that it is comparabe to 2-body effect?

  → **J-PARC E18**
- **Branching ratios of NMWD;** It has been so long, but accurate branching ratios are not available yet.

→ **Since the contribution of 3-body process seems significant, we have to measure first of all.**

Asymmetry measurement of decay proton

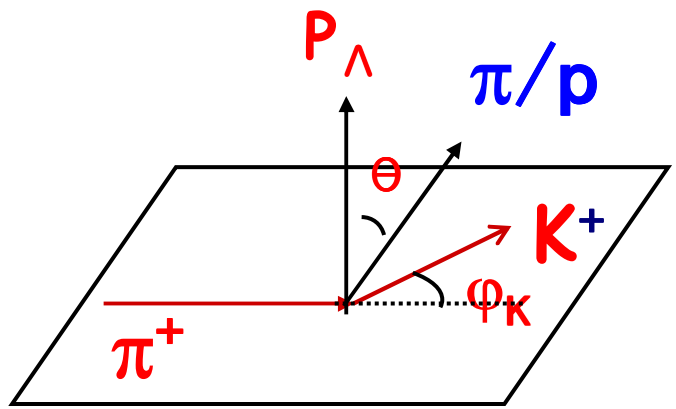


$$N(\theta) = N_0 \, (1 + Ay \cos\theta)$$

$$= N_0 \, (1 + \alpha_p P_\Lambda \cos\theta)$$

(α_p: Asymmetry parameter)

$$Ay = \frac{N(0) - N(180)}{N(0) + N(180)}$$



Previous situation of Asymmetry Parameter

Asymmetry Parameter

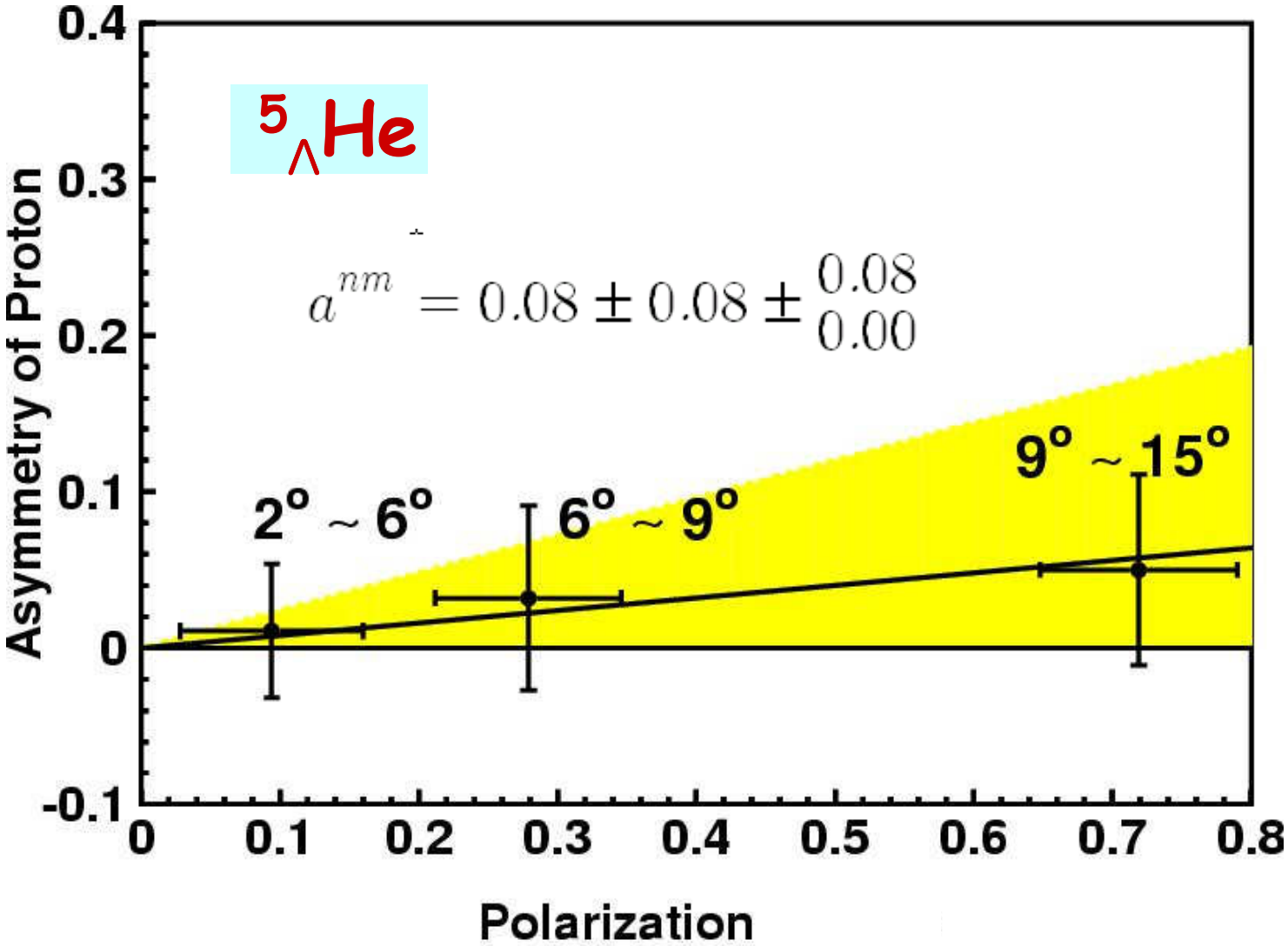
Previous experiments		Theoretical prediction
$^{5}{}_{\Lambda}He$: 0.24 ± 0.22	⟷	$-0.6 \sim -0.8$
$^{12}{}_{\Lambda}C, ^{11}{}_{\Lambda}B$: -1.3 ± 0.4		OME Ex.
Ajimura *et al.*		π+K+DQ Ex. etc.

- High Statistics
- Exclusive identification of $\Lambda p \rightarrow np$ channel

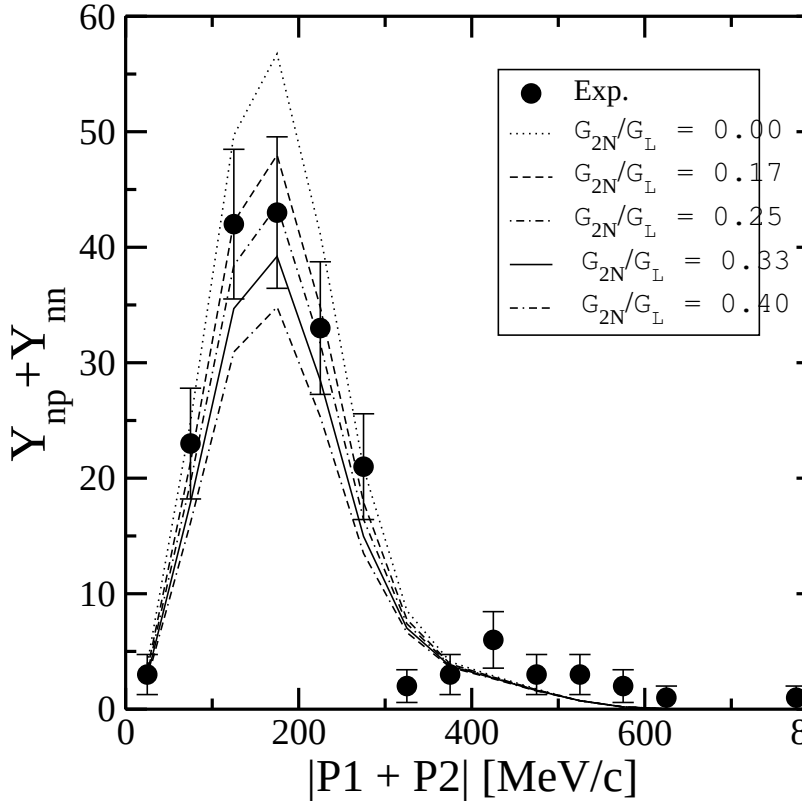
Exclusive Coin. Exp.

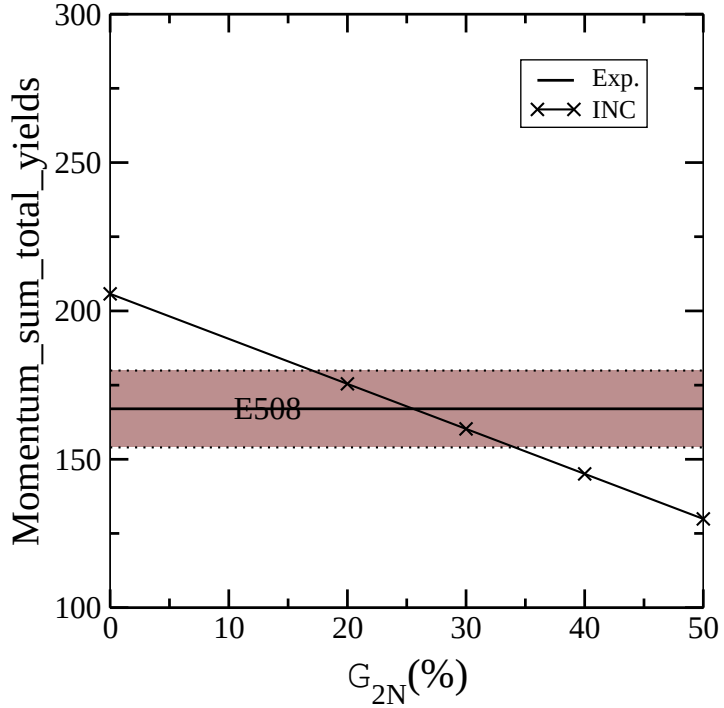
E462/E508

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



⟺ **Theory: - 0.6 ~ - 0.8**



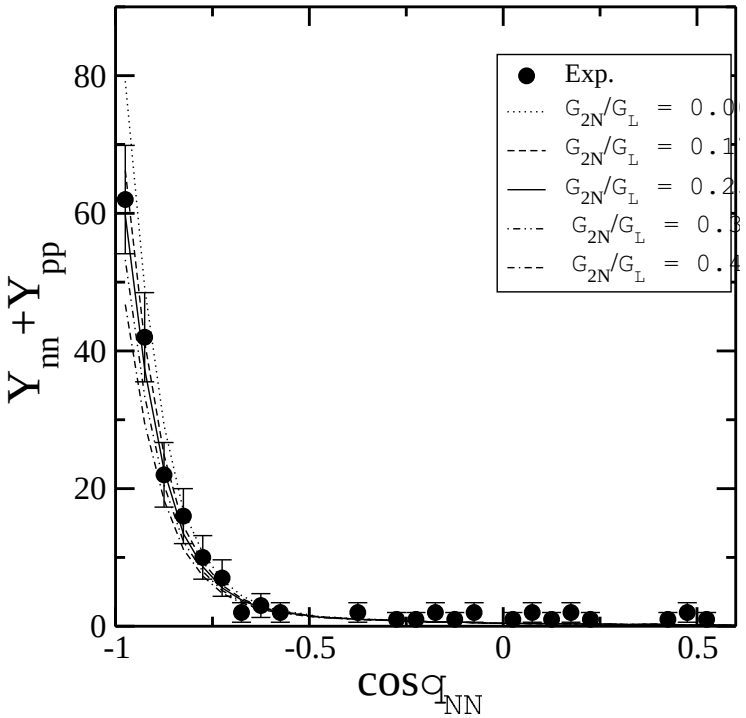


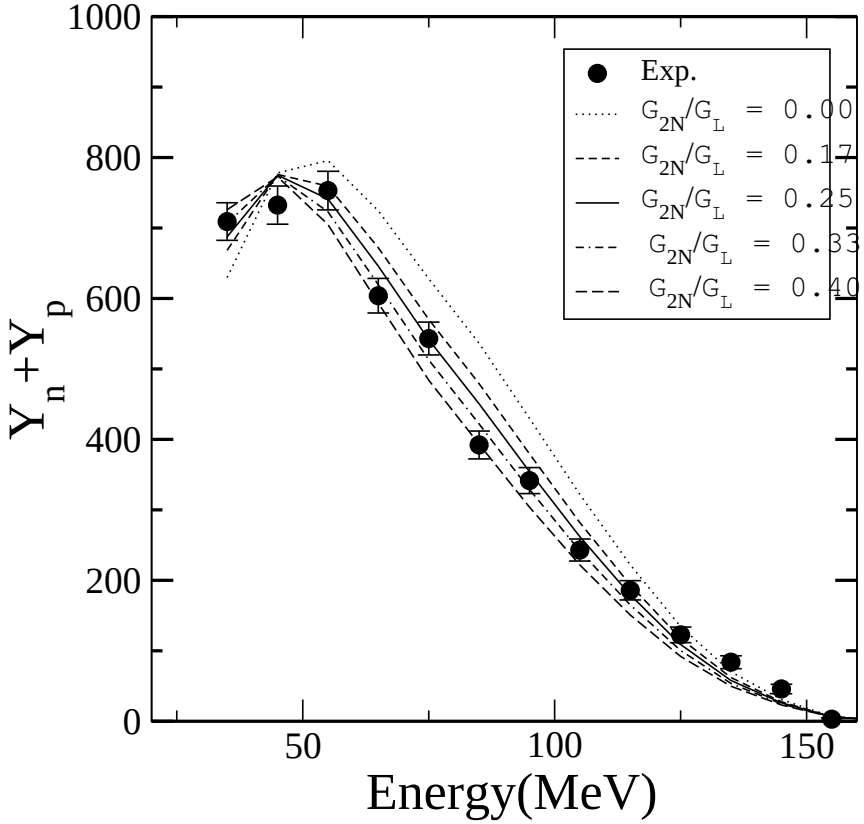
- **For 2N-NMWD, we adopted t kinematics of uniform phase space sharing of 3 nucleons.**
-

- Total yields in LM region is produced with

$$b_{2N} = \Gamma_{2N}/\Gamma_{nm}$$

$$= 0.261 \pm 0.086.$$


Exp.
G2N/GL = 0.0
G2N/GL = 0.1
G2N/GL = 0.2
G2N/GL = 0.3
G2N/GL = 0.4
Ynn+Ypp
cosθNN
80
60
40
20
0
-1
-0.5
0
0.5


Exp.
G2N/GL = 0.00
G2N/GL = 0.17
G2N/GL = 0.25
G2N/GL = 0.33
G2N/GL = 0.40
Yn+Yp
Energy(MeV)
1000
800
600
400
200
0
50
100
150

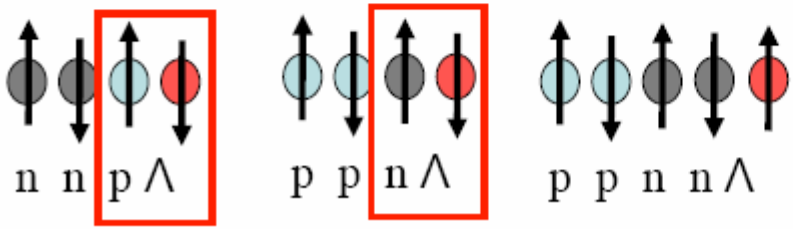
$\Delta I=1/2$ rule and Nonmesonic Weak Decay of ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$.

Spin / isospin dependence

$$\Gamma_{nm}({}^{4}_{\Lambda}H) = (3R_{n1} + R_{n0} + \boxed{2R_{p0}}) \times \rho_4 / 6$$
$$\Gamma_{nm}({}^{4}_{\Lambda}He) = (\boxed{2R_{n0}} + 3R_{p1} + R_{p0}) \times \rho_4 / 6$$
$$\Gamma_{nm}({}^{5}_{\Lambda}He) = (3R_{n1} + R_{n0} + 3R_{p1} + R_{p0}) \times \rho_5 / 8$$

R_{NS} … N : $\Lambda n \rightarrow nn$, $\Lambda p \rightarrow np$
S : spin = 0 or 1

${}^{4}_{\Lambda}H$ ${}^{4}_{\Lambda}He$ ${}^{5}_{\Lambda}He$

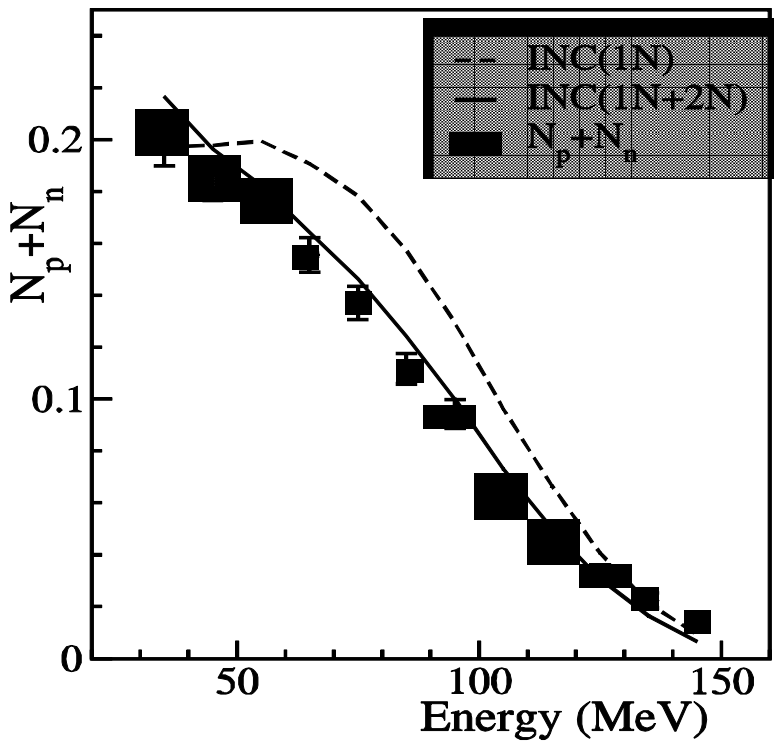


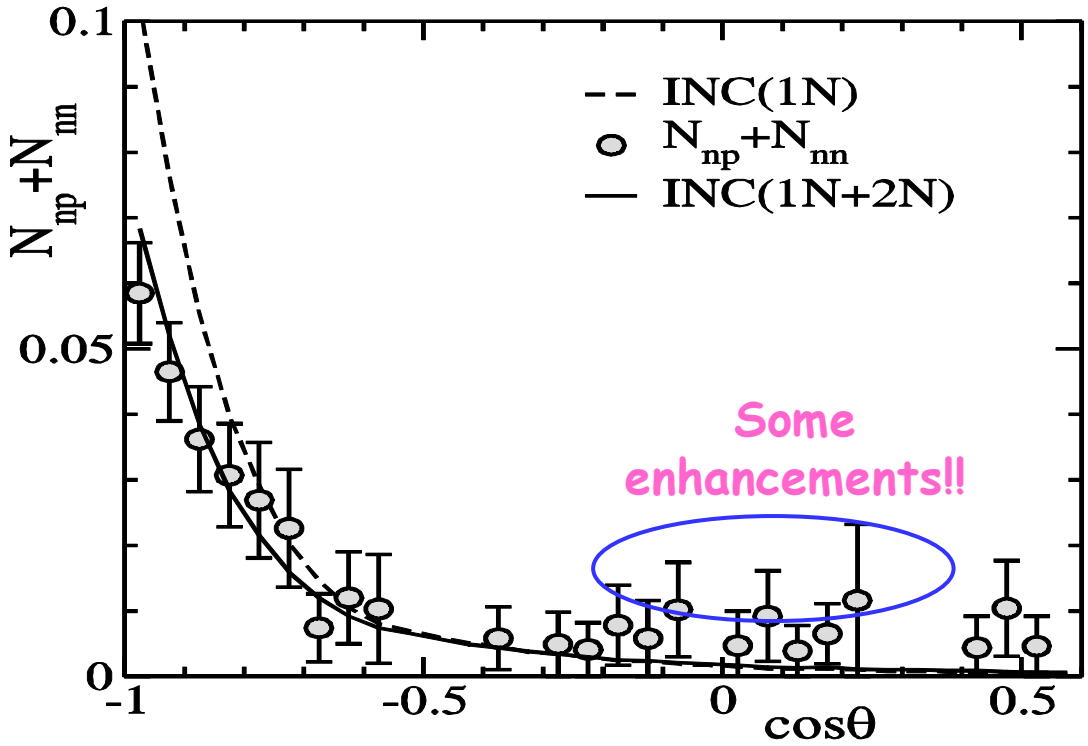
${}^{4}He$ (K^-,π^-) ${}^{4}_{\Lambda}He$ or
${}^{4}He$ (π^+,K^+) ${}^{4}_{\Lambda}He$
→ n+n back-to-back

${}^{4}He$ (K^-,π^0) ${}^{4}_{\Lambda}H$
→ p+n back-to-back
(π^0 spectrometer)

→ *Need one-order higher statistics.* → *J-PARC*

Extraction of Γ_{2N}.





For 2N-NMWD, we adopted the kinematics of uniform phase space sharing of 3 nucleons.

Γ_{2N} is extracted by fitting the N_p+N_n, $N_{pn}+N_{nn}$ (cosΘ).

In order to explain the quenching,

→ $\Gamma_{2N}\sim 0.4\Gamma_{nm}$

Momentum sum distribution.

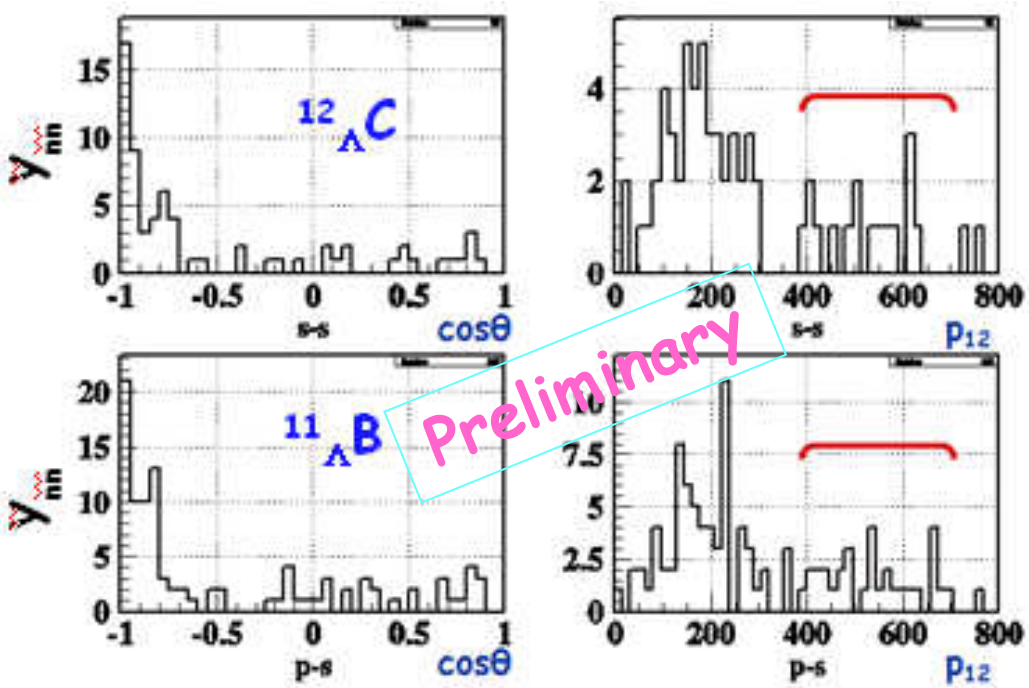
- Missing momentum dist.
  - $|p_1+p_2| \equiv p_{12}$
  - upper fig.; $^{12}{}_{\Lambda}C$
  - lower fig. ; $^{11}{}_{\Lambda}B$

We observe two groups;

- low mom(~150 MeV/c);

  1N NMWD?
- high mom(~500 MeV/c);

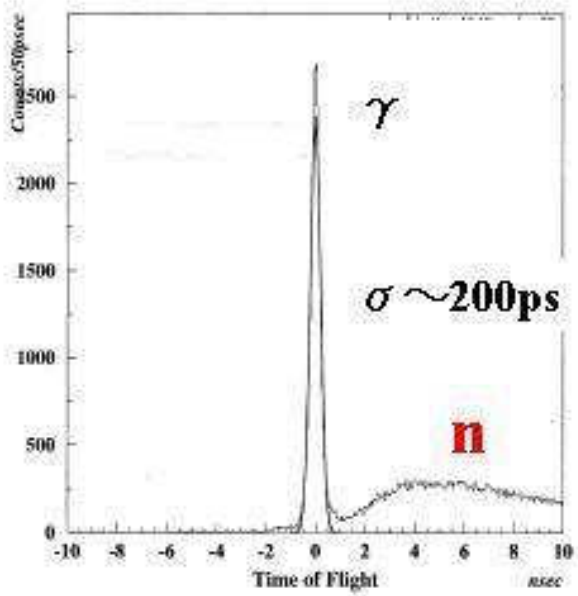
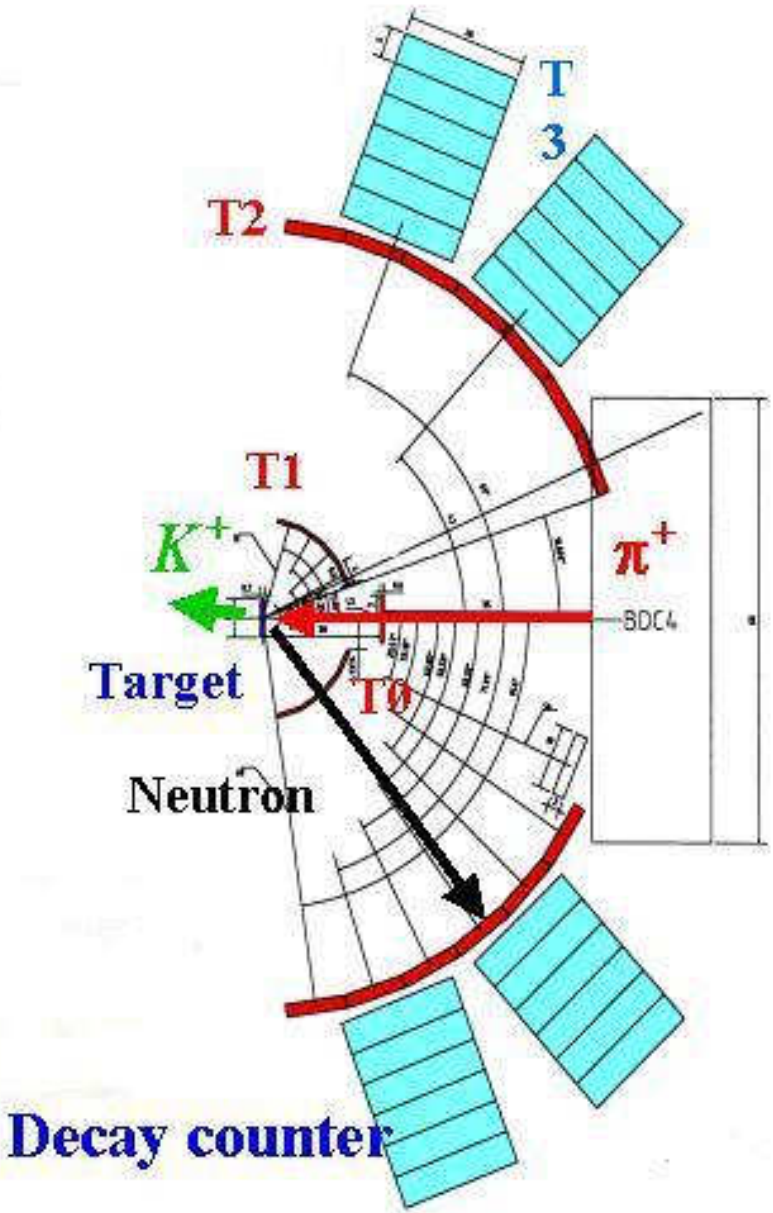
  What is this high mom group?



- Though the recoil momentum is high, the recoil energy should be small.
- It seems that not only the 3-nucleon-induced, but also many-nucleon induced NMWD exists..

E369 Experiment/Setup

Neutron spectra measured.

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

n / γ separation by TOF method