Towards a solution of the Γ_n/Γ_p Puzzle in the Non–Mesonic Weak Decay of Λ–Hypernuclei

G. Garbarino, *Università di Torino*

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- Decay Modes of Λ–Hypernuclei
- The Γ_n/Γ_p Puzzle
- The Asymmetry Puzzle
- Our approach
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- Conclusions

DECAY MODES OF Λ–HYPERNUCLEI

MESONIC

$$\Lambda \to \pi^0 n \qquad \Gamma_{\pi^0} \qquad p_N \simeq 100\,\text{MeV}$$
$$\Lambda \to \pi^- p \qquad \Gamma_{\pi^-}$$

NON–MESONIC

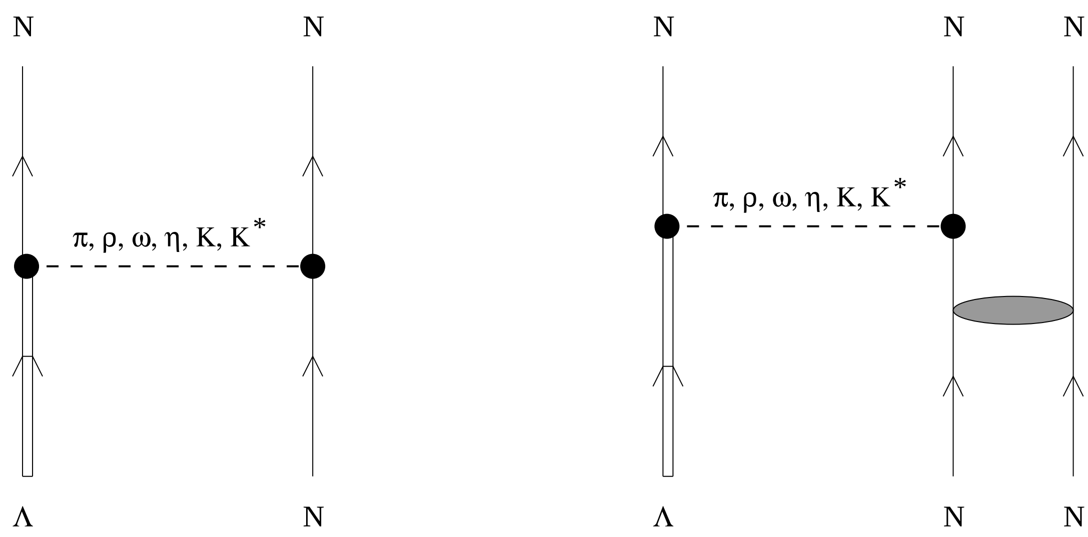
One–nucleon induced

$$\Lambda n \to nn \qquad \Gamma_n \qquad p_N \simeq 420\,\text{MeV}$$
$$\Lambda p \to np \qquad \Gamma_p$$

Two–nucleon induced

$$\Lambda NN \to nNN \qquad \Gamma_2 \qquad p_N \simeq 340\,\text{MeV}$$

$$\Gamma_{\rm T} = \Gamma_{\rm M} + \Gamma_{\rm NM} = \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_2$$



Pauli principle ⟹ the non–mesonic weak decay (NMWD) dominates over the mesonic one for all but the s–shell hypernuclei

THE Γ_n/Γ_p PUZZLE

For many years, a sound theoretical explanation of the large experimental values of Γ_n/Γ_p has been missing.

[W. M. Alberico and G. Garbarino, Phys. Rept. 369 (2002) 1–109]

Theory underestimates the central data for all considered hypernuclei:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Th} \ll \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Exp} \qquad 0.5 \lesssim \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Exp} \lesssim 2$$

but the large experimental error bars do not allow one to reach any definite conclusion.

The One–Pion–Exchange (OPE) model supplies very small ratios:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE} = 0.05 \div 0.20$$

but can reproduce the total non–mesonic rates observed for light and medium hypernuclei.

Other interaction mechanisms beyond the OPE might then be responsible for the overestimation of Γ_p and the underestimation of Γ_n

- heavier mesons (ρ, K, K^*, ω, η, $2\pi/\rho$, $2\pi/\sigma$)
- direct quark mechanism
- two–nucleon induced mechanism
- nucleon final state interactions

THE ASYMMETRY PUZZLE

Non–Mesonic Weak Decay of Polarized Λ–hypernuclei

Proton intensity:

$$I(\Theta) = I_0\left[1 + \mathcal{A}(\Theta)\right]$$

$$I_0 = \frac{\sum_M \sigma(J,M)}{2J+1} \qquad \mathcal{A}(\Theta) = P_y\, A_y \cos\Theta$$

$$\begin{aligned} P_y &= \text{hypernuclear polarization} \\ A_y &= \text{hypernuclear asymmetry parameter} \end{aligned}$$

$$A_y = \frac{3}{J+1}\,\frac{\sum_M M\,\sigma(J,M)}{\sum_M \sigma(J,M)}$$

$$\sigma(J,M) = \sum_F \left|\langle F|\mathcal{M}|I; J, M\rangle\right|^2$$

In the shell model weak–coupling scheme

$$\mathcal{A}(\Theta) = p_\Lambda\, a_\Lambda \cos\Theta$$

where

$$p_\Lambda = \begin{cases} -\dfrac{J}{J+1} P_y & \text{if } J = J_C - \frac{1}{2} \\ P_y & \text{if } J = J_C + \frac{1}{2} \end{cases}$$

Λ polarization

$$a_\Lambda = \begin{cases} -\dfrac{J+1}{J} A_y & \text{if } J = J_C - \frac{1}{2} \\ A_y & \text{if } J = J_C + \frac{1}{2} \end{cases}$$

intrinsic Λ asymmetry parameter

Experiments measure

$$\mathcal{A}^{\rm M}(0^\circ) = \frac{I^{\rm M}(0^\circ) - I^{\rm M}(180^\circ)}{I^{\rm M}(0^\circ) + I^{\rm M}(180^\circ)}$$

and determine

$$a_\Lambda^{\rm M} = \frac{\mathcal{A}^{\rm M}(0^\circ)}{p_\Lambda}$$

by using an indirect measurement (${}^{5}_{\Lambda}$He) or a theoretical evaluation (${}^{12}_{\Lambda}$C) of p_Λ. The relations

$$I^{\rm M}(\Theta) = I_0^{\rm M}\left[1 + \mathcal{A}^{\rm M}(\Theta)\right] \qquad \mathcal{A}^{\rm M}(\Theta) = p_\Lambda\, a_\Lambda^{\rm M} \cos\Theta$$

are thus assumed.

	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
K. Sasaki et al. a_Λ		
OPE	-0.44	
$\pi + K$	-0.36	
$\pi + K + \rm DQ$	-0.68	
A. Parreño et al.		
OPE	-0.25	-0.34
$\pi + K$	-0.61	-0.64
OME	-0.68	-0.73
KEK–E160 $a_\Lambda^{\rm M}$		-0.9 ± 0.3
KEK–E278	0.24 ± 0.22	
KEK–E508 (prel.)		-0.44 ± 0.32
KEK–E462 (prel.)	0.07 ± 0.08	

- Inconsistencies appear at the experimental level
- One expects $|a_\Lambda| > |a_\Lambda^{\rm M}|$ due to FSI effects

OUR APPROACH

[G. Garbarino, A. Parreño, A. Ramos, PRL 91 (2003) 112501, PRC 69 (2004) 054603]

Study of the NUCLEON DISTRIBUTIONS in the NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C hypernuclei

- SINGLE NUCLEON ENERGY SPECTRA
- NN ANGULAR AND ENERGY CORRELATIONS
- PROTON INTENSITIES FROM POLARIZED HYPERNUCLEI

$\Longrightarrow$ determine Γ_n/Γ_p and a_Λ

via the comparison with observed distributions

- Finite Nucleus treatment for $\Lambda N \to nN$ (OME $= \pi + \rho + K + K^* + \omega + \eta$)

  [A. Parreño, A. Ramos and C. Bennhold, PRC 56 (1997) 339; A. Parreño and A. Ramos, PRC 65 (2002) 015204]

- Polarization Propagator method in LDA for $\Lambda NN \to nNN$ (correlated OPE)

  [W.M. Alberico, A. De Pace, G. Garbarino and A. Ramos, PRC 61 (2000) 044314]

- Intranuclear Cascade calculation

  [A. Ramos, M. J. Vicente-Vacas and E. Oset, PRC 55 (1997) 735; C 66 (2002) 039903(E)]

RESULTS

SINGLE NUCLEON SPECTRA

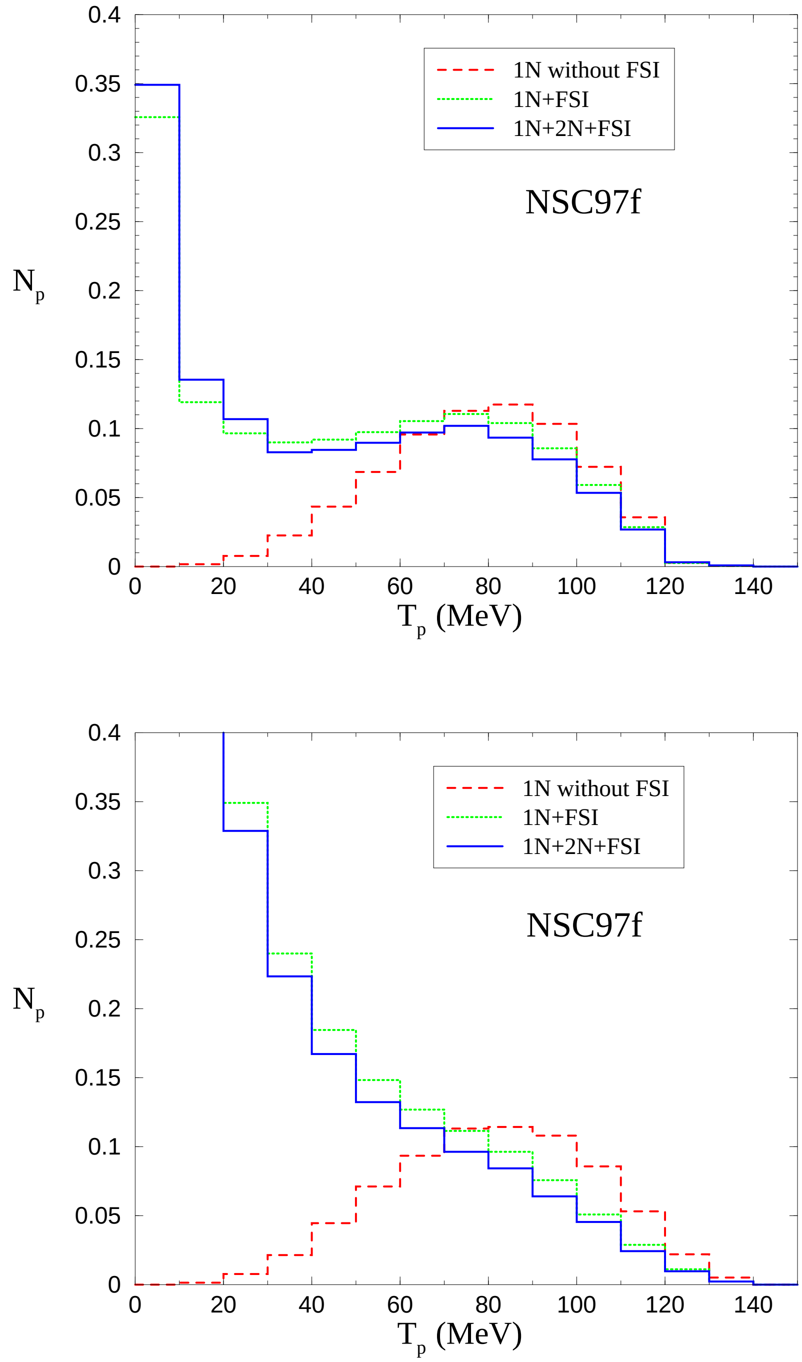


Figure 1: Single–proton kinetic energy spectra for the non–mesonic decay of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C.

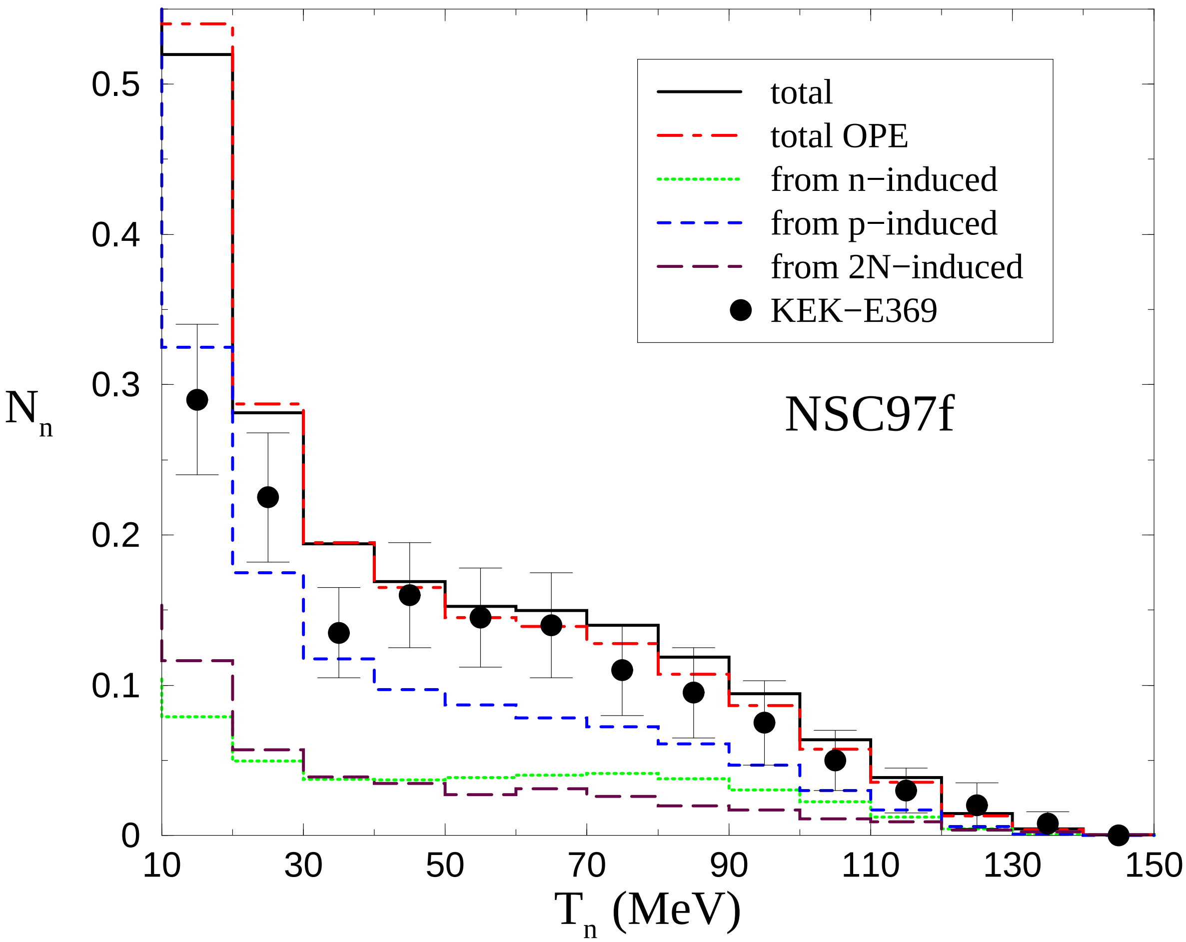


Figure 2: Single–neutron kinetic energy spectra for the non–mesonic decay of ${}^{12}_{\Lambda}C$. Data are from J. H. Kim et al., to appear on PRC.

Table 1: Predictions for the weak decay rates.

	$\Gamma_n + \Gamma_p$			Γ_n / Γ_p		
	OPE	OMEa	OMEf	OPE	OMEa	OMEf
${}^{5}_{\Lambda}He$	0.43	0.43	0.32	0.09	0.34	0.46
${}^{12}_{\Lambda}C$	0.75	0.73	0.55	0.08	0.29	0.34

Number of primary nucleons:

$$N_n^{\rm wd} \propto 2\,\Gamma_n + \Gamma_p$$
$$N_p^{\rm wd} \propto \Gamma_p$$

$$\Longrightarrow \quad \boxed{\frac{\Gamma_n}{\Gamma_p} \equiv \frac{1}{2}\left(\frac{N_n^{\rm wd}}{N_p^{\rm wd}} - 1\right)}$$

But, due to FSI:

$$\boxed{\frac{\Gamma_n}{\Gamma_p} \neq \frac{1}{2}\left(\frac{N_n}{N_p} - 1\right) \equiv R_1(T_N^{\rm th})}$$

N_n, N_p are the number of nucleons emitted by the nucleus

Table 2: Predictions for $R_1(T_N^{\rm th})$ for ${}^5_\Lambda$He.

	$T_N^{\rm th}$ (MeV) 0	30	60	Γ_n/Γ_p
OPE	0.04	0.13	0.16	0.09
OMEa	0.15	0.32	0.39	0.34
OMEf	0.19	0.40	0.49	0.46

$$\rm KEK - E462: \quad R_1(60\,MeV) = 0.6 \pm 0.2 \quad (preliminary)$$

[H. Bhang, HYP2003]

ANGULAR CORRELATIONS

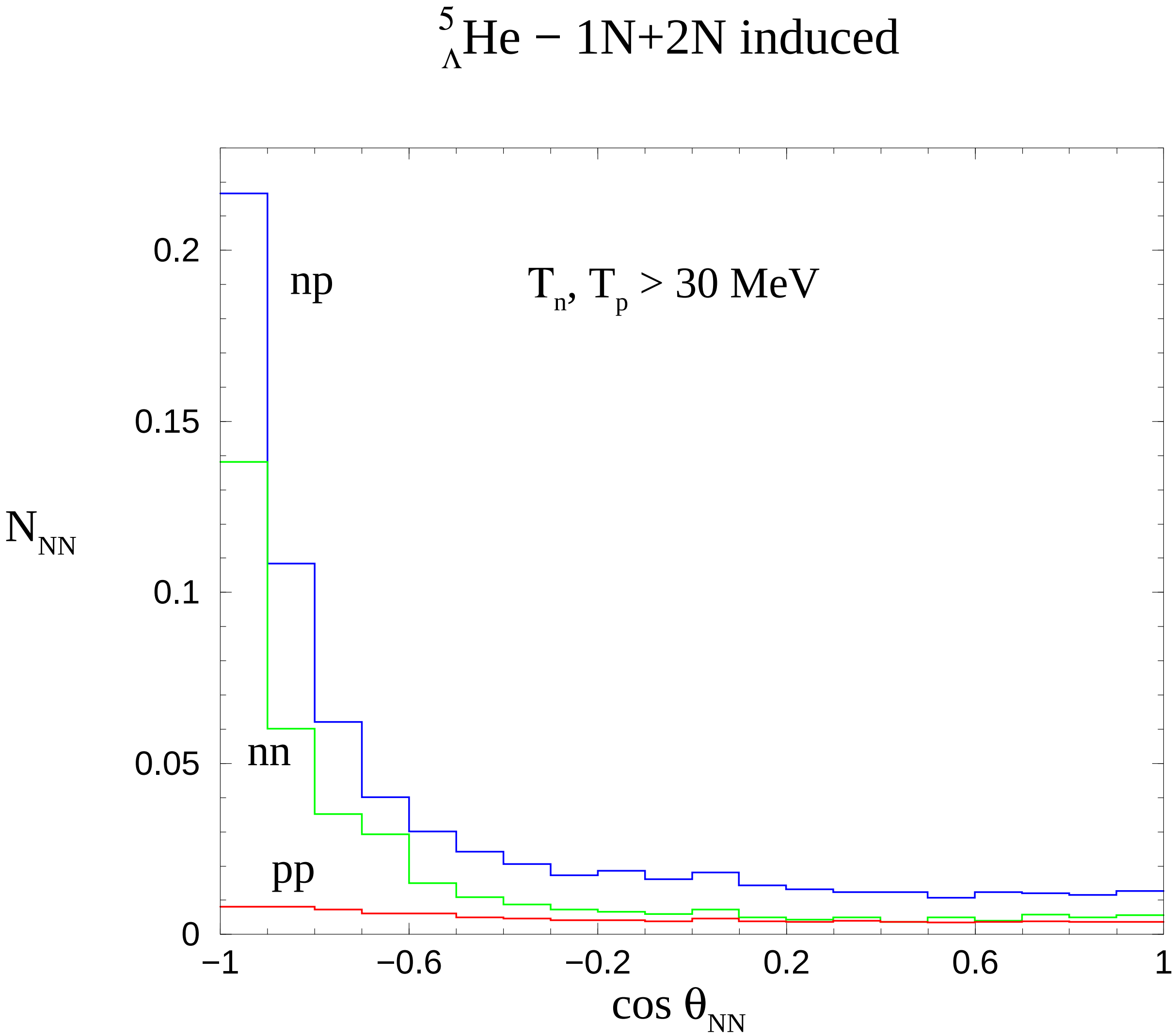


Figure 3: Opening angle distributions of *nn*, *np* and *pp* pairs emitted per NMWD of $^{5}_{\Lambda}$He

Table 3: Predictions for the weak decay rates

	$\Gamma_1 = \Gamma_n + \Gamma_p$	Γ_2	Γ_n/Γ_p
$^{5}_{\Lambda}$He	0.32	0.06	0.46
$^{12}_{\Lambda}$C	0.55	0.14	0.34

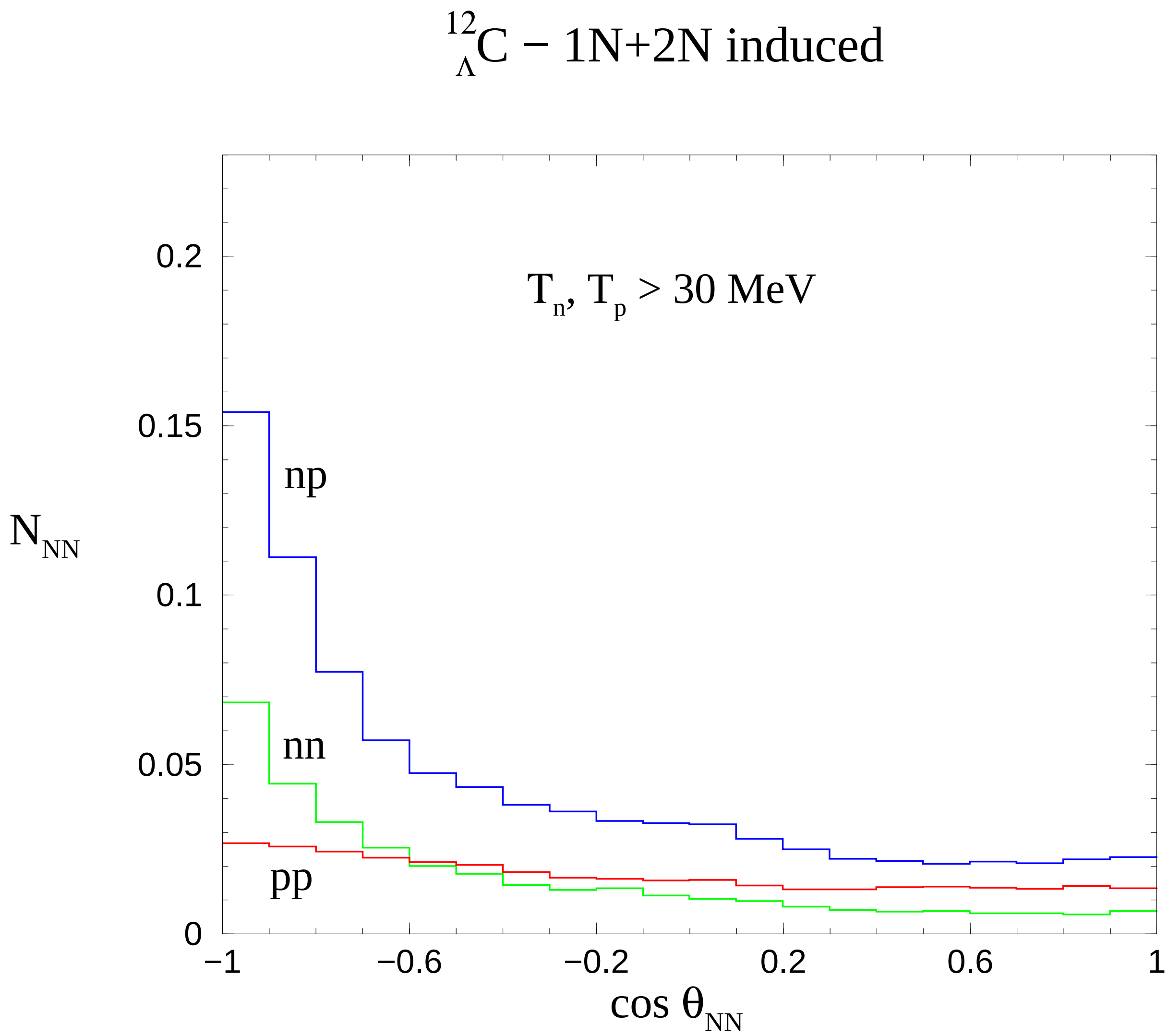


Figure 4: Angular distribution of *nn*, *np* and *pp* pairs emitted per NMWD of $^{12}_{\Lambda}$C

ENERGY CORRELATIONS

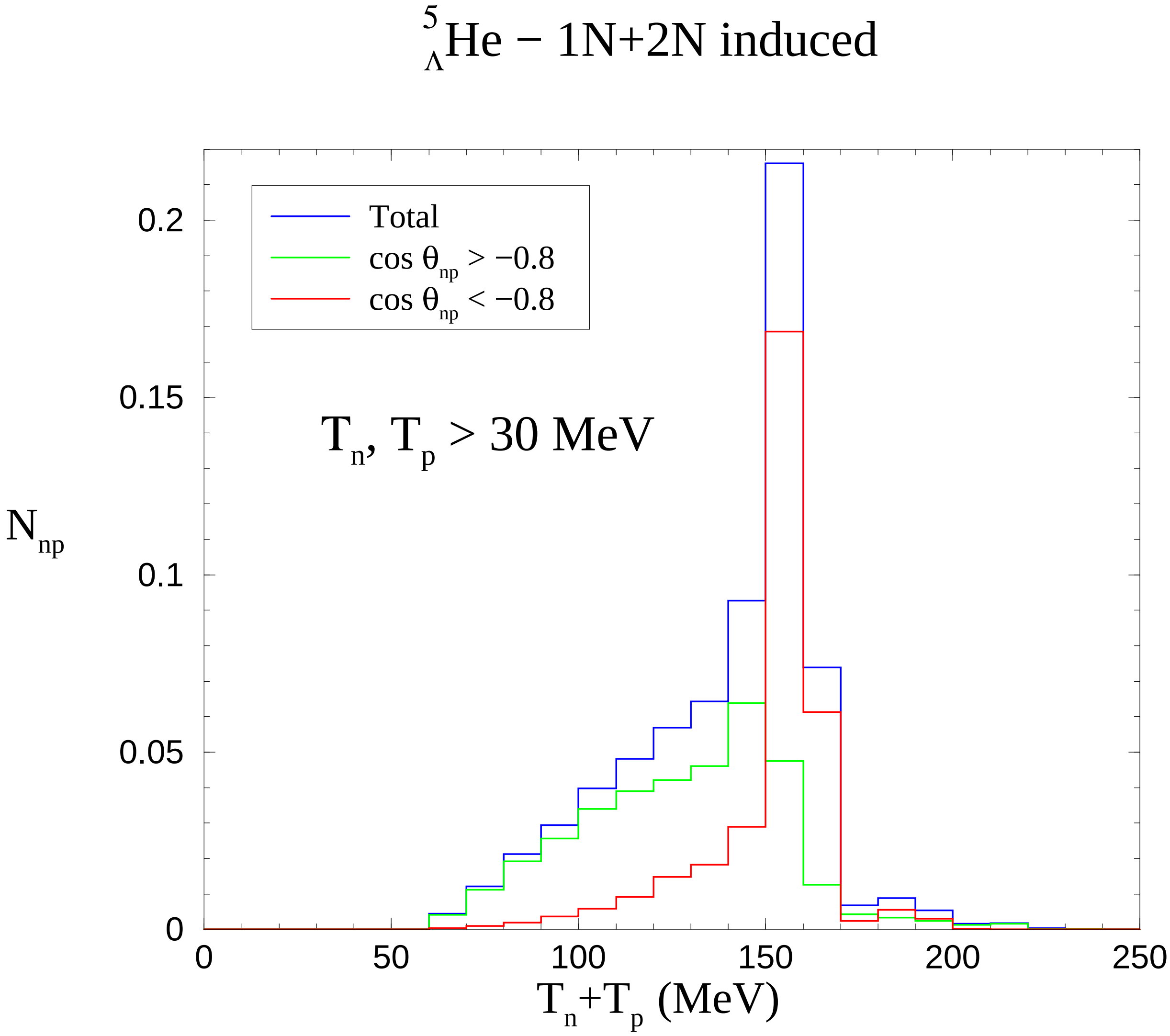


Figure 5: Kinetic energy correlations of *np* pairs emitted per NMWD of $^{5}_{\Lambda}$He

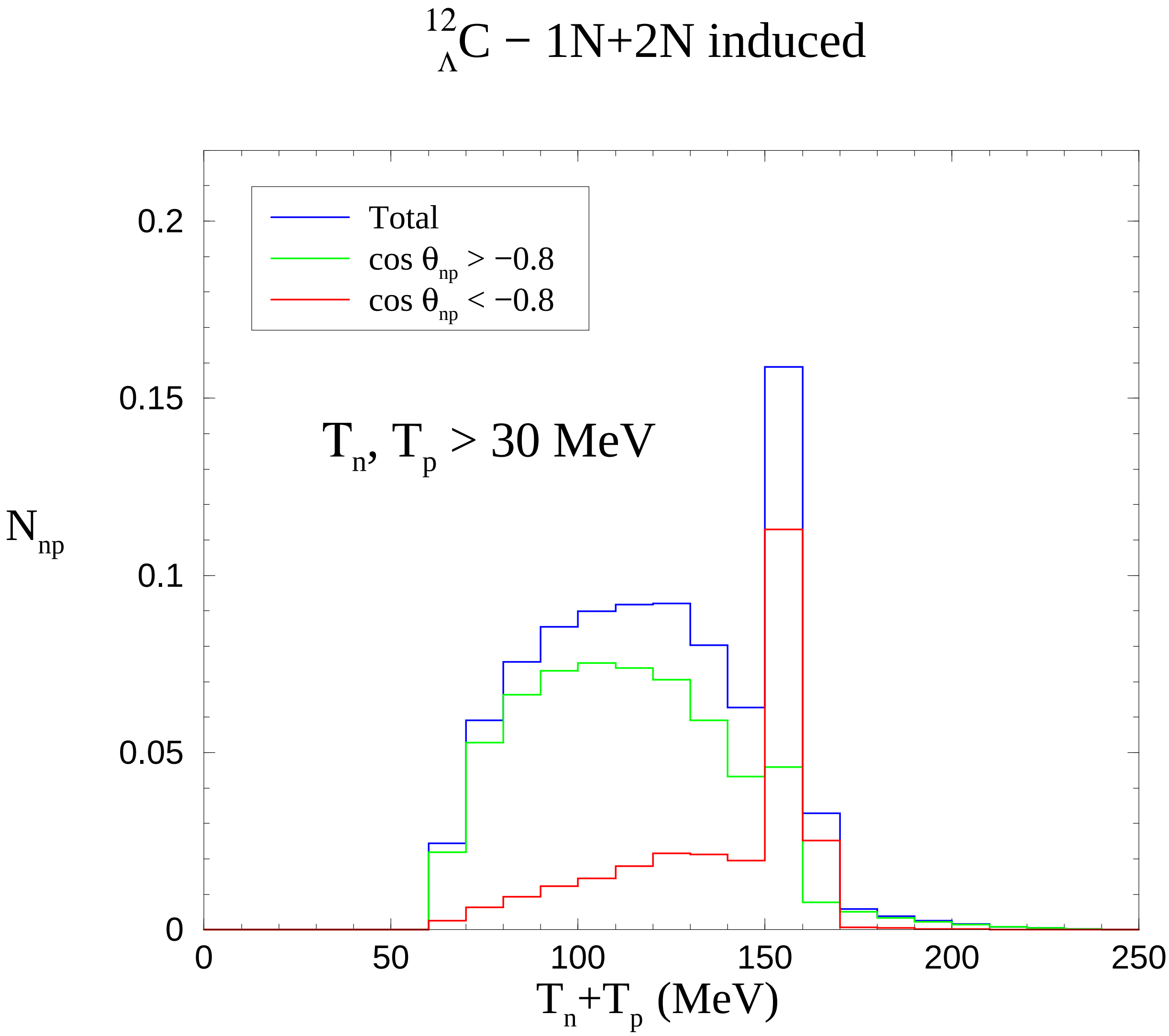


Figure 6: Kinetic energy correlations of np pairs emitted per NMWD of $^{12}_{\Lambda}$C

Number of primary NN pairs:

$$N_{nn}^{\rm wd} \propto \Gamma_n$$
$$N_{np}^{\rm wd} \propto \Gamma_p$$

Denoting with N_{nn} and N_{np} the number of nucleons emitted by the nucleus:

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N_{nn}^{\rm wd}}{N_{np}^{\rm wd}} \neq \frac{N_{nn}}{N_{np}} = R_2\left(\Delta\theta_{12}, T_N^{\rm th}\right)$$

Table 4: Predictions for N_{nn}/N_{np} for ${}^{5}_{\Lambda}$He ($\cos\theta_{NN} \leq -0.8$ and $T_N^{\rm th} = 30$ MeV)

	N_{nn}/N_{np}	Γ_n/Γ_p
OPE	0.25	0.09
OMEa	0.51	0.34
OMEf	0.61	0.46
KEK–E462	0.44 ± 0.11	

Data from: [H. Outa, HYP2003]

A model independent analysis of Γ_n/Γ_p

- Introduce the total number of NN pairs emitted per NMWD:

$$N_{nn} = \frac{N_{nn}^{\rm 1Bn}\,\Gamma_n + N_{nn}^{\rm 1Bp}\,\Gamma_p + N_{nn}^{\rm 2B}\,\Gamma_2}{\Gamma_n + \Gamma_p + \Gamma_2}$$

$$N_{np} = \frac{N_{np}^{\rm 1Bn}\,\Gamma_n + N_{np}^{\rm 1Bp}\,\Gamma_p + N_{np}^{\rm 2B}\,\Gamma_2}{\Gamma_n + \Gamma_p + \Gamma_2}$$

which define the six weak decay model–independent quantities: $N_{nn}^{\rm 1Bn}$ (the number of nn pairs emitted per neutron–induced NMWD), etc.

- Γ_n/Γ_p can thus be obtained from a measurement of N_{nn}/N_{np} as:

$$\frac{\Gamma_n}{\Gamma_p} = \frac{N_{nn}^{\rm 1Bp} + N_{nn}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1} - \left(N_{np}^{\rm 1Bp} + N_{np}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}}}{\left(N_{np}^{\rm 1Bn} + N_{np}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}} - N_{nn}^{\rm 1Bn} - N_{nn}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1}}$$

using Γ_n/Γ_p and Γ_2/Γ_1 as fitting parameters

- Using the KEK–E462 data $N_{nn}/N_{np} = 0.44 \pm 0.11$ we obtain:

$$\frac{\Gamma_n}{\Gamma_p} = 0.26 \pm 0.11 \qquad (\Gamma_2 = 0.2\,\Gamma_1)$$

$$\left(\frac{\Gamma_n}{\Gamma_p} = 0.39 \pm 0.11 \quad \text{if} \quad \Gamma_2 = 0\right)$$

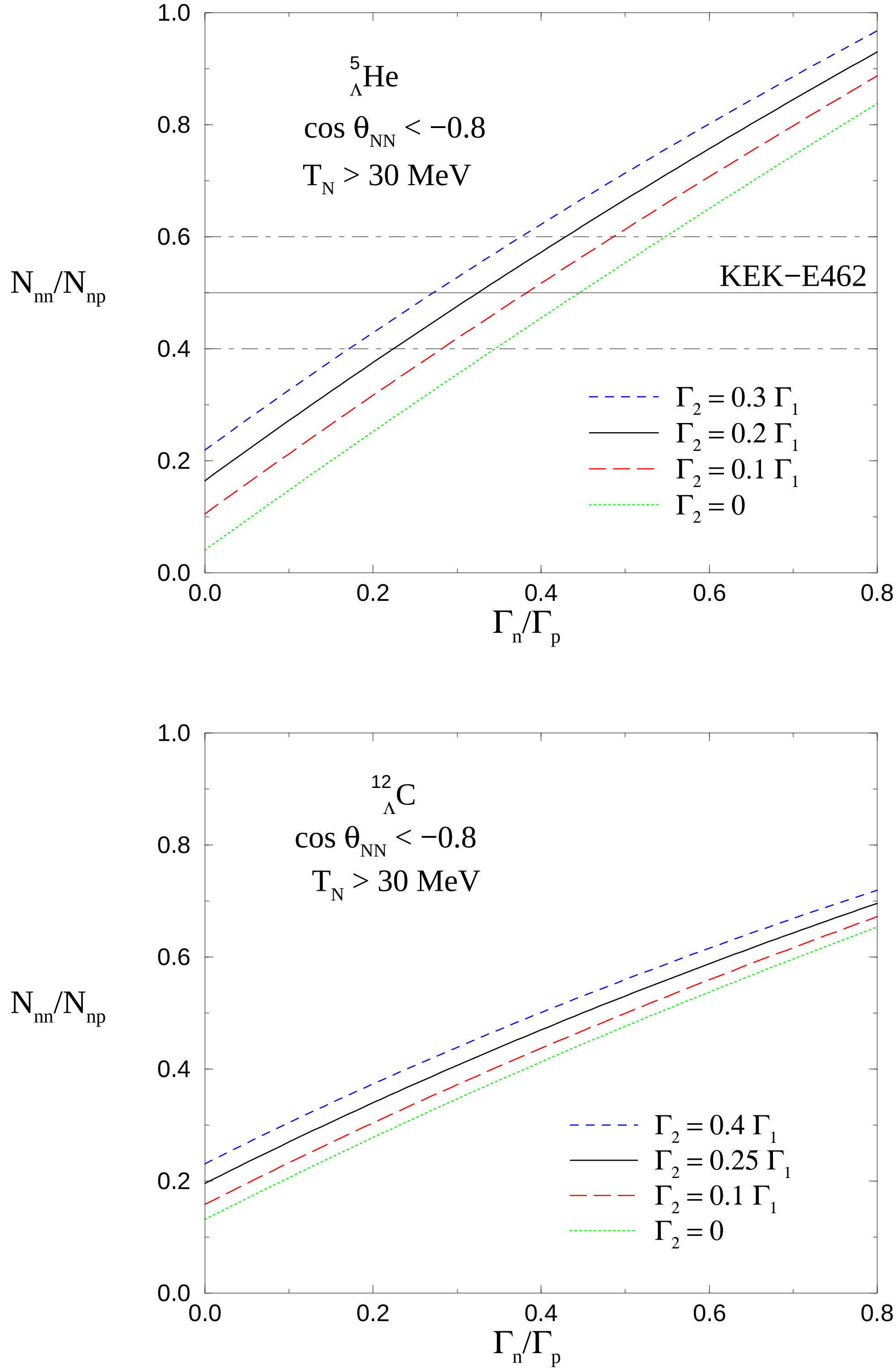


Figure 7: Dependence of the ratio N_{nn}/N_{np} on Γ_n/Γ_p and Γ_2/Γ_1 for $^5_\Lambda$He and $^{12}_\Lambda$C.

ASYMMETRY

The calculated proton intensities are well fitted by

$$I^{\rm M}(\Theta) = I^{\rm M}_0 \left[1 + p_\Lambda\, a^{\rm M}_\Lambda \cos\Theta\right]$$

where, normalizing per NMWD and assuming $P_y = 1$:

$$I^{\rm M}_0 = \text{total number of protons emitted per NMWD}$$

$$p_\Lambda = \begin{cases} 1 & \text{for } {}^{5}_{\Lambda}\text{He} \\ -1/2 & \text{for } {}^{12}_{\Lambda}\text{C} \end{cases}$$

Table 5: Asymmetry parameters for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C. The two–nucleon induced decay is neglected. Preliminary data are from [T. Maruta et al., nucl-ex/0402017, HYP2003]

	${}^{5}_{\Lambda}$He $I^{\rm M}_0$	$a^{\rm M}_\Lambda$	${}^{12}_{\Lambda}$C $I^{\rm M}_0$	$a^{\rm M}_\Lambda$
OPE	0.92	−0.25	0.93	−0.34
$T_N^{\rm Th} = 0$	1.56	−0.11	3.15	−0.03
$T_N^{\rm Th} = 30$ MeV	0.99	−0.16	1.23	−0.20
$T_N^{\rm Th} = 50$ MeV	0.78	−0.18	0.78	−0.26
OME	0.69	−0.68	0.75	−0.73
$T_N^{\rm Th} = 0$	1.28	−0.29	2.78	−0.13
$T_N^{\rm Th} = 30$ MeV	0.77	−0.45	1.05	−0.36
$T_N^{\rm Th} = 50$ MeV	0.60	−0.51	0.66	−0.49
KEK–E462		0.07 ± 0.08		
KEK–E508				-0.44 ± 0.32

CONCLUSIONS

With respect to single spectra studies, the treatment of CORRELATION OBSERVABLES permits a cleaner and more direct determination of Γ_n/Γ_p, with values in agreement with pure theoretical predictions

- Our predictions for single and double–coincidence observables for ${}^5_\Lambda$He are in reasonable agreement with KEK data

- From the model independent analysis of coincidence data:

$$\frac{\Gamma_n}{\Gamma_p}({}^5_\Lambda\mathrm{He}) = 0.26 \pm 0.11$$

$\Longrightarrow$ considerably smaller than

BNL91: 0.93 ± 0.55 KEK95: 1.97 ± 0.67

obtained by means of single nucleon spectra analyses!

- Asymmetric non–mesonic weak decay

$a_\Lambda^{\mathrm{M}}({}^5_\Lambda\mathrm{He}) = -0.51 \div -0.45 \Leftrightarrow 0.07 \pm 0.08$

strong disagreement! (KEK–E462 prel.)

$a_\Lambda^{\mathrm{M}}({}^{12}_\Lambda\mathrm{C}) = -0.49 \div -0.36 \Leftrightarrow -0.44 \pm 0.32$

good agreement (KEK–E508 prel.)