Non–Mesonic Weak Decay of Λ–Hypernuclei: a novel approach to the Γ_n/Γ_p Puzzle

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- Decay Modes of Λ–Hypernuclei
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Work done in collaboration with A. Parreño and A. Ramos

DECAY MODES OF Λ– HYPERNUCLEI

MESONIC

$$\begin{array}{llll} \Lambda \to \pi^0 n & \Gamma_{\pi^0} & p_N \simeq 100\,\mathrm{MeV} \\ \Lambda \to \pi^- p & \Gamma_{\pi^-} & \end{array}$$

NON–MESONIC

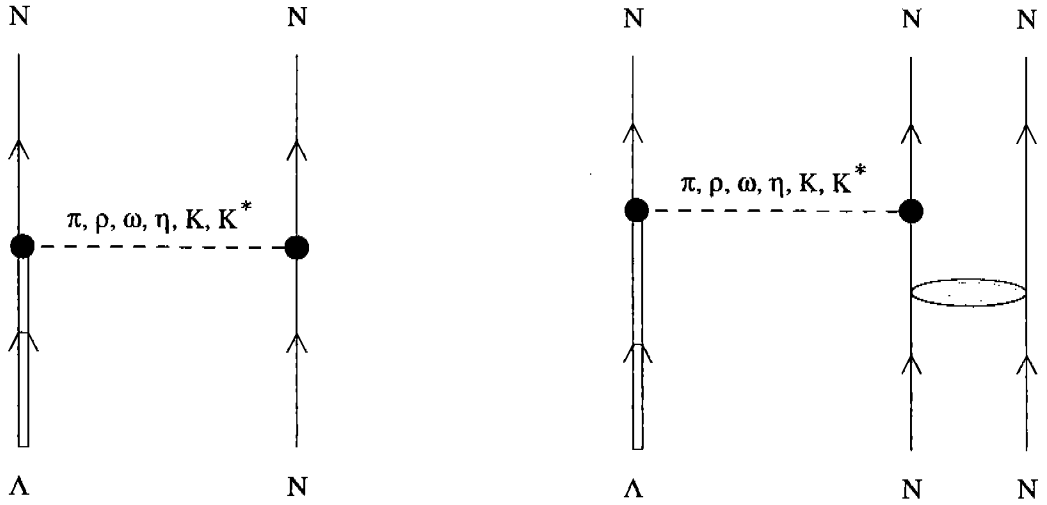
One–nucleon induced

$$\begin{array}{llll} \Lambda n \to nn & \Gamma_n & p_N \simeq 420\,\mathrm{MeV} \\ \Lambda p \to np & \Gamma_p & \end{array}$$

Two–nucleon induced

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

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



$\Longrightarrow$ the non–mesonic weak decay (NMWD) dominates over the mesonic one for all but the s–shell hypernclei

THE Γ_n/Γ_p PUZZLE

Since many years, a sound theoretical explanation of the large experimental values of Γ_n/Γ_p is missing.

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

Theory underestimates the central data for all considered hypernuclei:

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

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:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE} = \text{[illegible]}$$

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

Other interaction mechanisms [illegible] non-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

A few calculations with $\Lambda N \to nN$ transition potentials including **heavy–meson–exchange** and/or **direct quark contributions** – have recently improved the situation, without providing an explanation of the puzzle

[1] D. Jido, E. Oset and J. E. Palomar, NPA 694 (2001) 525;
A. Parreño and A. Ramos, PRC 65 (2002) 015204;
K. Itonaga, T. Ueda and T. Motoba, PRC 65 (2002) 034617.

[2] K. Sasaki, T. Inoue and M. Oka, NPA 669 (2000) 331;
Erratum: ibid. A 678 (2000) 455

In addition, a realistic analysis of the Γ_n/Γ_p ratio requires:

- the inclusion of the TWO–NUCLEON INDUCED DECAY MECHANISM

  $$[\text{quasi} - \text{deutron approximation} \Longrightarrow \Lambda np \to nnp]$$

  whose experimental identification is expected in NNN coincidence measurements (KEK, BNL, FINUDA)

- the estimation of the NUCLEON ENERGY LOSSES INSIDE THE RESIDUAL NUCLEUS AND IN THE EXPERIMENTAL SET–UP

OUR APPROACH TO THE PROBLEM

[G. Garbarino, A. Parreño, A. Ramos PRL 91 (2003) 112501]

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

✦ SINGLE NUCLEON ENERGY SPECTRA

✦ $\boxed{NN \text{ ANGULAR AND ENERGY CORRELATIONS}}$

$\Longrightarrow$ $\boxed{\text{determine } \Gamma_n/\Gamma_p}$

via the comparison with observed distributions

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

[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

[illegible] E. Oset PRC [illegible]

Finite Nucleus approach to NMWD

Shell Model nuclear (Ψ_R) and hypernuclear (Ψ_H) wave functions are used to compute:

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

$$\Gamma_{n(p)} = \int \frac{d\vec{p}_1}{(2\pi)^3} \int \frac{d\vec{p}_2}{(2\pi)^3}\, 2\pi\, \delta(\text{E.C.}) \overline{\sum} \left|\mathcal{M}_{n(p)}(\vec{p}_1, \vec{p}_2)\right|^2$$

where:

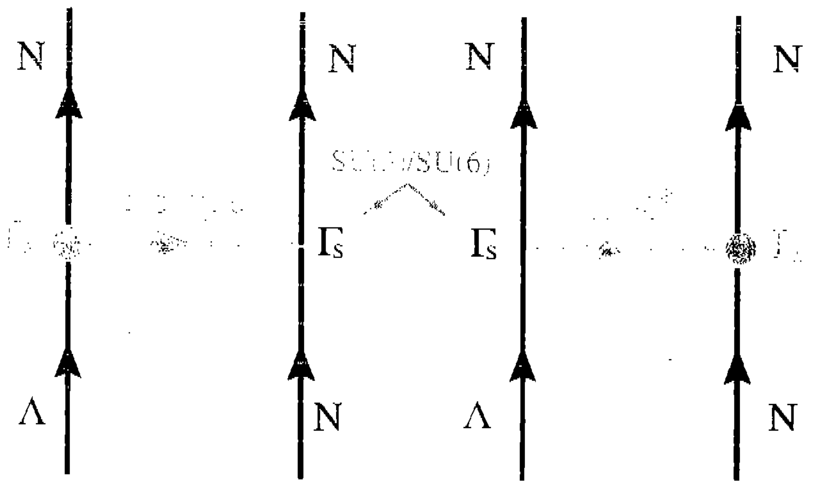
$$\delta(\text{E.C.}) = \delta\left(m_H - E_R - 2m_N - \frac{\vec{p}_1^{\,2}}{2m_N} - \frac{\vec{p}_2^{\,2}}{2m_N}\right)$$

$$\mathcal{M}_N(\vec{p}_1, \vec{p}_2) \equiv \langle \Psi_R; N(\vec{p}_1) N(\vec{p}_2) | \hat{T}_{\Lambda N \to NN} | \Psi_H \rangle$$

Weak–coupling scheme + technique of f.p.c.:

$$\mathcal{M}_N \Longrightarrow \langle NN | V_{\text{OME}} | \Lambda N \rangle$$

One–Meson–Exchange $\Lambda N \to NN$ transition potential



PV: SU(3)+SU(6)w

PC: Pole Model

Strong Interaction Model: NSC97f

Scattering NN wave function: Lippmann–Schwinger (T–matrix) equation

Nucleon FSI

Monte Carlo Simulation

Random number generator determines:

- the decay channel, $1N$–induced ($\Lambda n \to nn$ or $\Lambda p \to np$) or $2N$–induced, according to Γ_1/Γ_2 (Γ_n/Γ_p)
- positions, momenta and charges of primary nucleons $\Longleftarrow$ probability distributions given by the Finite Nucleus approach ($1N$–induced) and PPM in LDA ($2N$–induced)

Nucleons move under a Local Potential, $V(\vec{r}) = -\dfrac{k_F^2(\vec{r})}{2m_N}$, and collide with other nucleons of the medium according to NN cross sections corrected by Pauli blocking

The weak decay nucleons continuously change energy, direction, charge and secondary nucleons are emitted

Importance of Correlation Observables

With respect to single spectra studies, the treatment of CORRELATION OBSERVABLES permits a cleaner and more direct determination of Γ_n/Γ_p

Single nucleon observables are more affected than correlation observables by QM INTERFERENCE EFFECTS between n– and p–induced processes

An experiment detecting single protons measures:

$$\begin{aligned} & \left|\langle p|\hat{T}_{\rm FSI}\,\hat{T}_{\rm WD}|\Psi_H\rangle\right|^2 \\ = & \left|\alpha\,\langle p|\hat{T}_{\rm FSI}|nn,R\rangle+\beta\,\langle p|\hat{T}_{\rm FSI}|np,R'\rangle\right|^2 \end{aligned}$$

$$\hat{T}_{\rm WD}|\Psi_H\rangle=\alpha|nn,R\rangle+\beta|np,R'\rangle$$

$\Longrightarrow$ interference term

On the contrary, in the Monte Carlo simulations used to determine Γ_n/Γ_p from data, the proton distributions originating from n– and p–stimulated transitions are added incoherently

RESULTS

ANGULAR CORRELATIONS

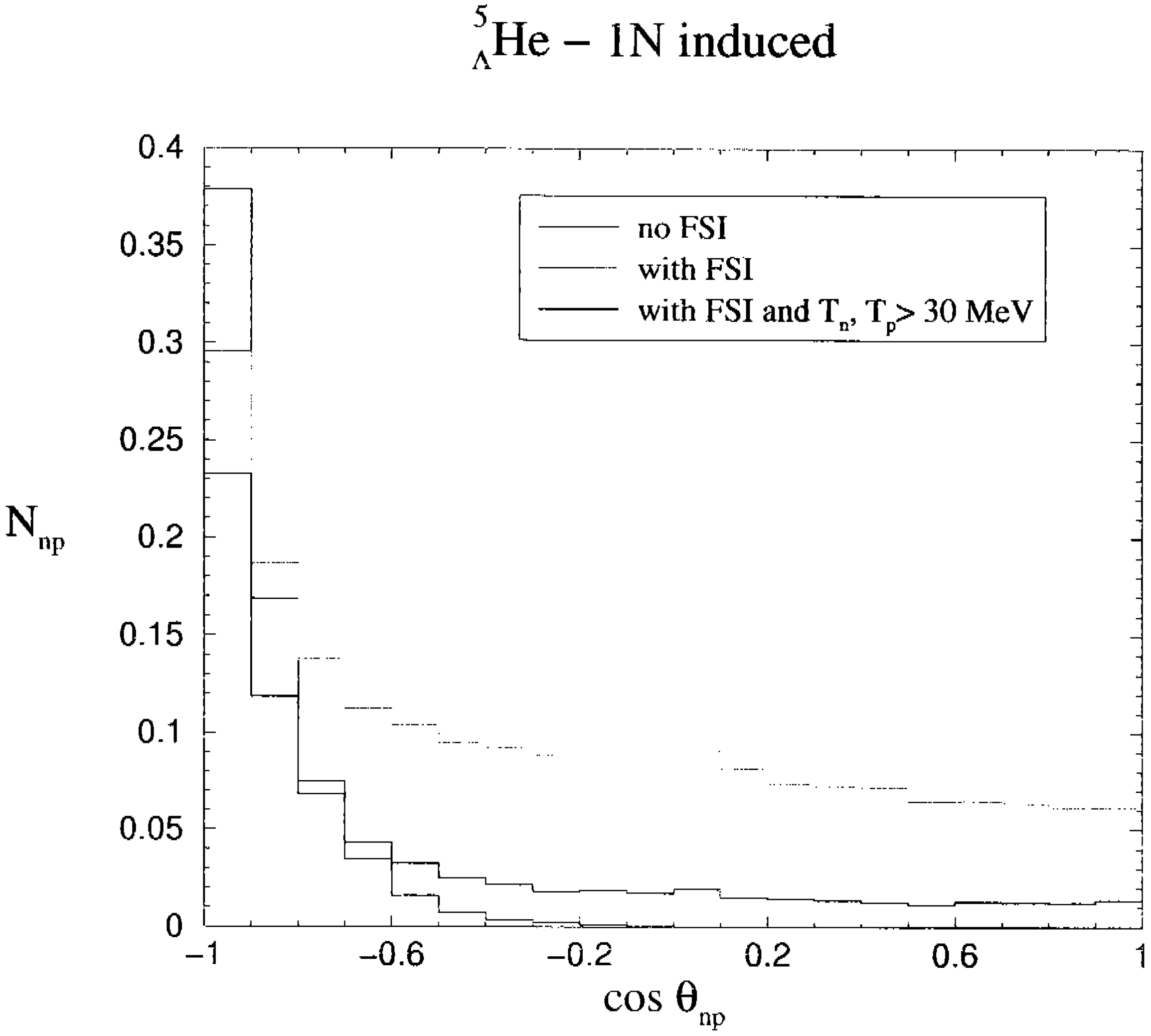


Figure 1: Opening angle distributions of primary *np* pairs emitted per one–nucleon induced NMWD of $^5_\Lambda$He

Table 1: 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

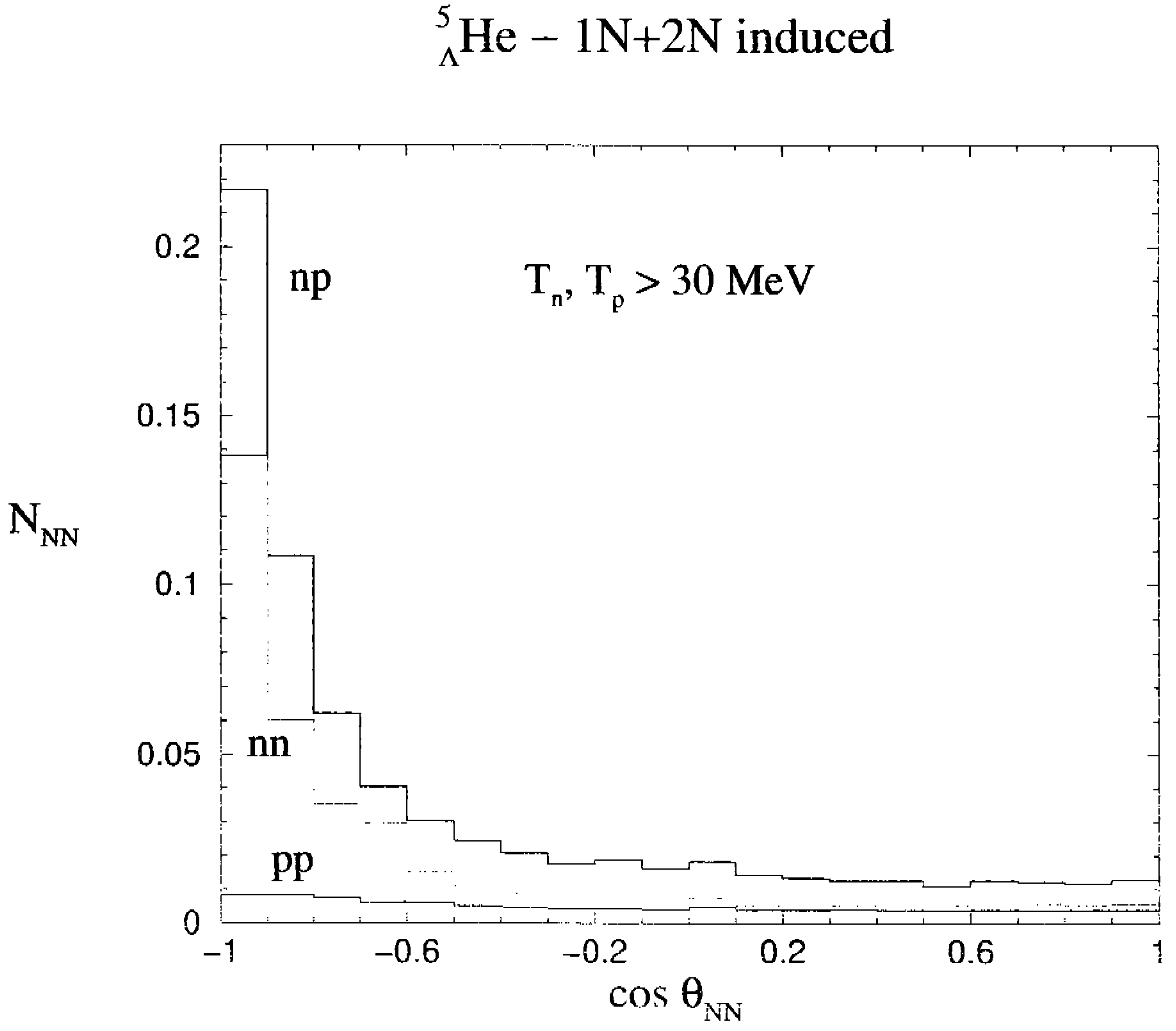


Figure 2: Opening angle distributions of nn, np and pp pairs emitted per NMWD of $^5_\Lambda$He

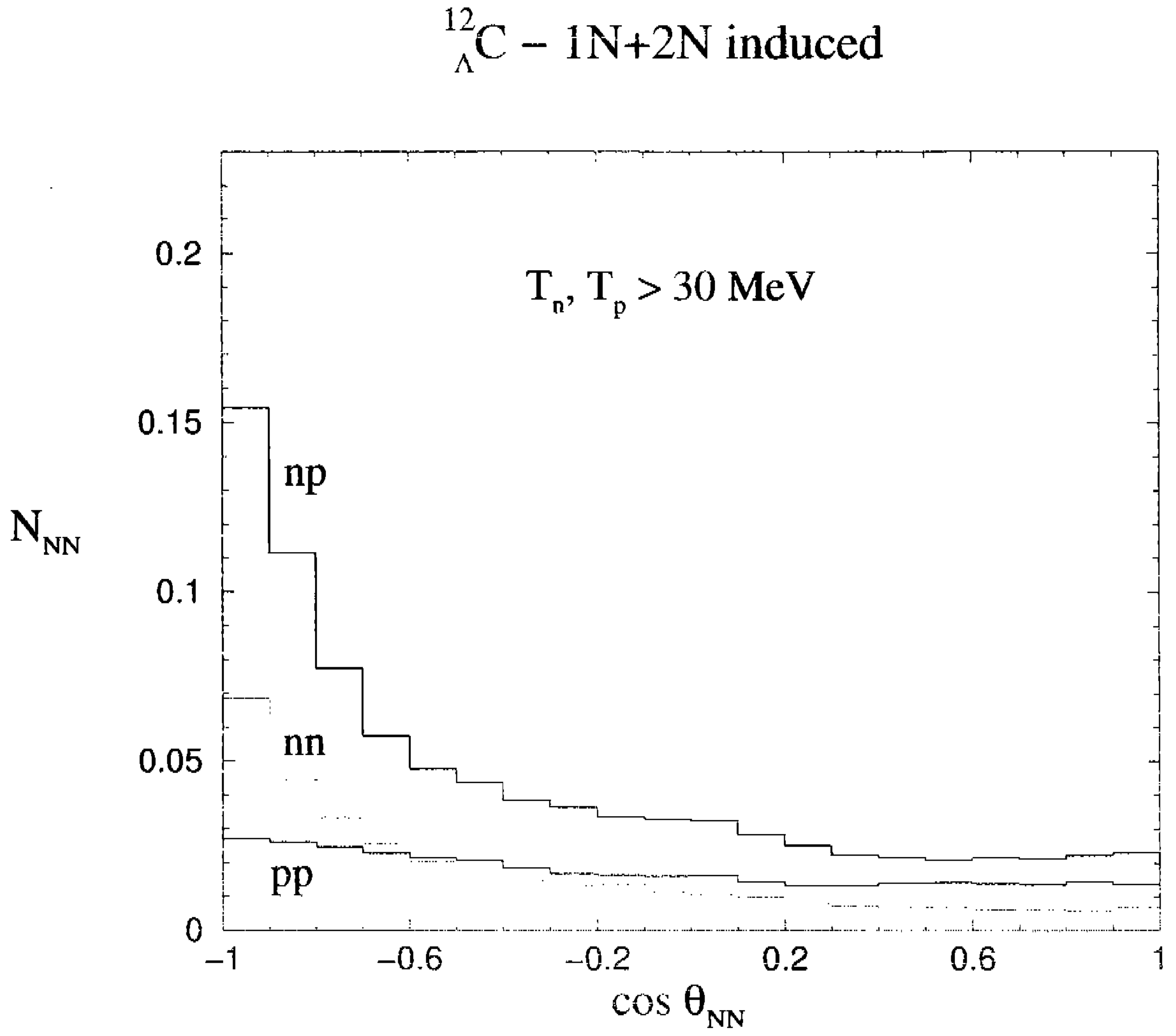


Figure 3: Angular distribution of *nn*, *np* and *pp* pairs emitted per NMWD of ${}^{12}_{\Lambda}$C

ENERGY CORRELATIONS

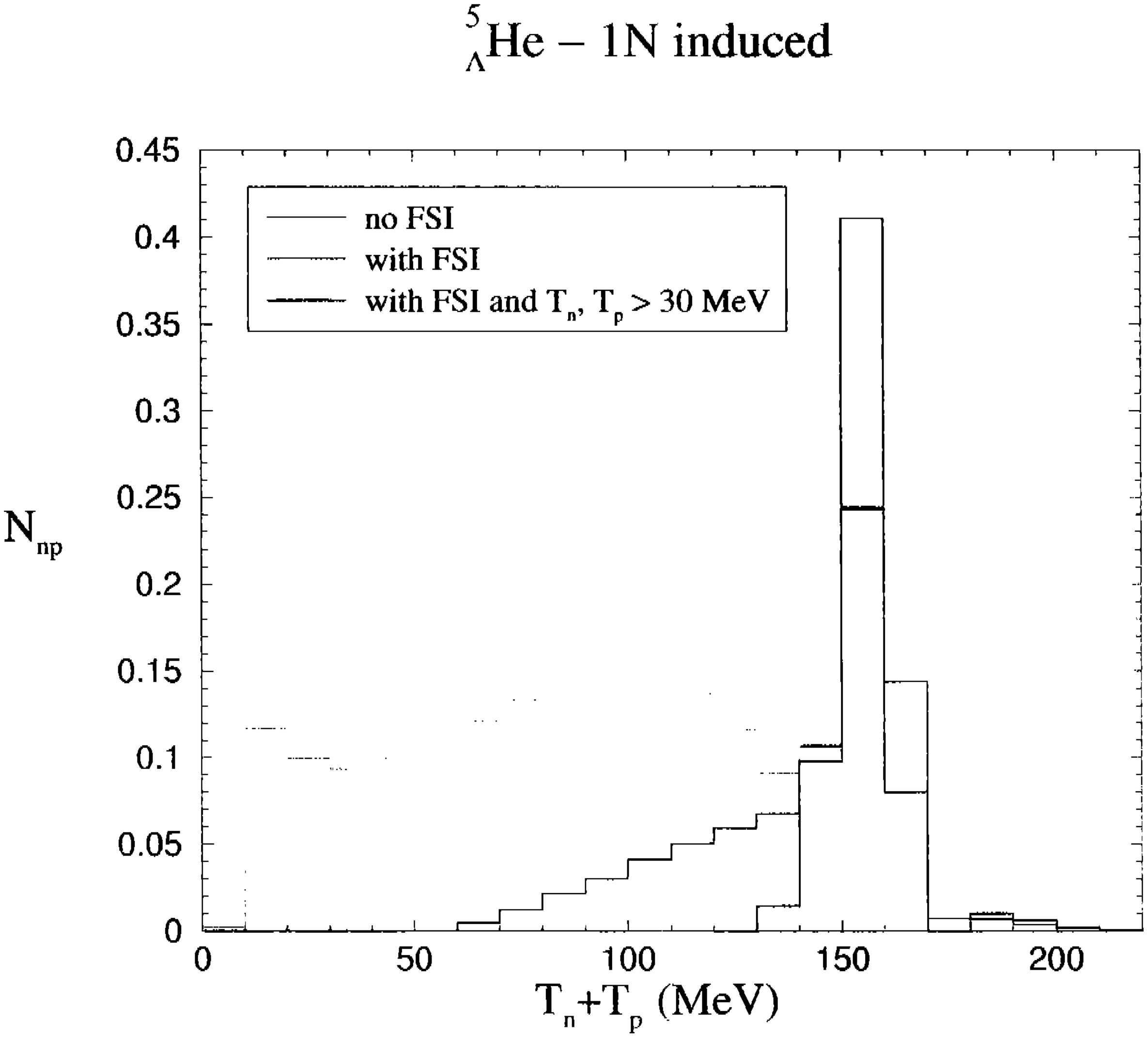


Figure 4: Kinetic energy sum distribution of primary np pairs emitted per one–nucleon induced NMWD of $^{5}_{\Lambda}$He

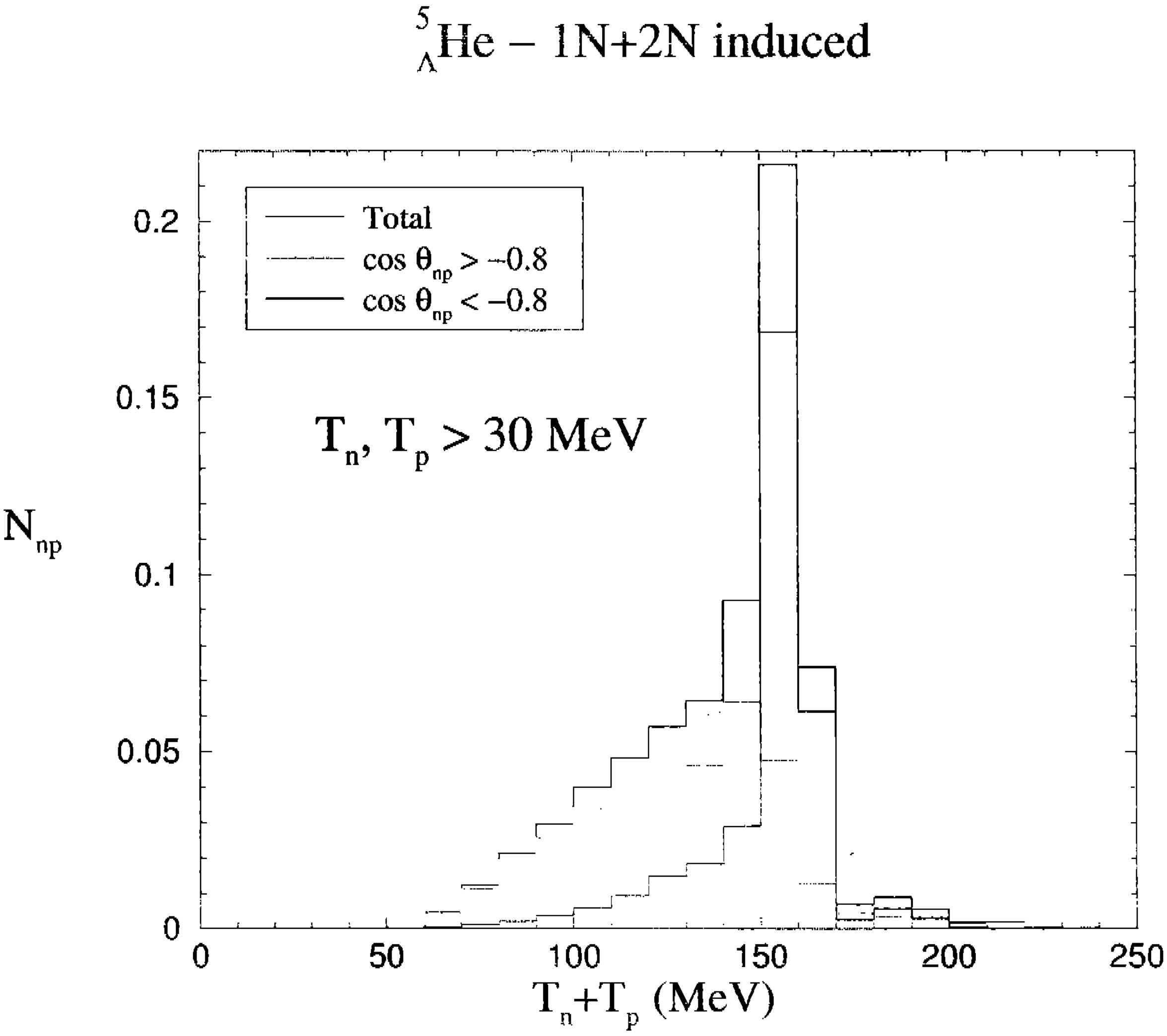


Figure 5: Kinetic energy correlations of *np* pairs emitted per NMWD of $^{5}_{\Lambda}$He

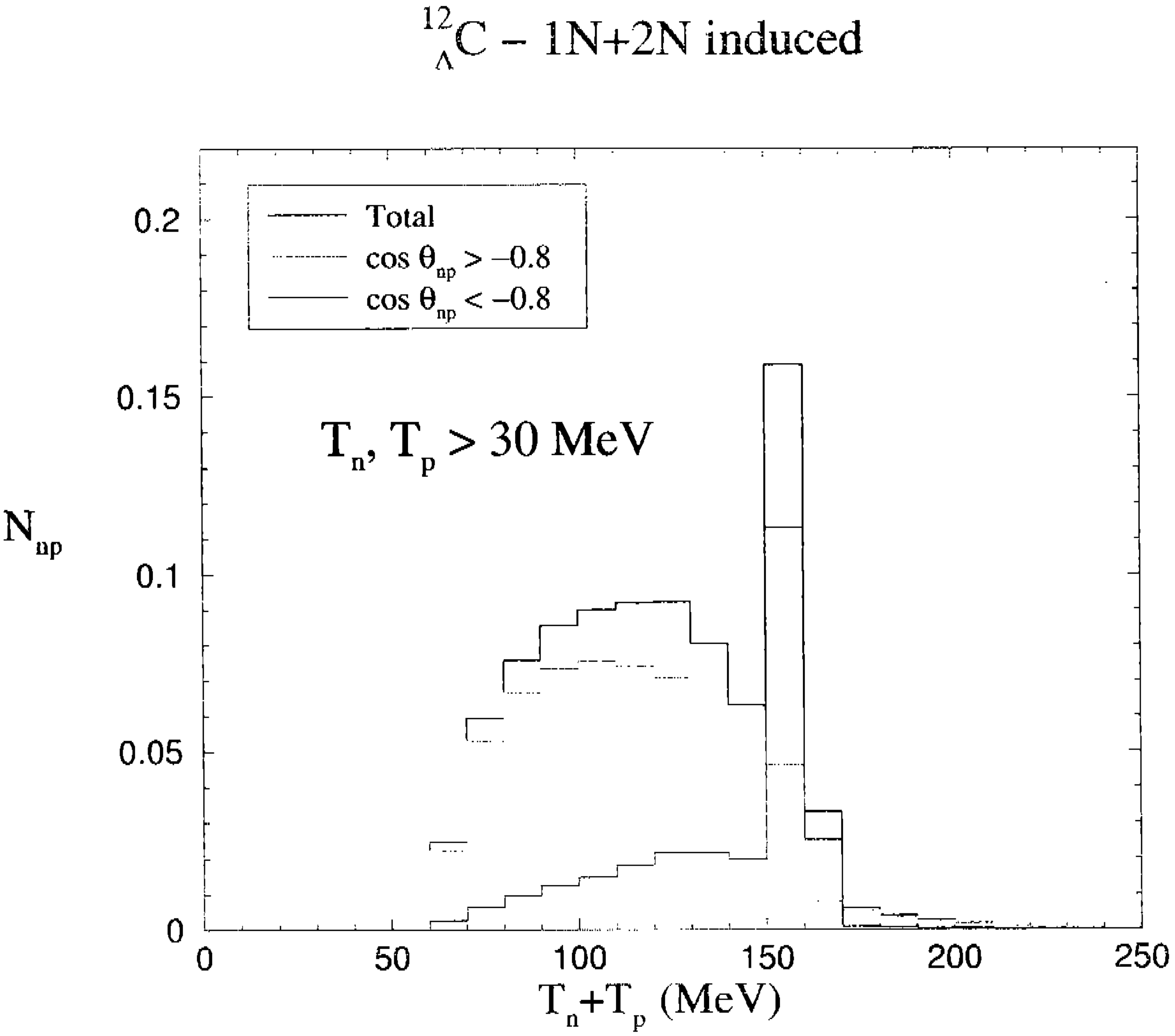


Figure 7: Kinetic energy correlations of np pairs emitted per NMWD of $^{12}_{\Lambda}$C

[illegible]

Number of primary [illegible]:

$$\propto \quad \Gamma_n$$

$$\propto \quad \Gamma_p$$

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

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

Table 4: Predictions for $\boxed{N_{nn}/N_{np}}$ **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	0.5 ± 0.1	

Data from: [H. Outa, PANIC02, SENDAI03]

$|0.44 \pm 0.11|$

[H. Outa, HYP2003]

A model independent analysis of Γ_n/Γ_p

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

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

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

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

- Consider then the ratio:

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

Γ_n/Γ_p and Γ_2/Γ_1 will be fitting parameters

- Using the KEK–E462 data $N_{nn}/N_{np} =$ ~~0.5 ± 0.1~~ we obtain:

[Outa] 0.44 ± 0.11

$$\boxed{\frac{\Gamma_n}{\Gamma_p} = \cancel{0.32 \pm 0.10} \; 0.26 \pm 0.11} \qquad (\Gamma_2 = 0.2\,\Gamma_1)$$

$$\left(\frac{\Gamma_n}{\Gamma_p} = \cancel{0.45 \pm 0.10} \; 0.39 \pm 0.11 \;\; \text{if} \;\; \Gamma_2 = 0\right)$$

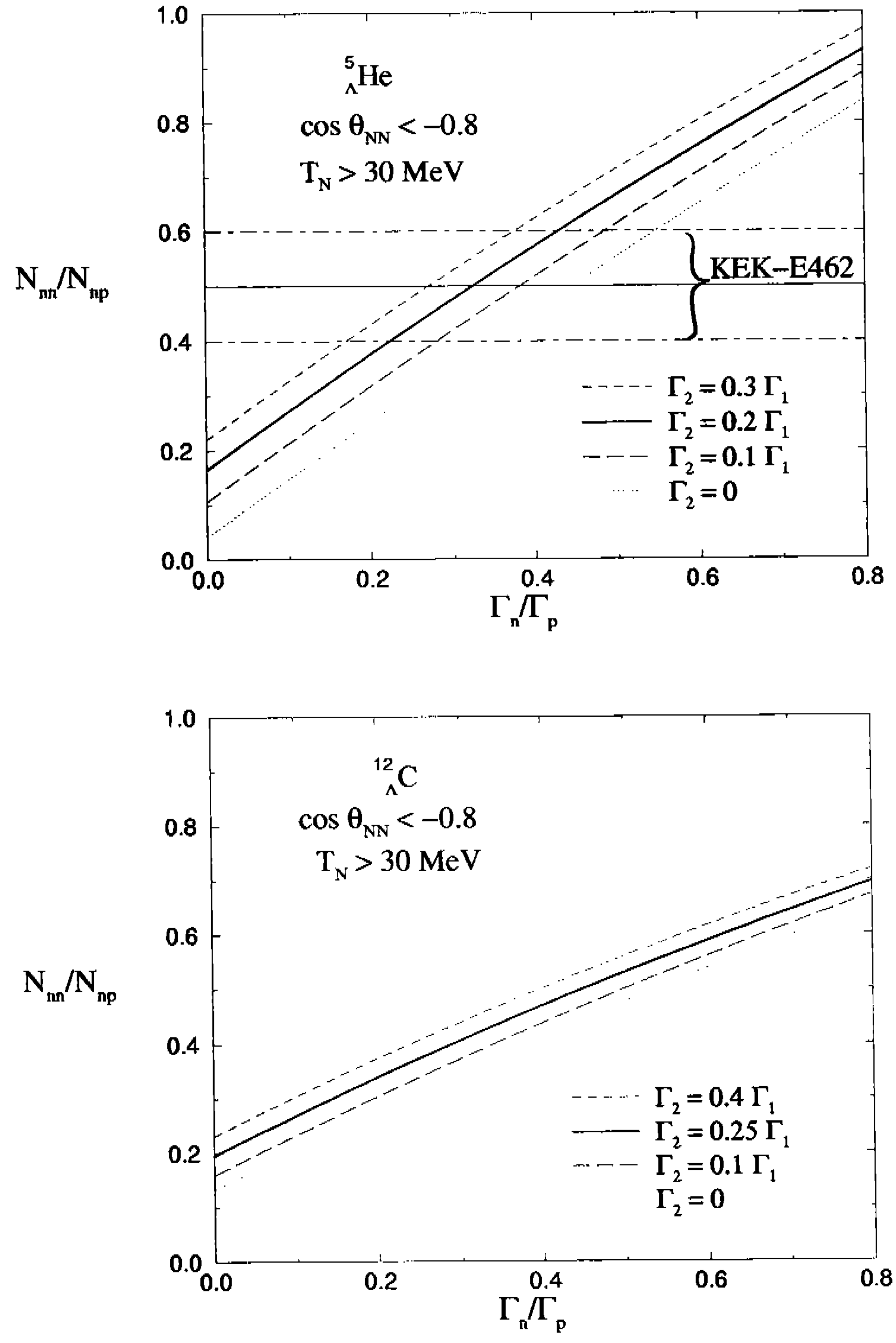


Figure 10: Dependence of the ratio N_{nn}/N_{np} on Γ_n/Γ_p and [illegible] for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C.

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

- ✦ KEK–E462 coincidence data for ${}^{5}_{\Lambda}\mathrm{He}$ are well reproduced by our calculations

- ✦ **From the** model independent analysis :

$$\boxed{\frac{\Gamma_n}{\Gamma_p}({}^{5}_{\Lambda}\mathrm{He}) = 0.32 \cancel{\pm 0.10}} \left\{ \begin{array}{l} 0.26 \pm 0.11 \\ (\Gamma_2/\Gamma_1 = 0.2) \\ 0.39 \pm 0.11 \\ (\Gamma_2 = 0) \end{array} \right.$$

$$\left(\frac{\Gamma_n}{\Gamma_p}\right)^{\mathbf{OME}} = 0.34(\mathbf{a}),\ 0.46(\mathbf{b})$$

$\Longrightarrow$ considerably smaller than

BNL91: 0.93 ± 0.55 **KEK95:** 1.97 ± 0.67

obtained by means of single nucleon spectra analyses!

- ✦ **New data for ${}^{4}_{\Lambda}\mathrm{H}$ (BNL) and ${}^{12}_{\Lambda}\mathrm{C}$ (KEK, JLAB, FINUDA) will help to clarify the situation**