Open problems in the Weak Decay of Hypernuclei

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- Decay Modes of Λ–Hypernuclei
- The Γ_n/Γ_p Puzzle
- The Asymmetry Puzzle
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In collaboration with W. M. Alberico, A. De Pace, A. Parreño and A. Ramos

DECAY MODES OF Λ–HYPERNUCLEI

MESONIC

$$\Lambda \to \pi^0 n \qquad \Gamma_{\pi^0} \qquad p_N \simeq 100\,\mathrm{MeV} << k_F^0 \simeq 270\,\mathrm{MeV}$$

$$\Lambda \to \pi^- p \qquad \Gamma_{\pi^-}$$

NON–MESONIC

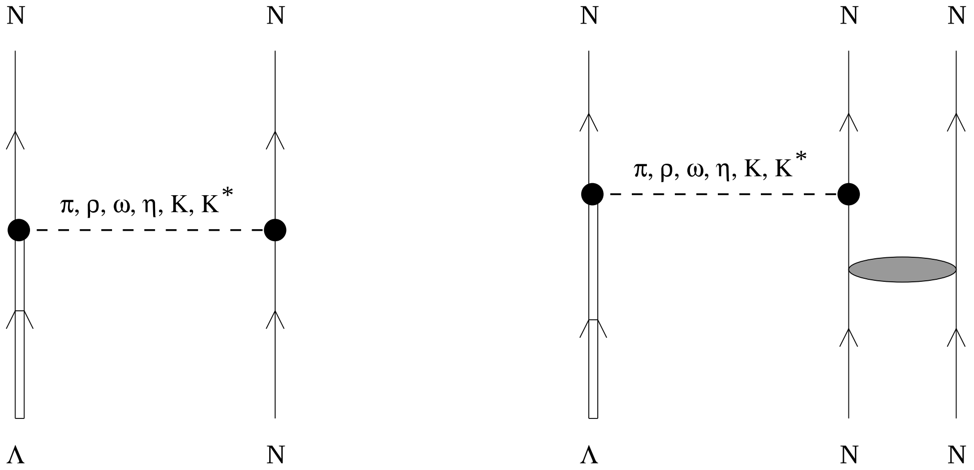
One–nucleon induced

$$\Lambda n \to nn \qquad \Gamma_n \qquad p_N \simeq 420\,\mathrm{MeV}$$

$$\Lambda p \to np \qquad \Gamma_p$$

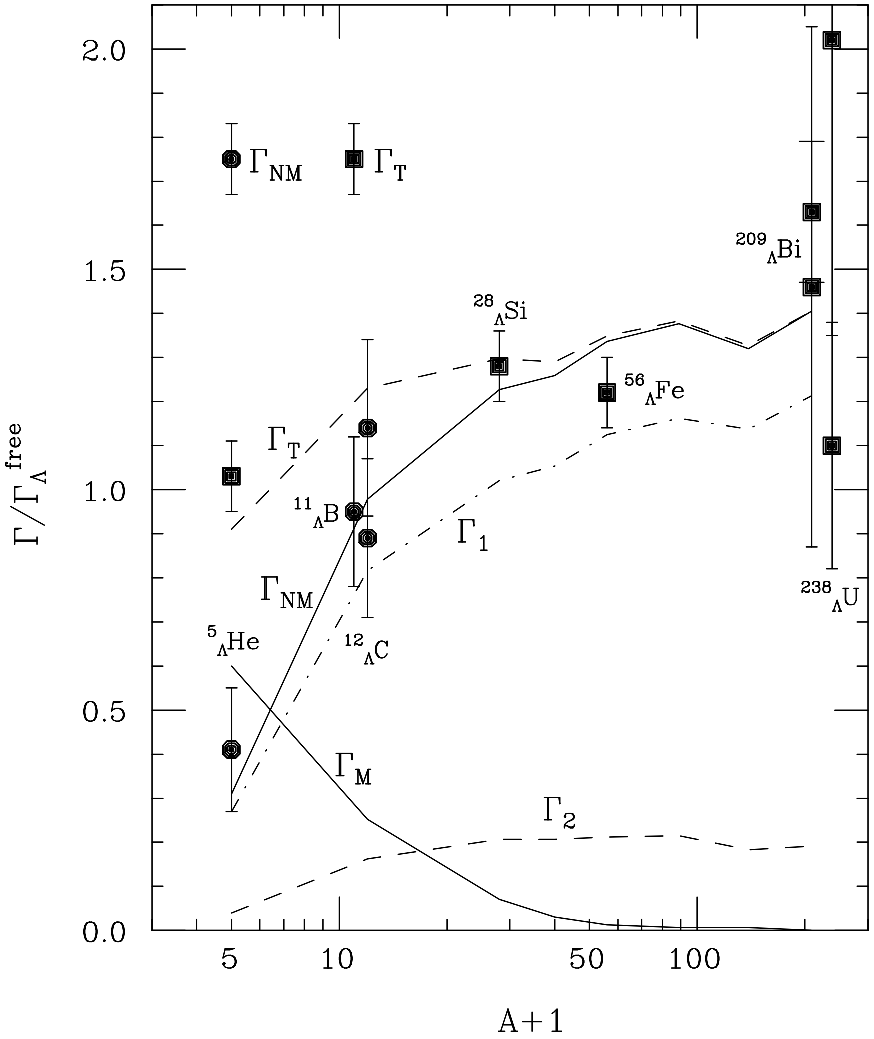
Two–nucleon induced

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



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

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



[W. M. Alberico, A. De Pace, G. G. and A. Ramos, Phys. Rev. **C 61**, 044314 (2000)]

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, 1 (2002)]

Theory strongly underestimated Γ_n/Γ_p data. For ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$:

$$\boxed{\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Th} \simeq 0.1 \div 0.5 \ll \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Exp} \simeq 1 \div 2}$$

Until recently, large uncertainties in the extraction of the ratio from data: only single proton spectra measured, very indirect determinations.

The One–Pion–Exchange (OPE) model predicts very small ratios for ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE} = 0.1 \div 0.2$$

but can reproduce the observed total non–mesonic rates.

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

A few calculations with $\Lambda N \to nN$ transition potentials including heavy meson exchange [1] and/or direct quark contributions [2] have recently improved the situation ($\Gamma_n/\Gamma_p \simeq 0.4 \div 0.5$), without providing an explanation of the origin 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; A 678 (2000) 455E.

In addition, a realistic analysis of the Γ_n/Γ_p ratio requires [3]:

- the inclusion of the TWO–NUCLEON INDUCED DECAY MECHANISM, whose experimental identification is expected in NNN coincidence measurements (FINUDA, KEK, BNL)

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

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

THE ASYMMETRY PUZZLE

Non–Mesonic Weak Decay of Polarized Λ–hypernuclei

Weak decay proton intensity from $\vec{\Lambda} p \to np$

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

$$\mathcal{A}(\Theta) = P_y\, A_y \cos\Theta$$

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

In the shell model weak–coupling scheme

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

where

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

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

Nucleon FSI modify the weak decay proton intensity $I(\Theta)$. Experiments measure

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

then $a_\Lambda^{\rm M}$ is determined as:

$$a_\Lambda^{\rm M} = \frac{1}{p_\Lambda}\frac{I^{\rm M}(0^\circ) - I^{\rm M}(180^\circ)}{I^{\rm M}(0^\circ) + I^{\rm M}(180^\circ)}$$

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

		$^{5}_{\Lambda}$He	$^{12}_{\Lambda}$C
Sasaki et al.	a_Λ		
$\pi + K + {\rm DQ}$		-0.68	
Parreño et al.			
$\pi + \rho + K + K^* + \omega + \eta$		-0.68	-0.73
Itonaga et al.			
$\pi + K + 2\pi/\rho + 2\pi/\sigma + \omega$		-0.33	
Barbero et al.			
$\pi + \rho + K + K^* + \omega + \eta$		-0.54	
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	

OUR APPROACH

PRL 91 (2003) 112501, PRC 69 (2004) 054603, nucl-th/0410107

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

  [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

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

RESULTS

ANGULAR CORRELATIONS

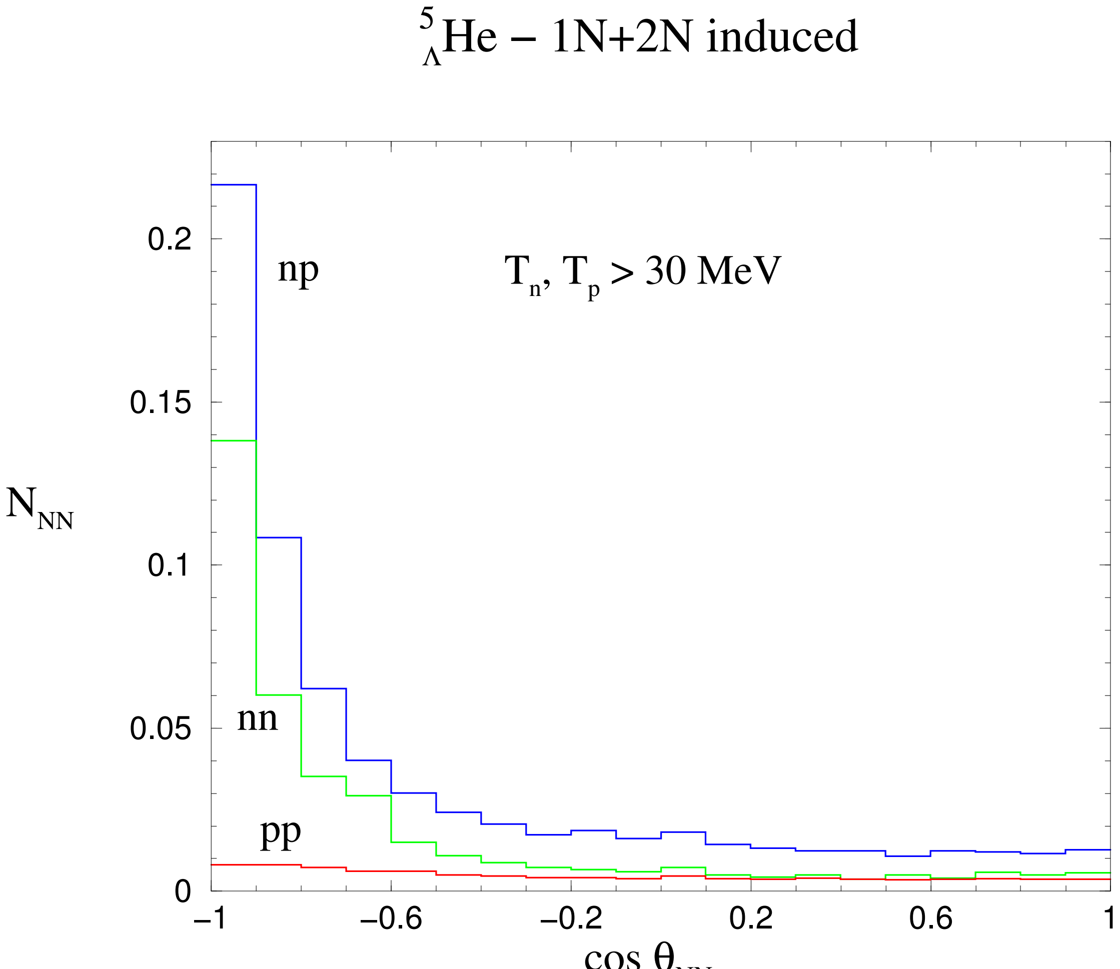


Figure 1: Opening angle distributions of *nn*, *np* and *pp* pairs emitted per NMWD of ${}^{5}_{\Lambda}$He

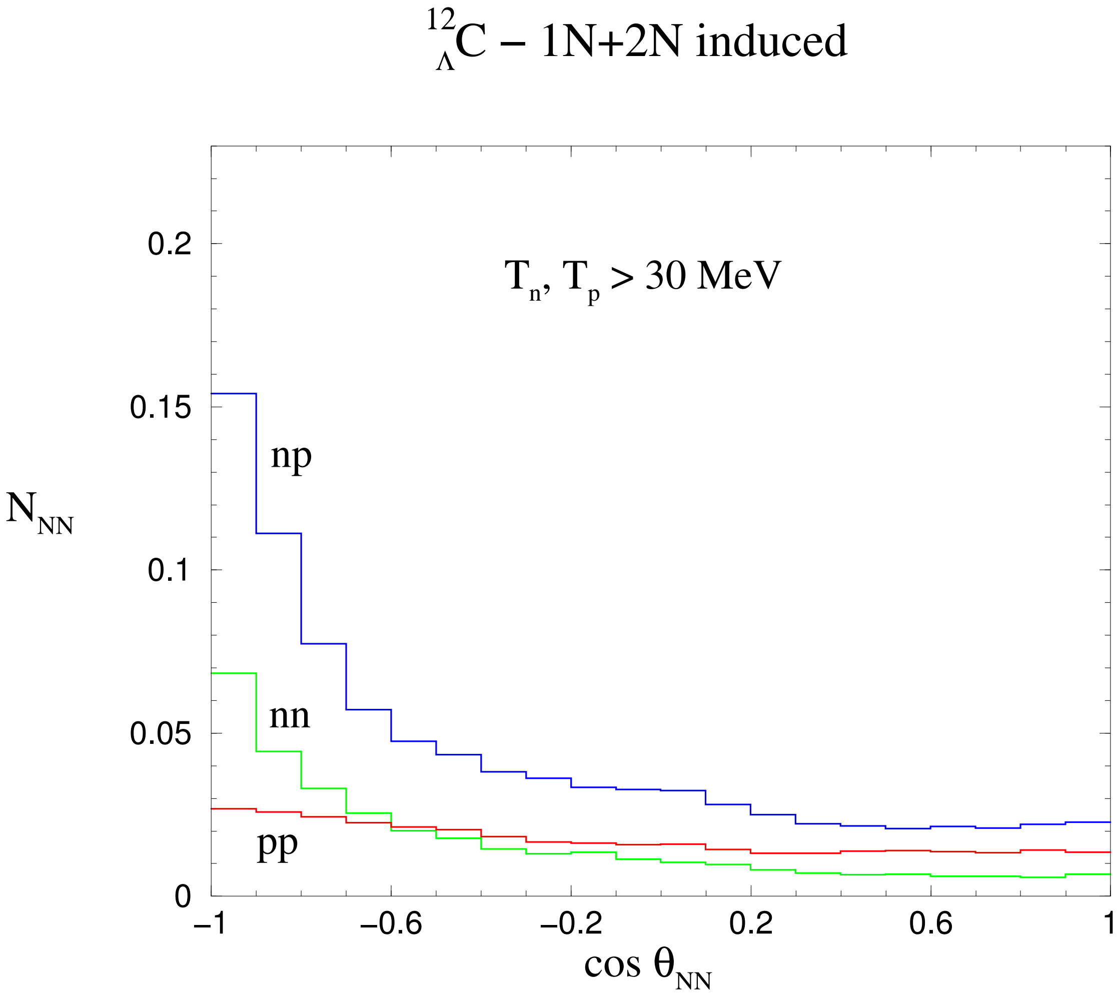


Figure 2: Angular distribution of *nn*, *np* and *pp* pairs emitted per NMWD of $^{12}_{\Lambda}$C

ENERGY CORRELATIONS

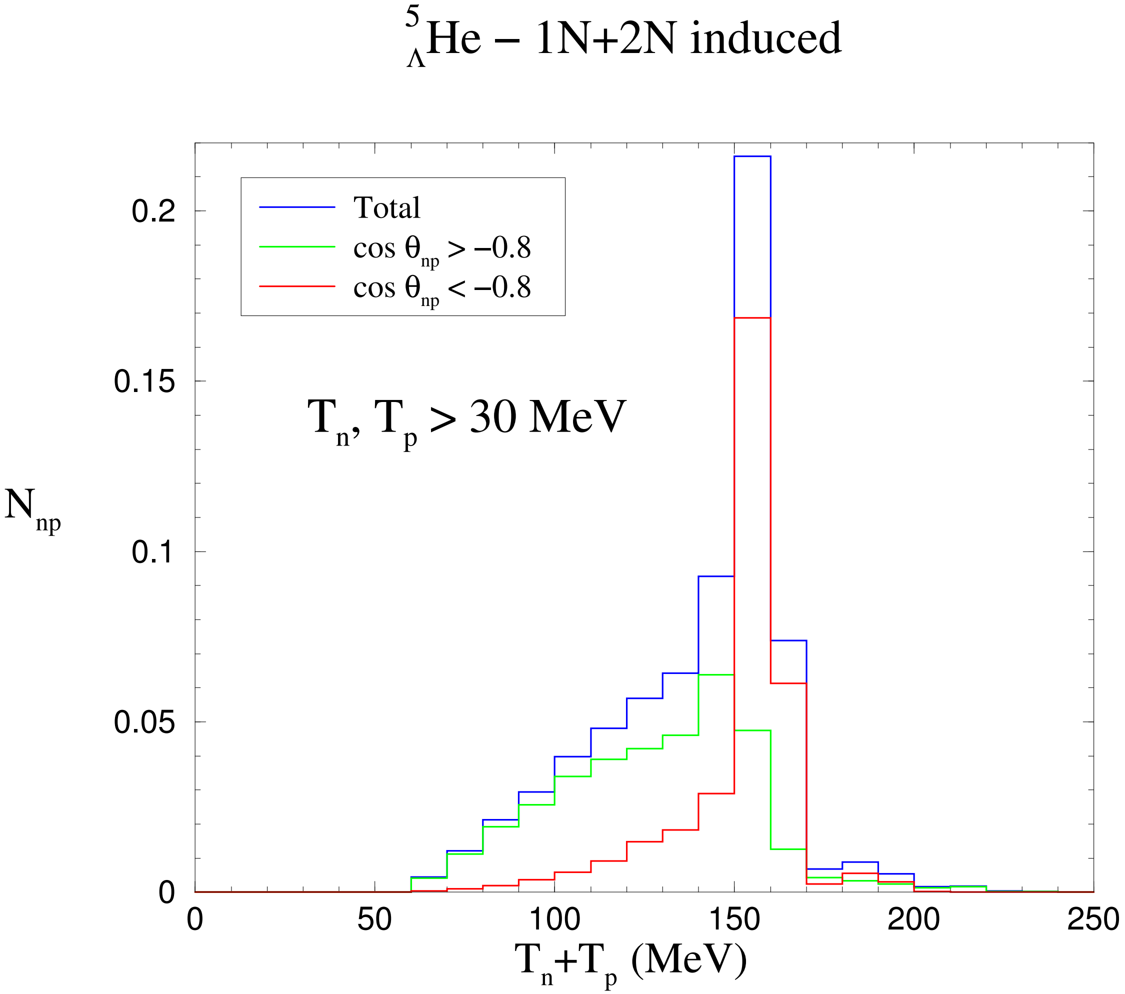


Figure 3: Kinetic energy correlations of *np* pairs emitted per NMWD of ${}^5_\Lambda$He

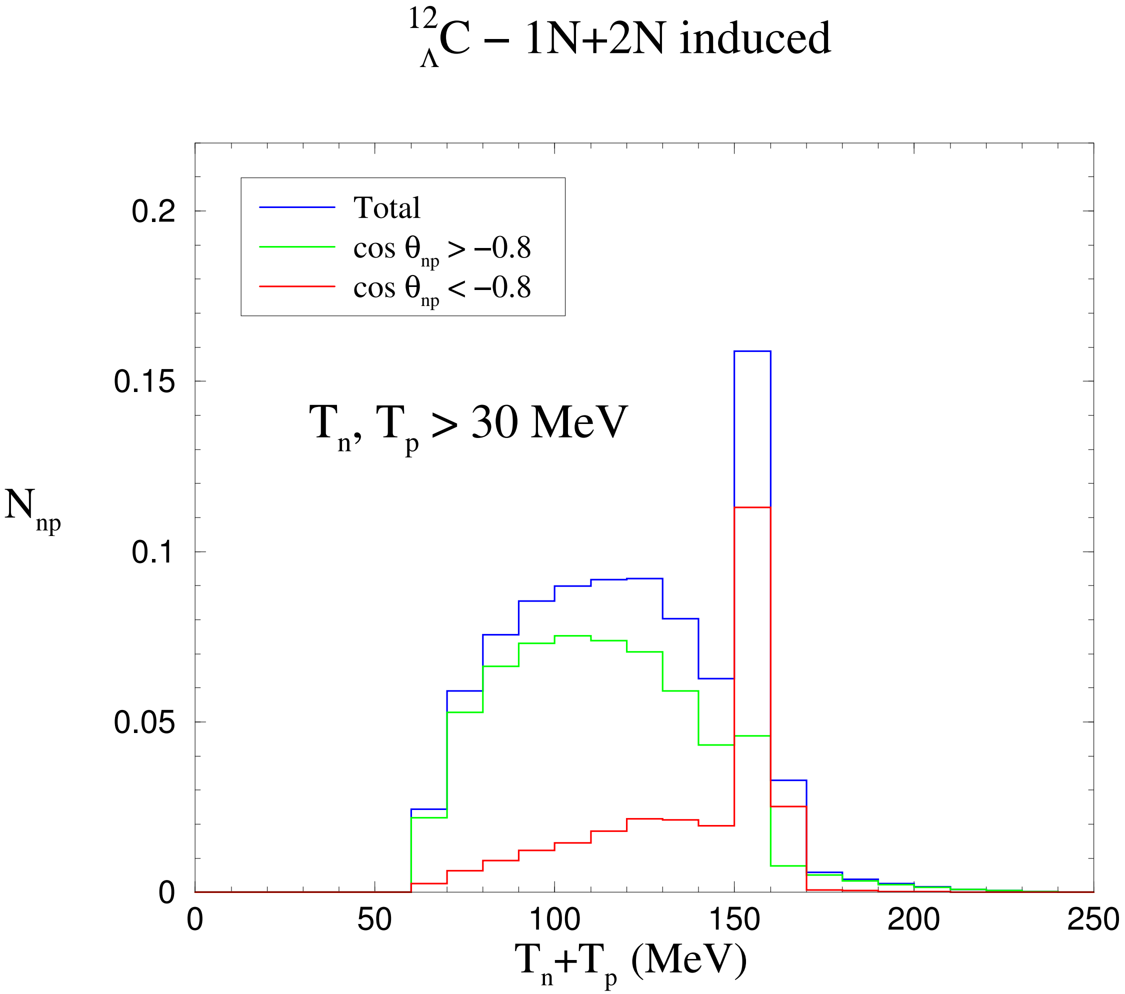


Figure 4: Kinetic energy correlations of *np* pairs emitted per NMWD of $^{12}_{\Lambda}$C

Number of primary NN pairs:

$$\begin{aligned} N_{nn}^{\rm wd} &\propto \Gamma_n \\ N_{np}^{\rm wd} &\propto \Gamma_p \end{aligned}$$

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

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

Table 1: $\boxed{N_{nn}/N_{np}}$ for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C ($\cos\theta_{NN} \leq -0.8$ and $T_N^{\rm th} = 30$ MeV)

	${}^{5}_{\Lambda}$He		${}^{12}_{\Lambda}$C	
	N_{nn}/N_{np}	Γ_n/Γ_p	N_{nn}/N_{np}	Γ_n/Γ_p
OPE	0.25	0.09	0.24	0.08
OMEa	0.51	0.34	0.39	0.29
OMEf	0.61	0.46	0.43	0.34
KEK–E462	0.45 ± 0.11			
KEK–E508			0.40 ± 0.09	

Data from H. Outa, HYP2003, Nucl. Phys. A (to be published)

A weak–decay–model independent analysis of Γ_n/Γ_p

- 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.

- From a measurement of N_{nn}/N_{np} and appropriate values for Γ_2/Γ_1:

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

- From KEK data we obtained:

${}^{5}_{\Lambda}\mathrm{He}$	$\Gamma_n/\Gamma_p = 0.27 \pm 0.11$	$\Gamma_2 = 0.20\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.40 \pm 0.11 \quad \Gamma_2 = 0)$
${}^{12}_{\Lambda}\mathrm{C}$	$\Gamma_n/\Gamma_p = 0.29 \pm 0.14$	$\Gamma_2 = 0.25\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.38 \pm 0.14 \quad \Gamma_2 = 0)$

ASYMMETRY

The calculated proton intensities turn out to be well fitted by

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

thus $a_\Lambda^{\rm M}$ can be obtained as:

$$a_\Lambda^{\rm M} = \frac{1}{p_\Lambda}\,\frac{I^{\rm M}(0^\circ) - I^{\rm M}(180^\circ)}{I^{\rm M}(0^\circ) + I^{\rm M}(180^\circ)}$$

Table 2: OME asymmetry parameters for ${}^{5}_{\Lambda}$He, ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C

	${}^{5}_{\Lambda}$He	${}^{11}_{\Lambda}$B	${}^{12}_{\Lambda}$C
a_Λ	-0.68	-0.81	-0.73
$a_\Lambda^{\rm M}(T_p^{\rm Th} = 0)$	-0.30	-0.18	-0.16
$a_\Lambda^{\rm M}(T_p^{\rm Th} = 30$ MeV$)$	-0.46	-0.39	-0.37
$a_\Lambda^{\rm M}(T_p^{\rm Th} = 50$ MeV$)$	-0.52	-0.55	-0.51
$a_\Lambda^{\rm M}(T_p^{\rm Th} = 70$ MeV$)$	-0.55	-0.70	-0.65
KEK–E462 (prel.)	0.07 ± 0.08		
KEK–E508 (prel.)		0.11 ± 0.44	-0.44 ± 0.32

Data from T. Maruta et al., HYP2003, nucl-ex/0402017, Nucl. Phys. A (to be published)

CONCLUSIONS

- Predictions for single and double–coincidence spectra for ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$ in reasonable agreement with KEK data

- Weak–decay–model model independent analysis of KEK coincidence data:

${}^{5}_{\Lambda}\mathrm{He}$	$\Gamma_n/\Gamma_p = 0.27 \pm 0.11$	$\Gamma_2 = 0.20\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.40 \pm 0.11$	$\Gamma_2 = 0)$
${}^{12}_{\Lambda}\mathrm{C}$	$\Gamma_n/\Gamma_p = 0.29 \pm 0.14$	$\Gamma_2 = 0.25\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.38 \pm 0.14$	$\Gamma_2 = 0)$

$\Longrightarrow$ in agreement with pure theoretical calculations

but considerably smaller than

${}^{5}_{\Lambda}\mathrm{He}$ BNL91: 0.93 ± 0.55, KEK95: 1.97 ± 0.67

${}^{12}_{\Lambda}\mathrm{C}$ BNL91: $1.33^{+1.12}_{-0.81}$, KEK95: $1.87^{+0.67}_{-1.16}$, KEK04: 0.87 ± 0.23

obtained by means of single nucleon spectra analyses!

- TOWARD A SOLUTION OF THE Γ_n/Γ_p PUZZLE

  Forthcoming coincidence data from FINUDA, KEK and BNL for better determinations of Γ_n/Γ_p and first constraints on Γ_2/Γ_1

Nucleon FSI turn out to be an important ingredient also when studying the NMWD of polarized hypernuclei but cannot explain the present asymmetry data

$a_\Lambda^{\rm M}({}^{12}_{\Lambda}{\rm C}) = -0.51 \div -0.37$ ⇔ -0.44 ± 0.32

agreement (KEK–E508 preliminary)

$a_\Lambda^{\rm M}({}^{11}_{\Lambda}{\rm B}) = -0.55 \div -0.39$ ⇔ 0.11 ± 0.44

disagreement (KEK–E508 preliminary)

$a_\Lambda^{\rm M}({}^{5}_{\Lambda}{\rm He}) = -0.52 \div -0.46$ ⇔ 0.07 ± 0.08

strong disagreement! (KEK–E462 preliminary)

- While THEORY predicts negative asymmetry values, with a moderate dependence on the hypernucleus, EXPERIMENT favors $a_\Lambda^{\rm M}({}^{12}_{\Lambda}{\rm C}) < 0$ and $a_\Lambda^{\rm M}({}^{5}_{\Lambda}{\rm He}) > 0$
- Theoretically, there seems to be no reaction mechanism which may be responsible for positive or vanishing asymmetries
- Experimentally, the present anomalous discrepancies among data need to be resolved