Weak Decay of Hypernuclei: Theory Review and Perspectives

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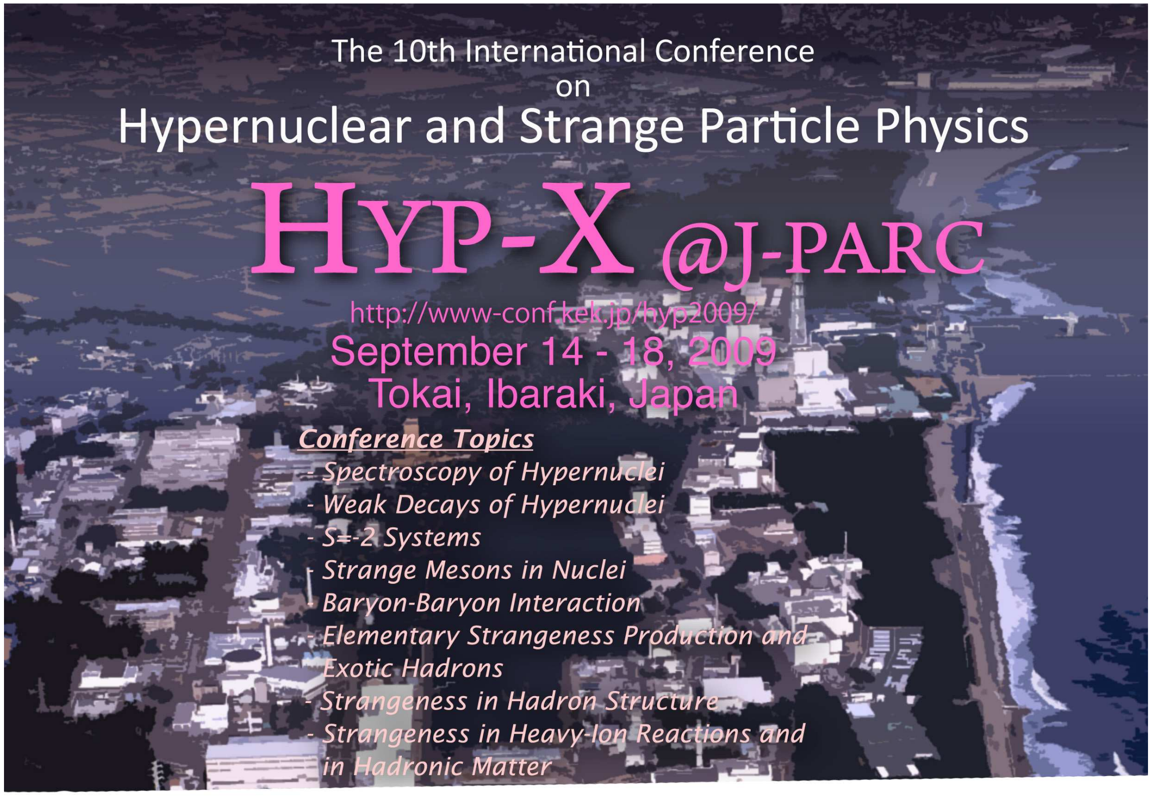

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on
Hypernuclear and Strange Particle Physics

HYP-X @J-PARC

http://www-conf.kek.jp/hyp2009/
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Tokai, Ibaraki, Japan

Conference Topics
- *Spectroscopy of Hypernuclei*
- *Weak Decays of Hypernuclei*
- *S=-2 Systems*
- *Strange Mesons in Nuclei*
- *Baryon-Baryon Interaction*
- *Elementary Strangeness Production and Exotic Hadrons*
- *Strangeness in Hadron Structure*
- *Strangeness in Heavy-Ion Reactions and in Hadronic Matter*

OUTLINE

- Weak Decay Modes of Hypernuclei
  - Mesonic vs Non–Mesonic
  - $S = -1$ and $S = -2$ Hypernuclei
- Models for Calculation
  - Finite Nucleus vs Nuclear Matter in LDA
- The Ratio Γ_n/Γ_p
- Polarized Hypernuclei: The Decay Asymmetry
- Perspectives
  - i) s–shell Hypernuclei and the $\Delta I = 1/2$ Rule
  - ii) Extraction of $\Gamma_2 = \Gamma(\Lambda NN \to nNN)$ from Data
  - iii) Weak Decay of $S = -2$ Hypernuclei
- Conclusions

WEAK DECAY MODES OF HYPERNUCLEI

MESONIC

$$\begin{array}{lcll} \Lambda & \rightarrow & \pi^0 n & \Gamma_{\pi^0} \\ \Lambda & \rightarrow & \pi^- p & \Gamma_{\pi^-} \end{array}$$

- $Q_{\mathrm{M}} = m_\Lambda - m_N - m_\pi \simeq 40$ MeV $\Longrightarrow p_N \simeq 100\,\mathrm{MeV} < k_F^0 \simeq 270\,\mathrm{MeV} \Longrightarrow$ forbidden, by Pauli principle, in normal infinite nuclear matter

- It occurs in finite nuclei, but largely suppressed in medium and heavy systems

  – hyperon momentum distribution allows $p_N > 100$ MeV

  – $\omega(\vec{q}) = \sqrt{\vec{q}^2 + m_\pi^{*2}} < \sqrt{\vec{q}^2 + m_\pi^2} \Longrightarrow p_N > 100$ MeV

  – at the nuclear surface $k_F(r) < p_N$

- $\Gamma_M = \Gamma_{\pi^0} + \Gamma_{\pi^-}$ rapidly decreases with A

- Γ_M very sensitive to the in medium pion self–energy (significantly enhanced by the actractive P–wave part) $\Longrightarrow$ information on the pion–nucleus optical potential

NON–MESONIC

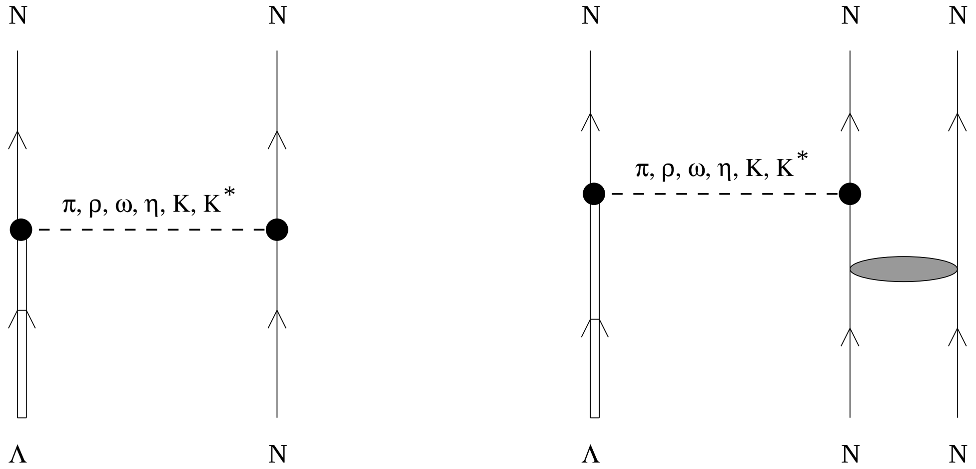
One–nucleon induced

$$\Lambda n \rightarrow nn \qquad \Gamma_n$$

$$\Lambda p \rightarrow np \qquad \Gamma_p$$

Two–nucleon induced

$$\Lambda nn \rightarrow nnn \quad \Gamma_{nn} \qquad \Lambda pp \rightarrow npp \quad \Gamma_{pp} \qquad \Lambda np \rightarrow nnp \quad \Gamma_{np}$$



$$\Gamma_T = \Gamma_M + \Gamma_{NM} \qquad \Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_{nn} + \Gamma_{pp} + \Gamma_{np}$$

- Only possible in nuclei: the only practical way to get information on Baryon–Baryon Weak Interactions

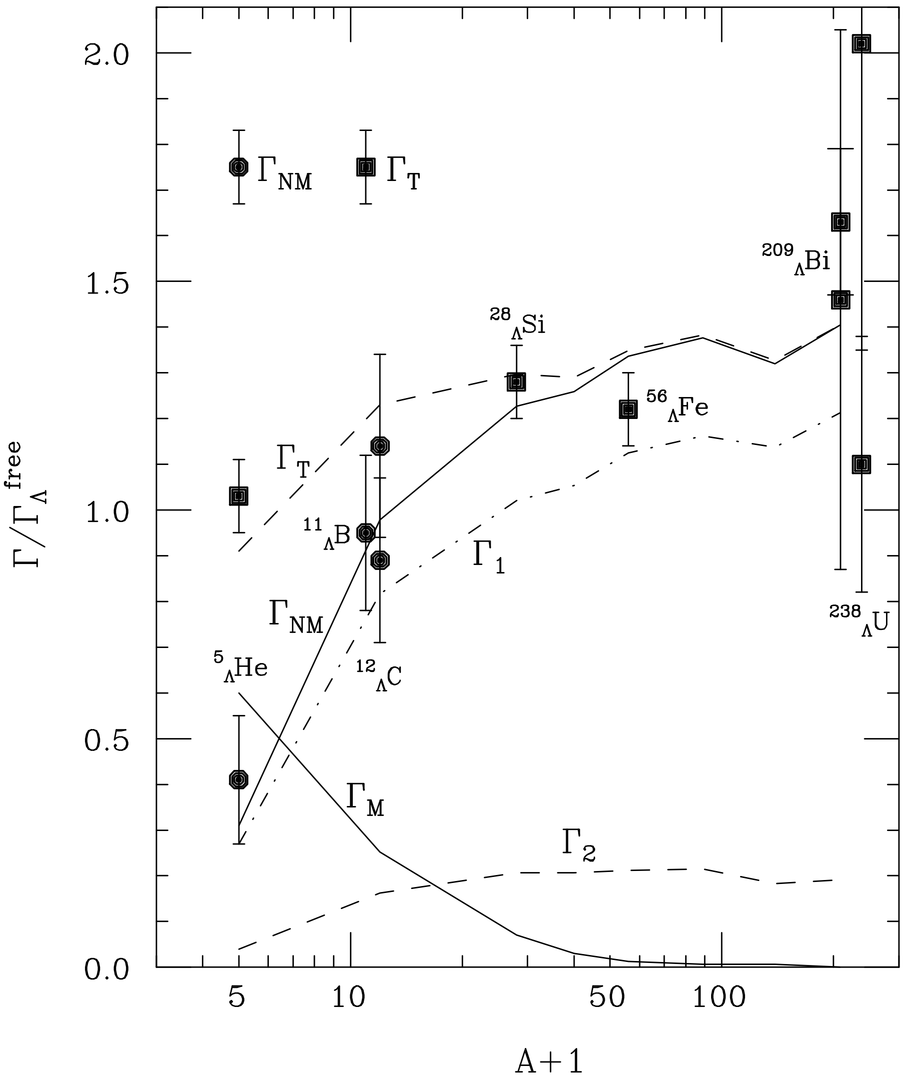
- $Q_{\mathrm{NM}} = m_\Lambda - m_N \simeq 176$ MeV $\Longrightarrow$ large p_N ($p_N \simeq 410$ MeV for $1N$–induced)

    - overcoming the Pauli blocking $\Longrightarrow$ the non–mesonic weak decay dominates over the mesonic one for all but the s–shell hypernuclei

    - non–mesonic channel mediated by Heavy Mesons ($\pi + \rho + K + K^* + \omega + \eta + 2\pi + 2\pi/\rho + 2\pi/\sigma + \ldots$) and/or Quark Exchange

- Study of $\Gamma_n \equiv \Gamma(\Lambda n \to nn)$ and $\Gamma_p \equiv \Gamma(\Lambda p \to np)$: Spin– and Isospin–dependence (validity of the $\Delta I = 1/2$ rule)

- Anticorrelation between Mesonic and Non–Mesonic decay modes: $\Gamma_{\mathrm{T}} = \Gamma_{\mathrm{M}} + \Gamma_{\mathrm{NM}}$ quite stable from light to heavy hypernuclei



[W. M. Alberico and G. G., Phys. Rep. **369**, 1 (2002)]

OTHER $S = -1$ HYPERNUCLEI?

- Σ–Hypernuclei

  Only ${}^{4}_{\Sigma}$He exist, V_{Σ} repulsive

  The rapid $\Sigma N \to \Lambda N$ strong reaction prevents the observation of the much slower $\Sigma N \to NN$ weak decay

$S = -2$ HYPERNUCLEI

- Ξ–Hypernuclei

  The $\Xi N \to \Lambda\Lambda$ strong conversion prevents the observation of the $\Xi N \to \Lambda N$ and $\Xi N \to \Sigma N$ $\Delta S = 1$ weak decays

- $\Lambda\Lambda$–Hypernuclei

  Weak decays: $\Lambda\Lambda \to \Lambda n$, $\Lambda\Lambda \to \Sigma N$, $\Lambda\Lambda \to nn$

  Very difficult to detect: $\Gamma_{\Lambda\Lambda} \simeq \Gamma^{\rm free}_{\Lambda}/(25 \div 60)$

Actual possibility of performing *both* theoretical and experimental studies on Baryon–Baryon Weak Interactions $\Longleftrightarrow$ Λ–Hypernuclei

MODELS FOR CALCULATION

Finite Nucleus: Mesonic Decay

[K. Itonaga, T. Motoba, H. Bando, NPA 489, 683 (1988)]
[J. Nieves, E. Oset and C. Garcia-Recio, NPA 554, 509 (1993)]

$$\mathcal{H}^{W}_{\Lambda\pi N} = iGm_\pi^2\overline{\psi}_N(A+B\gamma_5)\vec{\tau}\cdot\vec{\phi}_\pi\psi_\Lambda$$

$$\begin{aligned}\Gamma_{\pi^0(\pi^-)} \quad = \quad & c_{\pi^0(\pi^-)}(Gm_\pi^2)^2\sum_{N>F}\int\frac{d\vec{q}}{(2\pi)^3\,2\omega(\vec{q})}\,2\pi\,\delta[E_\Lambda-\omega(\vec{q})-E_N] \\ & \times\left\{A^2\left|\int d\vec{r}\phi_\Lambda(\vec{r})\phi_\pi(\vec{q},\vec{r})\phi_N^*(\vec{r})\right|^2+\frac{B^2}{4m_N^2}\left|\int d\vec{r}\phi_\Lambda(\vec{r})\vec{\nabla}\phi_\pi(\vec{q},\vec{r})\phi_N^*(\vec{r})\right|^2\right\}\end{aligned}$$

- Shell Model Λ and nucleon wave functions, ϕ_Λ and ϕ_N
- Pion wave function, ϕ_π, solution of the Klein–Gordon equation with proper pion–nucleus optical potential $V_{\rm opt}$:

$$\left\{\vec{\nabla}^2-m_\pi^2-2\omega V_{\rm opt}(\vec{r})+\left[\omega-V_C(\vec{r})\right]^2\right\}\phi_\pi(\vec{q},\vec{r})=0$$

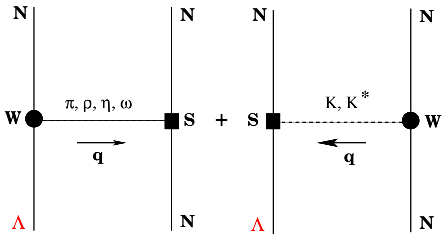
Finite Nucleus: Non–Mesonic Decay

[J. F. Dubach, G. B. Feldman and B. R. Holstein, Ann. Phys. 249, 146 (1996)]
[A. Parreno, A. Ramos and C. Bennhold, PRC 56, 339 (1997)]
[C. Barbero, D. Horvat, F. Krmpotic, T.T.S. Kuo, Z. Narancic, D. Tadic, PRC66, 055209 (2002)]

Shell Model Nuclear (Ψ_R) and Hypernuclear (Ψ_H) wave functions used to compute:

$$\Gamma_{n(p)} = \int \frac{d\vec{p}_1}{(2\pi)^3} \int \frac{d\vec{p}_2}{(2\pi)^3} 2\pi\,\delta\left(m_H - E_R - E_1 - E_2\right) \overline{\sum} \left|\mathcal{M}_{n(p)}(\vec{p}_1, \vec{p}_2)\right|^2$$

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



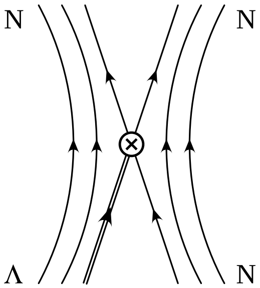
- Weak–Coupling scheme: $\mathcal{M}_N \Longrightarrow \langle nN | V_{\rm ME} | \Lambda N \rangle$
- $V_{\rm ME}$: Meson–Exchange $\Lambda N \to nN$ transition potential
  - OME: Mesons of the Pseudoscalar (π, η, K) and Vector (ρ, ω, K^*) Octets
  - TPE: uncorrelated (2π) and correlated ($2\pi/\sigma$)

Finite Nucleus: Quarks

Hybrid Model: long range interactions $\Longrightarrow$ hadronic degrees of freedom (OPE)
short range interactions $\Longrightarrow$ 6–quark cluster model

[C.-Y. Cheung, D. P. Heddle and L. S. Kisslinger, PRC 27, 335 (1983)
[D. P. Heddle and L. S. Kisslinger, PRC 33, 608 (1986)]

Direct Quark Model combined with OME ($\pi + K + \sigma$)



[T. Inoue, M. Oka, T. Motoba and K. Itonaga, NPA 633, 312 (1998)]

[K. Sasaki, T. Inoue and M. Oka, 669, 331 (2000); NPA 678, 455(E) (2000)]

- Baryon–baryon short range repulsion from quark exchange between baryons (quark antisymetrization)
- Naturally includes both $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions
- Main uncertainty from the parameterization of the effective 4–quark weak Hamiltonian

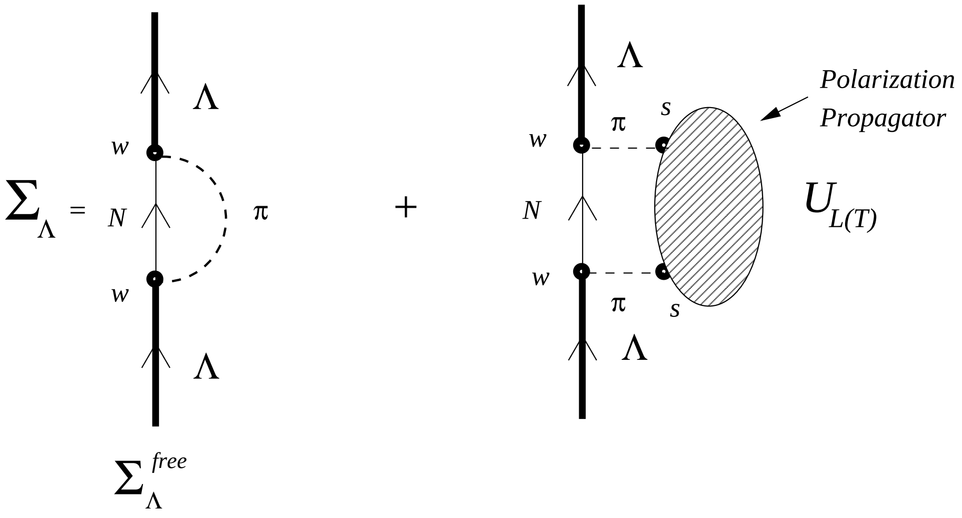
Nuclear Matter in LDA

[E. Oset, L.L. Salcedo, NPA 443, 704 (1985)]

- Many–Body technique for nuclear matter calculations, extended to finite nuclei via the LDA
- Unified picture of Mesonic and Non–Mesonic decay channels, equivalent to the finite nucleus approach

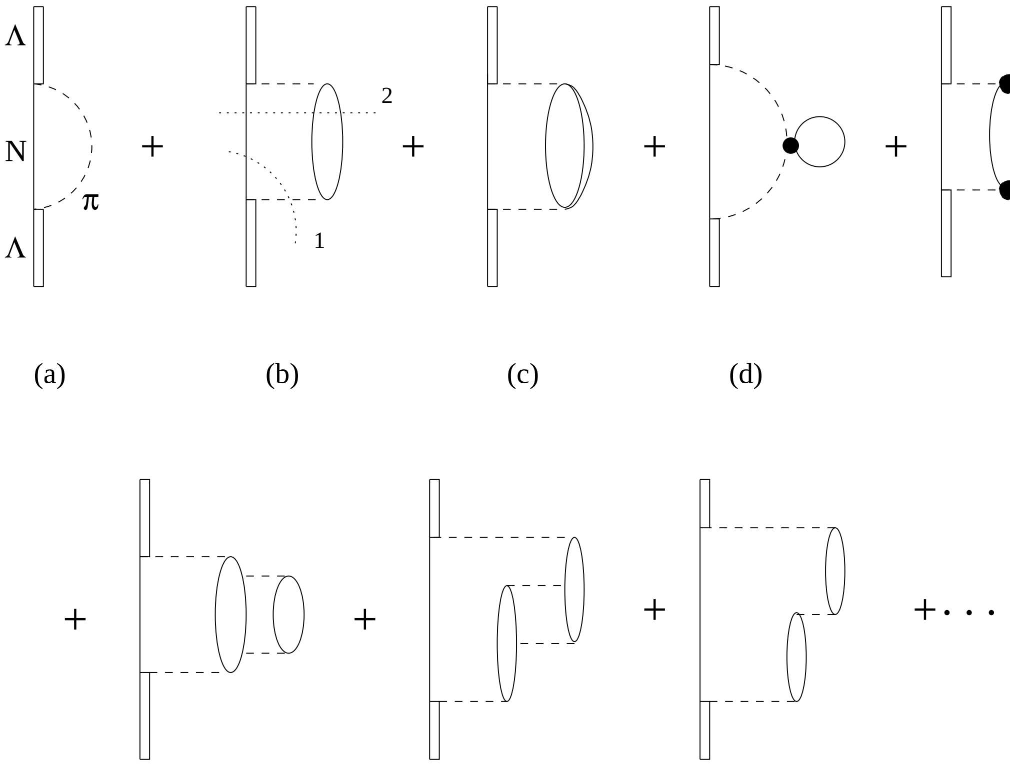
Nuclear Matter

$$\Gamma_\Lambda = -2\,\mathrm{Im}\,\Sigma_\Lambda$$



$$\Sigma_\Lambda(k) = 3i(Gm_\pi^2)^2 \int \frac{d^4q}{(2\pi)^4} \left(A^2 + \frac{B^2}{4m_N^2}\vec{q}^{\,2} \right) F_\pi^2(q) G_N(k-q) G_\pi(q)$$

$$
\begin{aligned}
G_N(p) &= \frac{\theta(\mid \vec{p}\mid - k_F)}{p_0 - E_N(\vec{p}) - V_N + i\epsilon} + \frac{\theta(k_F - \mid \vec{p}\mid)}{p_0 - E_N(\vec{p}) - V_N - i\epsilon} \\
G_\pi(q) &= \frac{1}{q_0^2 - \vec{q}^{\,2} - m_\pi^2 - \Sigma_\pi^*(q)}
\end{aligned}
$$



(a) (b) (c) (d) (e)

(f) (g) (h)

LDA

Local Fermi See of nucleons:

$$k_F(\vec{r}) = \left\{ \frac{3}{2} \pi^2 \rho(\vec{r}) \right\}^{1/3}$$

$$\begin{aligned} \Gamma_\Lambda(\vec{k}) &= \int d\vec{r}\, |\psi_\Lambda(\vec{r})|^2 \Gamma_\Lambda\left[\vec{k}, \rho(\vec{r})\right] \\ \Gamma_\Lambda &= \int d\vec{k}\, |\tilde{\psi}_\Lambda(\vec{k})|^2 \Gamma_\Lambda(\vec{k}) \end{aligned}$$

◆ Phenomenological Approach to the $2N$–induced channel

[W.M. Alberico, A. De Pace, M. Ericson and A. Molinari, PLB 256, 134 (1991)]

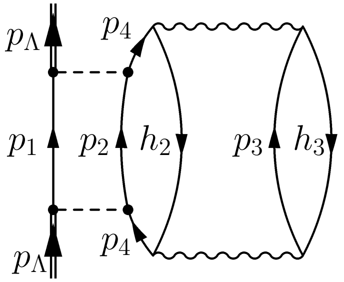
* [A. Ramos, E. Oset and L. L. Salcedo, PRC50, 2314 (1994)]

Data on pion absorption in nuclei

* Phase space argument for the $2p2h$ configurations

$\Lambda np \rightarrow nnp$

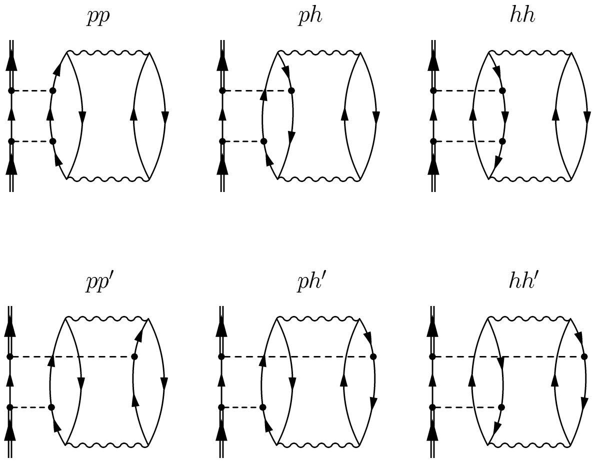
* $\Gamma_2/\Gamma_{\rm NM} = 0.16$



❖ Microscopic Approach to the $2N$–induced channel

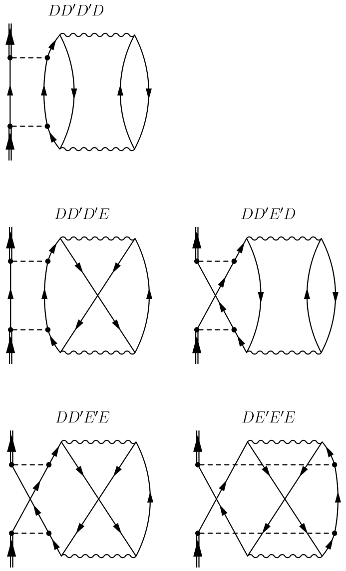
All isospin channels included: $\Gamma_2 = \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}$

$\Gamma_2/\Gamma_{\rm NM} = 0.29\,, \quad \Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$



[E. Bauer and F. Krmpotic, NPA 739, 109 (2004)]

[E. Bauer, NPA 818, 174 (2009)]

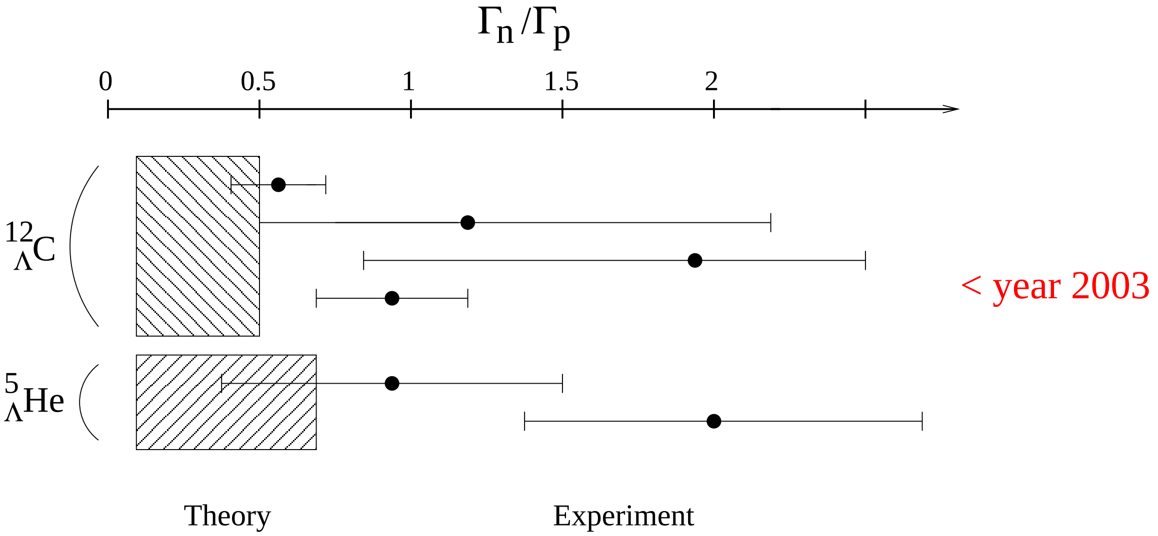


Pauli Exchange terms

[E. Bauer and G. G., NPA 828, 29 (2009)]

THE RATIO Γ_n/Γ_p

For many years, a sound theoretical explanation of the large experimental values of $\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Gamma(\Lambda n \to nn)}{\Gamma(\Lambda p \to np)}$ has been missing



Theory strongly underestimated Experiment!

[W. M. Alberico and G. G., Phys. Rep. 369, 1 (2002)]
[E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41, 191 (1998)]

Experiment

- ✦ Large uncertainties in the extraction of Γ_n/Γ_p from “old” data ($<$ year 2002)
  - only Single–Proton Spectra measured
  - very indirect determination of the decay rates, probable overestimation of
    $$\frac{\Gamma_n}{\Gamma_p} = \frac{\Gamma_{\rm T} - \Gamma_{\rm M} - \Gamma_2 - \Gamma_p}{\Gamma_p} \Longleftarrow \Gamma_p \text{ underestimated}, \Gamma_2 \text{ neglected}$$
    $$(\Gamma_2 = 0\,, \Gamma_p = 0.8[\Gamma_p]^{\rm th} : \Gamma_n/\Gamma_p = 1 \iff [\Gamma_n/\Gamma_p]^{\rm th} = 0.3)$$
- ✦ KEK–E462/E508: simultaneous measurement of Single–Proton and Single–Neutron Spectra (year 2003) [1]
  - improved (but model–dependent) determination of $\dfrac{\Gamma_n}{\Gamma_p}$ from $\dfrac{N_n}{N_p}$ ratio
- ✦ KEK–E462/E508: Nucleon–Nucleon Coincidence Spectra (years 2003–2006) [2]
  - more direct (but model–dependent) determination of $\dfrac{\Gamma_n}{\Gamma_p}$ from $\dfrac{N_{nn}}{N_{np}}$ ratio
- ✦ First data from FINUDA@DAΦNE [3], experiments planned at J–PARC and HypHI@GSI

[1] S. Okada et al., PLB 597, 249 (2004) KEK experiments: [Plenary Talk by Outa]

[2] B. H. Kang et a., PRL 96, 062301 (2006); M. J. Kim et al., PLB 641, 28 (2006)

[3] M. Agnello et al., NPA 804, 151 (2008) FINUDA experiments: [Plenary Talk by Botta]

Theory

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

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE}({}^5_\Lambda{\rm He},\,{}^{12}_\Lambda{\rm C}) = 0.1 \div 0.2$$

  $[\Delta I = 1/2$ rule + strong tensor component $\Lambda N(^3S_1) \to nN(^3D_1)$ requiring $I_{nN} = 0 \Longleftrightarrow N = p]$

- but reproduces the observed total non–mesonic rates $\Gamma_{\rm NM} = \Gamma_n + \Gamma_p (+\Gamma_2)$

Other Interaction Mechanisms beyond the OPE should then be responsible for the overestimation of Γ_p and the underestimation of Γ_n

- Heavier Mesons (ρ, K, K^*, ω, η, 2π, $2\pi/\rho$, $2\pi/\sigma$) [Parreño et al., Itonaga et al., Jido et al., Krmpotic et al.]
- Direct Quark Mechanism [Oka et al.]
- Two–Nucleon Induced Mechanism [Alberico et al., Ramos et al., Bauer et al.]
- Nucleon Final State Interactions [Ramos et al., Garbarino et al.]

Improvement from Heavy Meson Exchange (especially Kaons) [1] and Direct Quark contributions [2]

$$\boxed{\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\mathrm{TH}} = 0.3 \div 0.7}$$

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

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

The determination of Γ_n/Γ_p from N_{nn}/N_{np} Data required Theoretical Analyses [3]:

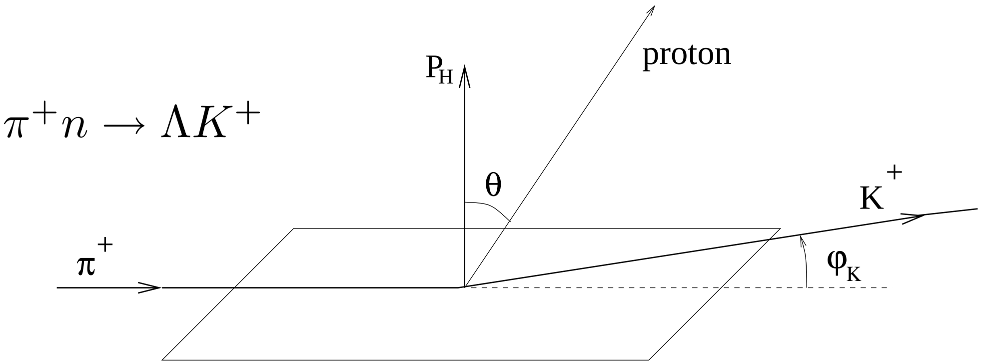
- Two–Nucleon Induced Decays
- Nucleon FSI (INC)

$$\boxed{\left[\frac{N_{nn}}{N_{np}}\right]^{\mathrm{KEK}} \simeq 0.5 \pm 0.1 \quad \Longrightarrow \quad \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{“EXP”}} = (0.3 \div 0.4) \pm 0.1}$$

convincing evidence for a SOLUTION OF THE PUZZLE

[3] G. G., A. Parreño, A. Ramos, PRL 91, 112501 (2003); PRC 69, 054603 (2004);
C. Chumillas, G. G., A. Parreño, A. Ramos, NPA 804, 162 (2008) [Talk by Bauer]

POLARIZED HYPERNUCLEI: THE DECAY ASYMMETRY



❖ Weak Decay Proton Intensity from $\vec{\Lambda} p \to np$: $I(\theta) = I_0\,[1 + p_\Lambda\, a_\Lambda \cos\theta]$

$$p_\Lambda \quad = \quad \Lambda\,\text{Polarization}$$

$$a_\Lambda \quad = \quad \text{Intrinsic }\Lambda\text{ Asymmetry Parameter}$$

$a_\Lambda \iff$ Interference among PC and PV $\vec{\Lambda} p \to np$ channels

$\Longrightarrow$ information on strengths and relative phases of the decay amplitudes

	$^{5}_{\Lambda}$He	$^{12}_{\Lambda}$C
Sasaki et al. (2002)		
$\pi + K + \mathrm{DQ}$	-0.68	
Parreño et al. (2002)		
$\mathrm{OME} = \pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
Barbero et al. (2005)		
$\mathrm{OME} = \pi + \rho + K + K^* + \omega + \eta$	-0.54	-0.53
Alberico et al. (2005)		
$\mathrm{OME} + \mathrm{FSI}$	-0.46	-0.37
Chumillas et al. (2007)		
$\mathrm{OME} + 2\pi + 2\pi/\sigma + \mathrm{FSI}$	$+0.028$	-0.126
Itonaga et al. (2007)		
$\pi + K + \omega + 2\pi/\rho + 2\pi/\sigma + \rho\pi/a_1 + \sigma\pi/a_1$	$+0.083$	$+0.045$
KEK–E508		$-0.16 \pm 0.28^{+0.18}_{-0.00}$
KEK–E462	$+0.07 \pm 0.08^{+0.08}_{-0.00}$	

$\Longrightarrow$ Importance of the Scalar–Isoscalar channel in Asymmetry calculations

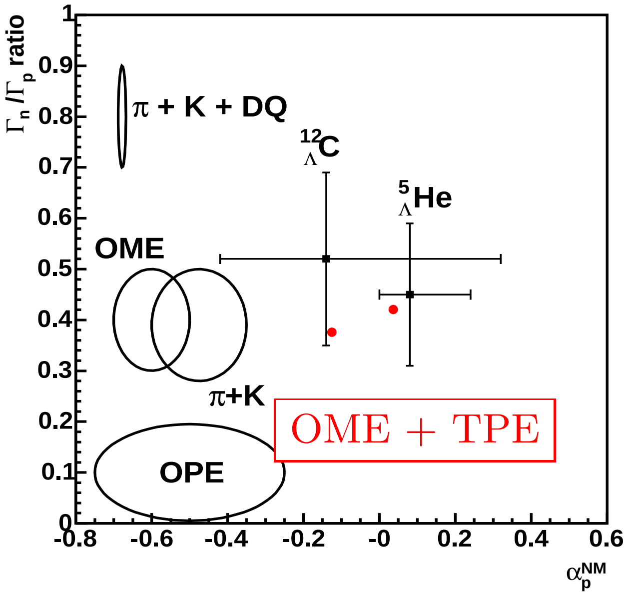
OME + TPE: Agreement also with the Decay Rate data for *both* $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C!

An Effective Field Theory approach ($\pi + K+$ Leading–Order Contact Interactions) predicted a dominance of Spin– and Isospin–Independent contact terms

[A. Parreño, C. Bennhold and B.R. Holstein, PRC70, 051601 (2004)]

PERSPECTIVES

- Recent Experimental and Theoretical developments have brought to a solution of the long–standing puzzles on Γ_n/Γ_p and the Decay Asymmetry



OME + TPE reproduces all data (no exotic mechanisms and $\Delta I = 3/2$ contributions)

- However, improvements in Experiment and Theory are necessary to achieve a detailed understanding of the Non–Mesonic Weak Decay reaction mechanisms
  - Obtain an accurate determination of Partial Decay Rates and Asymmetries
  - Still model–dependendent results in OME and DQ calculations
(unknown weak meson–baryon–baryon couplings, validity of $\Delta I = 1/2$ rule)

i) s–shell Hypernuclei and the $\Delta I = 1/2$ Rule

- Block–Dalitz Phenomenological Model $\Longrightarrow$ Spin–Isospin structure of $\Lambda N \to nN$

- Introducing the rates R_{NJ} for the spin–singlet $(R_{n0},\, R_{p0})$ and spin–triplet $(R_{n1},\, R_{p1})$ elementary $\Lambda N \to nN$ interactions:

$$\begin{aligned}
\Gamma_{\rm NM}({}^{3}_{\Lambda}{\rm H}) &= (3R_{n0} + R_{n1} + 3R_{p0} + R_{p1})\,\frac{\rho_2}{8} \\
\Gamma_{\rm NM}({}^{4}_{\Lambda}{\rm H}) &= (R_{n0} + 3R_{n1} + 2R_{p0})\,\frac{\rho_3}{6} \\
\Gamma_{\rm NM}({}^{4}_{\Lambda}{\rm He}) &= (2R_{n0} + R_{p0} + 3R_{p1})\,\frac{\rho_3}{6} \\
\Gamma_{\rm NM}({}^{5}_{\Lambda}{\rm He}) &= (R_{n0} + 3R_{n1} + R_{p0} + 3R_{p1})\,\frac{\rho_4}{8}
\end{aligned}$$

- Relations which test the $\Delta I = 1/2$ Rule

$$\frac{\Gamma_n({}^{4}_{\Lambda}{\rm He})}{\Gamma_p({}^{4}_{\Lambda}{\rm H})} = \frac{\dfrac{\Gamma_n}{\Gamma_p}({}^{4}_{\Lambda}{\rm H})\dfrac{\Gamma_n}{\Gamma_p}({}^{4}_{\Lambda}{\rm He})}{\dfrac{\Gamma_n}{\Gamma_p}({}^{5}_{\Lambda}{\rm He})} = \frac{R_{n0}}{R_{p0}} \quad \Longleftrightarrow \quad \Delta I = 1/2\ \text{Rule}: \quad \frac{R_{n1}}{R_{p1}} \le \frac{R_{n0}}{R_{p0}} = 2$$

- $\Gamma_{\rm NM}({}^5_\Lambda{\rm He}) = 0.411 \pm 0.024 \quad \frac{\Gamma_n}{\Gamma_p}({}^5_\Lambda{\rm He}) = 0.3 \pm 0.1$ (KEK):

$\Delta I = 1/2$ rule		Experiment	
$\Gamma_{\rm NM}({}^4_\Lambda{\rm He}) = 0.25^{+0.04}_{-0.01}$	$\Longleftrightarrow$	0.177 ± 0.028	(BNL–E788)
$\Gamma_{\rm NM}({}^4_\Lambda{\rm H}) = 0.08^{+0.03}_{-0.02}$	$\Longleftrightarrow$	0.17 ± 0.11	(KEK)

$\Longrightarrow$ violation of the $\Delta I = 1/2$ rule? Too early to conclude!

- E22@J–PARC: precise measurement of Γ_n and Γ_p for ${}^4_\Lambda{\rm H}$ and ${}^4_\Lambda{\rm He}$

[Poster by Ajimura]

- Also important: demonstration of the reliability of Block–Dalitz Model

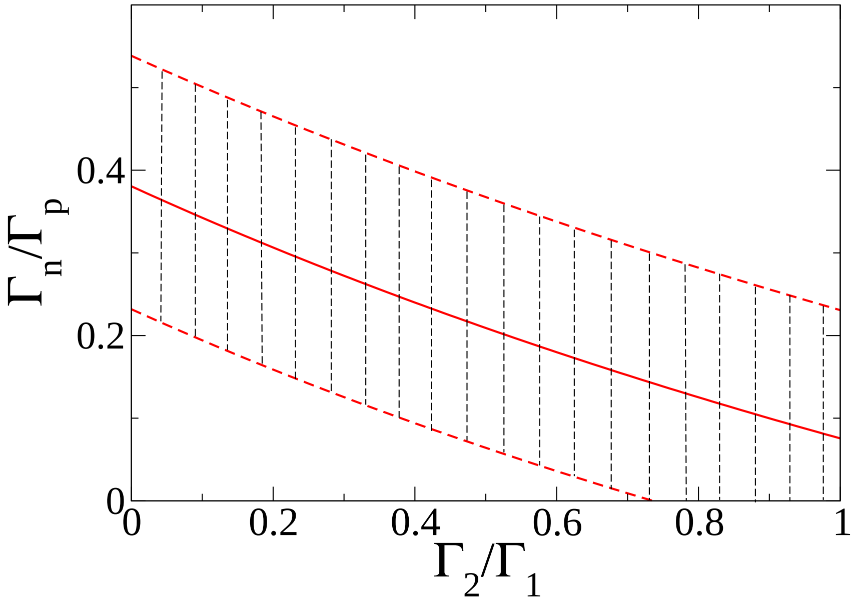
ii) Extraction of $\Gamma_2 = \Gamma(\Lambda NN \rightarrow nNN)$ from Data

Theoretical analysis of KEK Coincidence Data only establishes a correlation property between Γ_n/Γ_p and Γ_2/Γ_1

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

$$\text{KEK–E462 } {}^{12}_{\Lambda}\text{C:} \quad \frac{N_{nn}}{N_{np}} = 0.4 \pm 0.1 \qquad (T_N > 30 \text{ MeV}, \cos\theta_{NN} \leq -0.8)$$

Γ_n/Γ_p–Γ_2/Γ_1 Correlation



- Theory for ${}^{12}_{\Lambda}$C:

  $\Gamma_2/\Gamma_{\rm NM} = 0.16$ $\Gamma_2 = \Gamma_{np}$

  [A. Ramos, E. Oset, and L.L. Salcedo, PRC50, 2314 (1994)]

  $\Gamma_2/\Gamma_{\rm NM} = 0.29$ $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$

  [E. Bauer and G. G., NPA 828, 29 (2009)]

- KEK ${}^{12}_{\Lambda}$C Data + simplistic Assumptions: $\Gamma_2/\Gamma_{\rm NM} \simeq 0.4$

  [H. Bhang et al., EPJA 33, 259 (2007)]

- BNL–E788 ${}^{4}_{\Lambda}$He Data: $\Gamma_2/\Gamma_{\rm NM} \leq 0.24$ (95% CL)

  [J. D. Parker et al., PRC 76, 035501 (2007)]

- FINUDA *s*– and *p*–shell Data: $\Gamma_2/\Gamma_{\rm NM} = 0.27 \pm 0.06$

  [Plenary Talk by Botta]

- E18@J–PARC: determination of Γ_n, Γ_p and Γ_2 for ${}^{12}_{\Lambda}$C with a 10% error level via Double– and Triple–Nucleon Coincidence

  [Talk by Kim Mijung]

iii) Weak Decay of $S = -2$ Hypernuclei

- Ξ and $\Lambda\Lambda$ Hypernuclei
- $\Xi^- p \to \Lambda\Lambda$ strong conversion produces $\Lambda\Lambda$ hypernuclei
- Hyperon–Induced Non–Mesonic Weak Decay
  - $\Lambda\Lambda \to \Lambda n \quad \Lambda\Lambda \to \Sigma^0 n \quad \Lambda\Lambda \to \Sigma^- p \quad (\Delta S = 1)$
  - $\Lambda\Lambda \to nn \quad (\Delta S = 2)$
  - $\Gamma_{\Delta S=1}({}^{6}_{\Lambda\Lambda}\mathrm{He})/\Gamma_\Lambda = 0.017$ [1], 0.026 [2], 0.040 [3]

[1] K. Sasaki, T. Inoue and M. Oka, NPA 726, 349 (2003)

[2] K. Itonaga, T. Ueda and T. Motoba, NPA 691, 197c (2001)

[3] A. Parreño, A. Ramos and C. Bennhold, PRC 65,015205 (2002)

- KEK–E373: NAGARA event [H. Takahashi et al., PRL 87, 212502 (2001)]
  - Production of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ ($\Lambda\Lambda$ interaction is weakly attractive)
  - Recent observation of a Weak Decay to $\Sigma^- p$ ($BR^{\mathrm{exp}} \simeq 0.01$)

[T. Watanabe et al., EPJA 33, 265 (2007)]

$\Lambda\Lambda \to \Sigma^- p$ (but $BR^{\mathrm{th}} \simeq 0.001$)

$H(uuddss) \to \Sigma^- p$ ($BR^{\mathrm{th}} \simeq 0.01$)

[J.F. Donoghue, E. Golowich and B.R. Holstein, PRD 34, 3434 (1986)]

$\Lambda\Lambda \to H \to \Sigma^- p$?

- New investigations: E07@J–PARC, PANDA@FAIR [Plenary Talk by Gianotti]

CONCLUSIONS

- Reasonable agreement obtained between Experiment and Theory on Decay Rates ($\Gamma_{\rm NM}$ and Γ_n/Γ_p) and Asymmetries:
  The Scalar–Isoscalar mechanism is essential in Asymmetry calculations

  $\Gamma_{\rm NM}({}^{5}_{\Lambda}{\rm He})/\Gamma_\Lambda \sim 0.4 \;\; \Gamma_{\rm NM}({}^{12}_{\Lambda}{\rm C})/\Gamma_\Lambda \sim 0.9$ (good agreement Exp – Th)

  $\dfrac{\Gamma_n}{\Gamma_p}({}^{5}_{\Lambda}{\rm He}) \sim \dfrac{\Gamma_n}{\Gamma_p}({}^{12}_{\Lambda}{\rm C}) \sim 0.3 \div 0.5$ (data error bars, model dependencies)

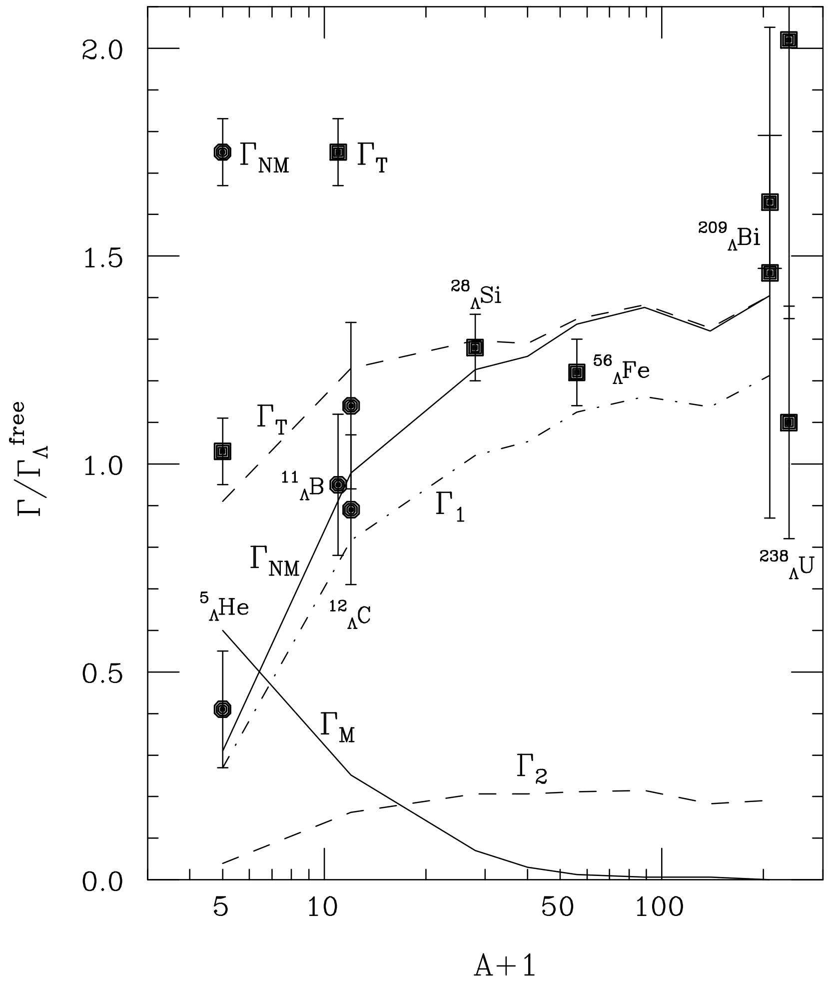
  $a_\Lambda({}^{5}_{\Lambda}{\rm He}) \sim 0 \div 0.2 \;\; a_\Lambda({}^{12}_{\Lambda}{\rm C}) \sim -0.1 \div +0.3$ (data error bars, model dependencies)

- Improved models and measurements essential to achieve a detailed understanding of the reaction mechanisms for the Non–Mesonic Weak Decay
  - s–shell Hypernuclei and the $\Delta I = 1/2$ rule
  - Extraction of $\Gamma_2 = \Gamma(\Lambda NN \to nNN)$ from Data
  - Weak Decay of $S = -2$ Hypernuclei

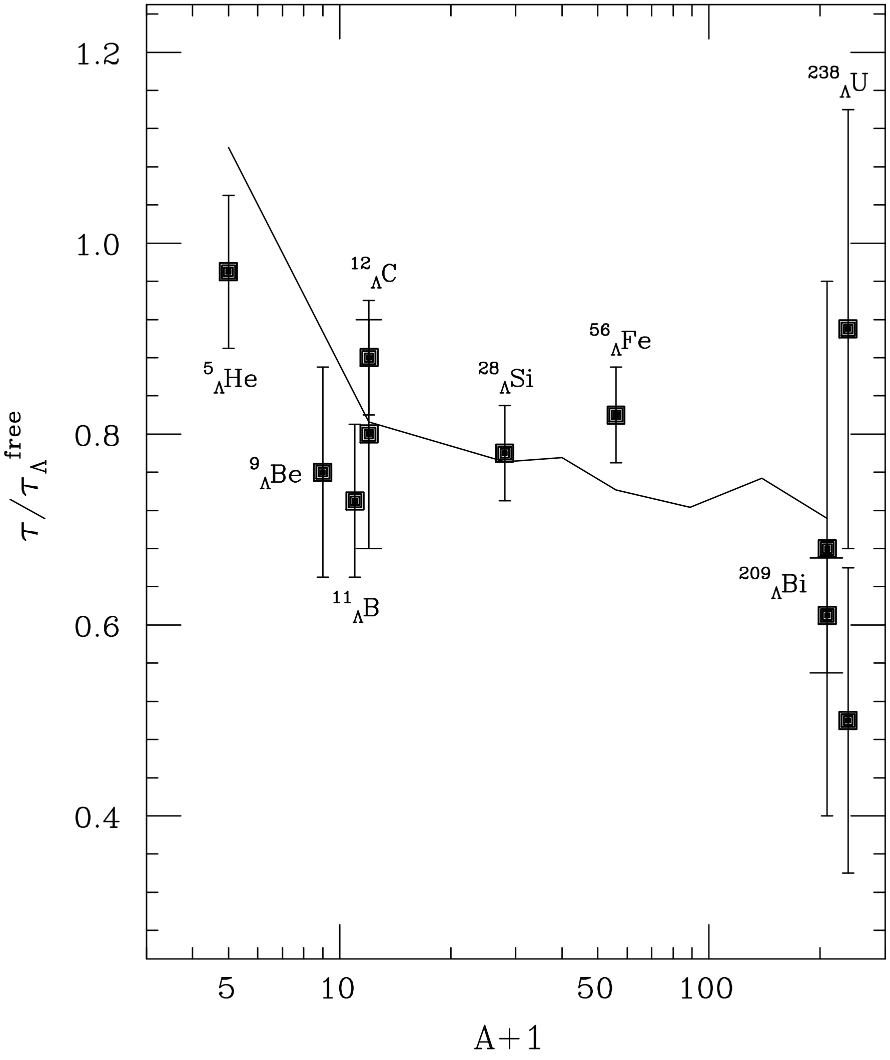
- Still a lot of work to do: various theoretical groups and experiments (E07, E18 and E22@J–PARC, FINUDA@DAPHNE, HypHI@GSI, PANDA@FAIR)

ADDITIONAL SLIDES

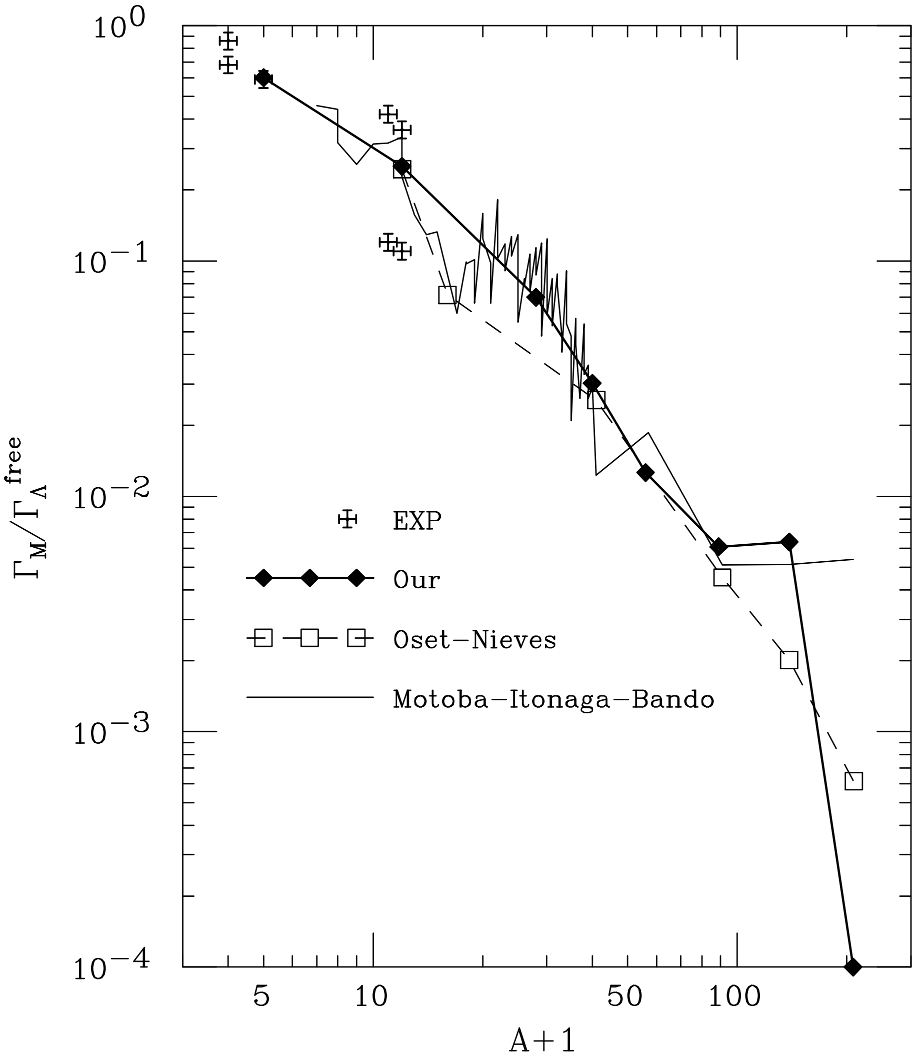
RESULTS



[W. M. Alberico and G. G., Phys. Rep. **369**, 1 (2002)]



[W. M. Alberico and G. G., Phys. Rep. **369**, 1 (2002)]



[W. M. Alberico and G. G., Phys. Rep. **369**, 1 (2002)]

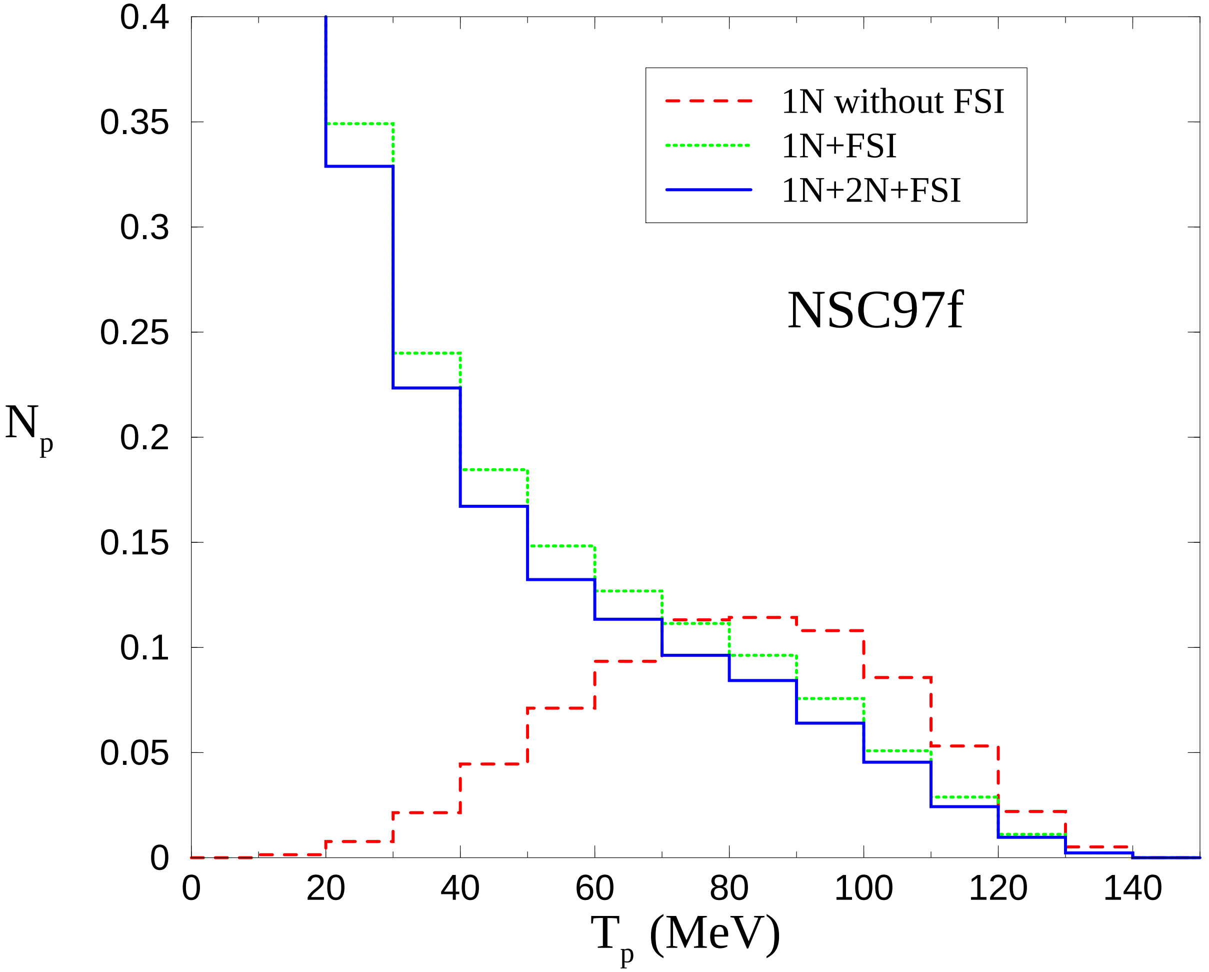


Figure 1: Single–proton kinetic energy spectra per NMWD of ${}^{12}_{\Lambda}C$.

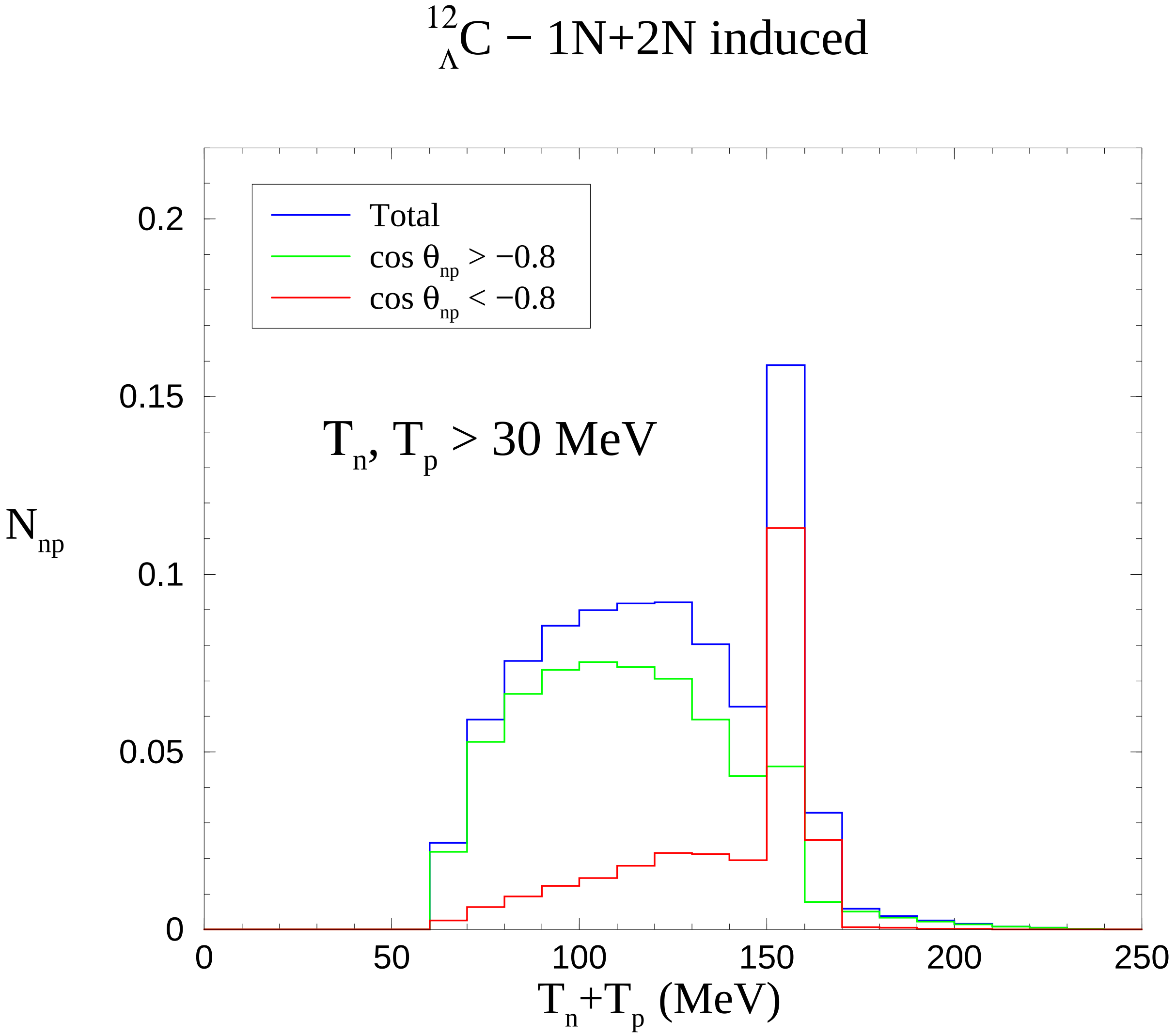


Figure 2: Kinetic energy correlations of *np* pairs emitted per NMWD of $^{12}_{\Lambda}\mathrm{C}$

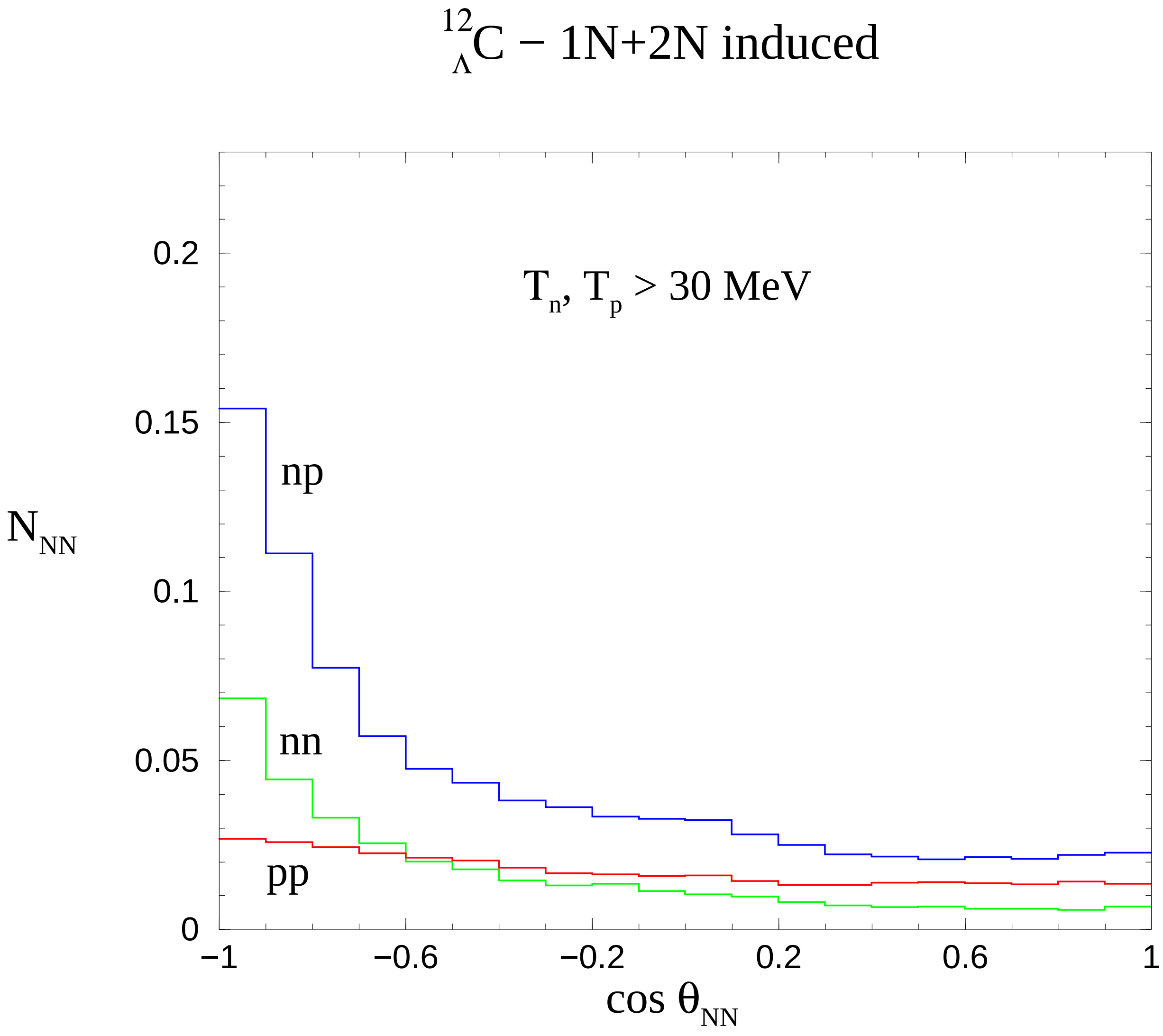


Figure 3: Angular distribution of *nn*, *np* and *pp* pairs emitted per NMWD of $^{12}_{\Lambda}C$

Γ_n/Γ_p

Number of primary nn and np pairs:

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

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

$$\boxed{\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Gamma(\Lambda n \to nn)}{\Gamma(\Lambda p \to np)} \equiv \frac{N_{nn}^{\rm wd}}{N_{np}^{\rm wd}} \neq \frac{N_{nn}}{N_{np}} = R_2\,(\Gamma_2, {\rm FSI})}$$

Table 1: 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 N_{nn}/N_{np}	Γ_n/Γ_p	${}^{12}_\Lambda$C N_{nn}/N_{np}	Γ_n/Γ_p
OPE	0.25	0.09	0.24	0.08
OME	0.51	0.34	0.39	0.29
KEK–E462	$0.45 \pm 0.11 \pm 0.03$			
KEK–E508			0.40 ± 0.10	

Data from B. H. Kang et al., PRL 96, 062301 (2006); M. J. Kim et al., PLB 641, 28 (2006); H. Outa, NPA 754, 157c (2005)

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

- Total number of NN pairs emitted per NMWD:

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

  which define the six weak–decay–model independent quantities: $N_{nn}^{\rm 1Bn}$ (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:

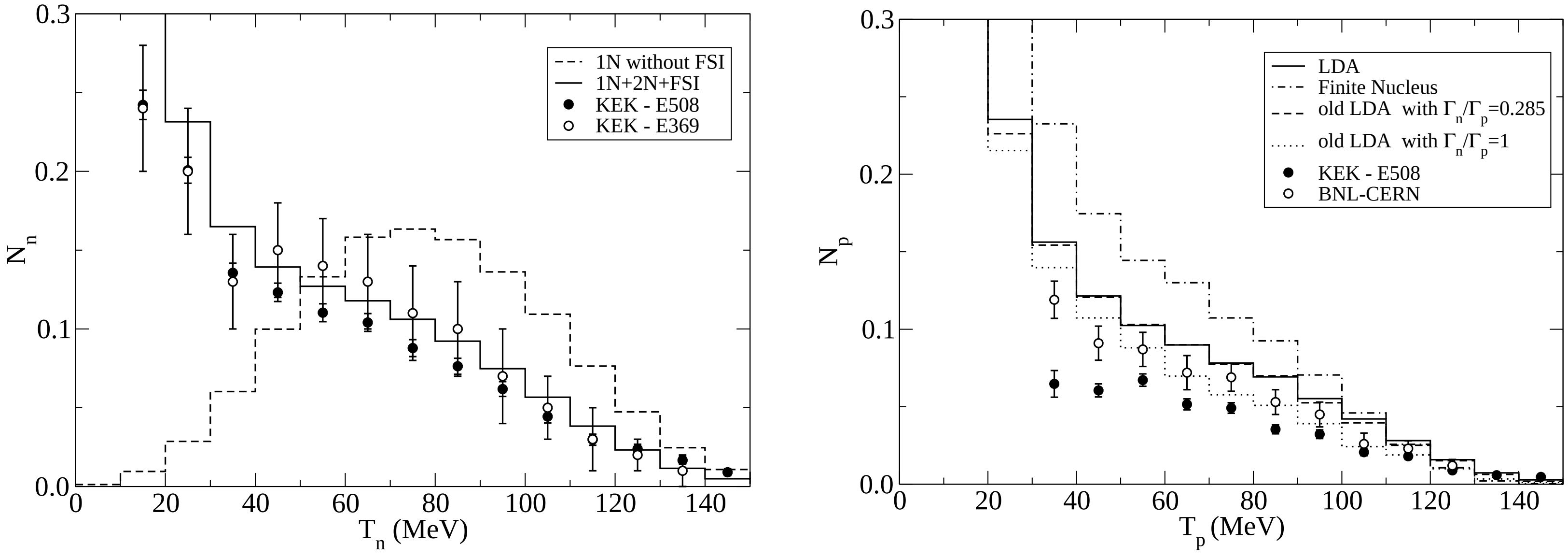
$$\frac{\Gamma_n}{\Gamma_p} = \frac{N_{nn}^{\rm 1Bp} + N_{nn}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1} - \left(N_{np}^{\rm 1Bp} + N_{np}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}}}{\left(N_{np}^{\rm 1Bn} + N_{np}^{\rm 2B}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}} - N_{nn}^{\rm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

- From KEK data we obtained:

${}^{5}_{\Lambda}\mathrm{He}$	$\Gamma_n/\Gamma_p = 0.26 \pm 0.11$	$\Gamma_2 = 0.20\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.39 \pm 0.11$	$\Gamma_2 = 0)$
${}^{12}_{\Lambda}\mathrm{C}$	$\Gamma_n/\Gamma_p = 0.29 \pm 0.14$	$\Gamma_2 = 0.25\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.38 \pm 0.14$	$\Gamma_2 = 0)$

Exp–Th disagreement on Proton Spectra

Agreement for Neutrons $^{12}_{\Lambda}\mathrm{C}$ Disagreement for Protons

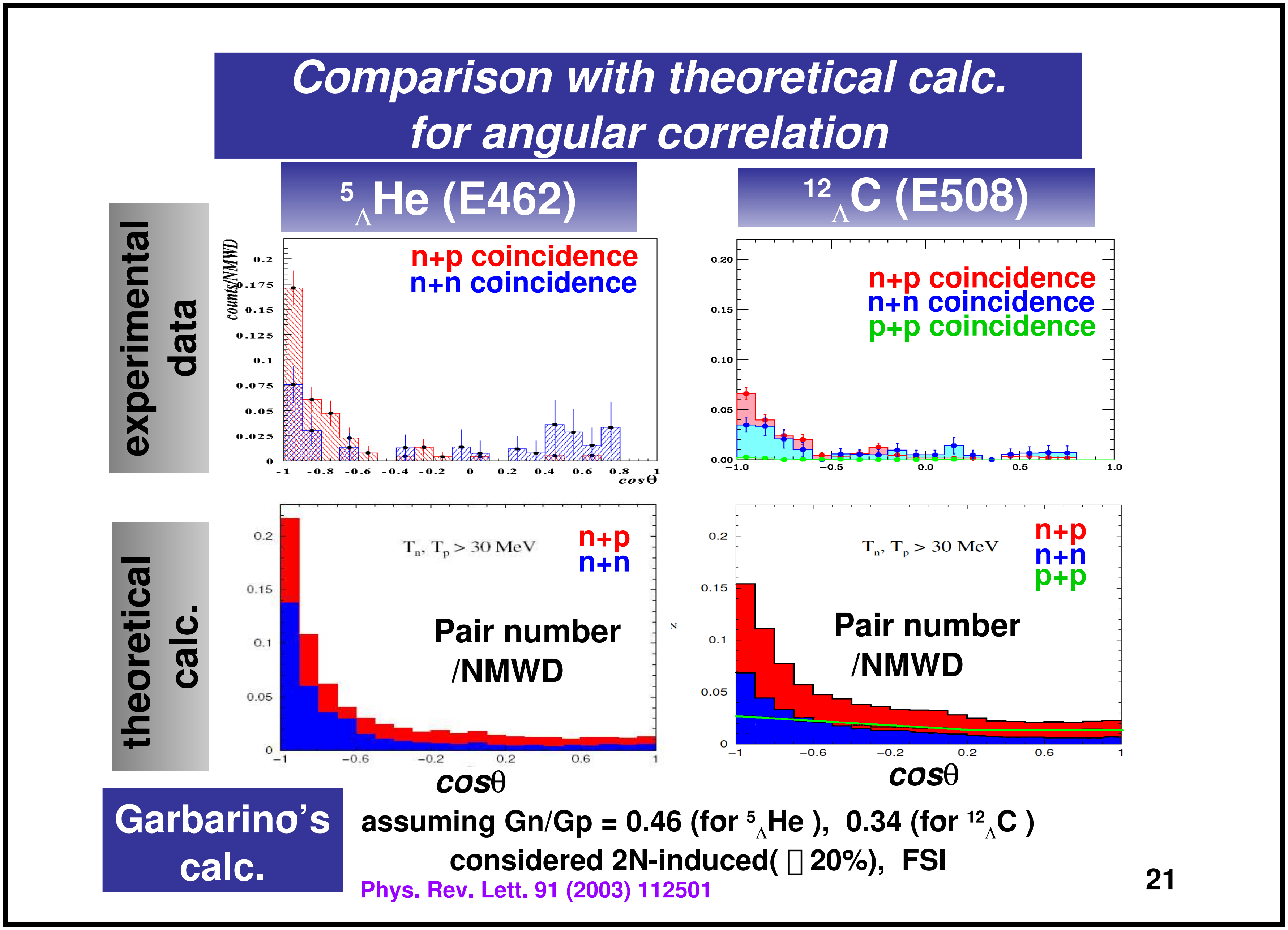


- BNL–E788: Neutron and Proton Spectra for $^{4}_{\Lambda}\mathrm{He}$

  [J. D. Parker at al., PRC 76, 035501 (2007)]

- FINUDA: Proton Spectra for $^{5}_{\Lambda}\mathrm{He}$ to $^{16}_{\Lambda}\mathrm{O}$:
  peaking structure at $\simeq$ 80 MeV

  [M. Agnello et al., NPA 804, 151 (2008)]



Comparison with theoretical calc. for angular correlation

$^{5}_{\Lambda}$He (E462) **$^{12}_{\Lambda}$C (E508)**

Garbarino's calc.

assuming Gn/Gp = 0.46 (for $^{5}_{\Lambda}$He), 0.34 (for $^{12}_{\Lambda}$C)

considered 2N-induced(□20%), FSI

Phys. Rev. Lett. 91 (2003) 112501

Asymmetry: OME + Nucleon FSI

[W. M. Alberico, G.G., A. Parreño and A. Ramos, PRL 94, 082501 (2005)]

$$\mathrm{OME} = \pi + \rho + K + K^* + \eta + \omega$$

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

	${}^{5}_{\Lambda}\mathrm{He}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$
a_Λ	-0.68	-0.81	-0.73
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 30$ MeV$)$	-0.46	-0.39	-0.37
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 50$ MeV$)$	-0.52	-0.55	-0.51
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 70$ MeV$)$	-0.55	-0.70	-0.65
KEK–E462	$0.07 \pm 0.08^{+0.08}_{-0.00}$		
KEK–E508		$-0.16 \pm 0.28^{+0.18}_{-0.00}$	

Data from [T. Maruta et al., EPJA 33, 255 (2007)]

- Effective Field Theory: $\pi + K +$ Leading–Order Contact Interactions

[A. Parreño, C. Bennhold and B. R. Holstein, PRC 70, 051601 (2004)]

  - LOCI coefficients fixed to reproduce experimental $\Gamma_{\rm NM}$ and Γ_n/Γ_p for ${}^{5}_{\Lambda}$He, ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C and $a_\Lambda({}^{5}_{\Lambda}\mathrm{He})$
  - Predicted a dominating Central, Spin– and Isospin–Independent contact term

- $\pi + K + \sigma +$ Direct Quark

[K. Sasaki, M. Izaki, M. Oka, PRC 71, 035502 (2005)]

  - Decay data for s-shell hypernuclei fitted to obtain the weak couplings of the Scalar–Isoscalar σ–meson, $\mathcal{H}^{\rm W}_{\Lambda\sigma N} = g_W \bar{\psi}_N (A_\sigma + B_\sigma \gamma_5) \phi_\sigma \psi_\Lambda$
  - All ${}^{5}_{\Lambda}$He decay observables reasonably reproduced. No calculation for ${}^{12}_{\Lambda}$C

- OME $+ \sigma$, OME$= \pi + \rho + K + K^* + \eta + \omega$

[C. Barbero and A. Mariano, PRC 73, 024309 (2006)]

  - Unknown σ couplings fixed to reproduce measured $\Gamma_{\rm NM}({}^{5}_{\Lambda}\mathrm{He})$ and $\Gamma_n/\Gamma_p({}^{5}_{\Lambda}\mathrm{He})$
  - Improved overall agreement with experiment for ${}^{12}_{\Lambda}$C and ${}^{5}_{\Lambda}$He but data for $a_\Lambda({}^{5}_{\Lambda}\mathrm{He})$ could not be reproduced

- $\Longrightarrow$ Importance of the Scalar–Isoscalar channel in Asymmetry calculations

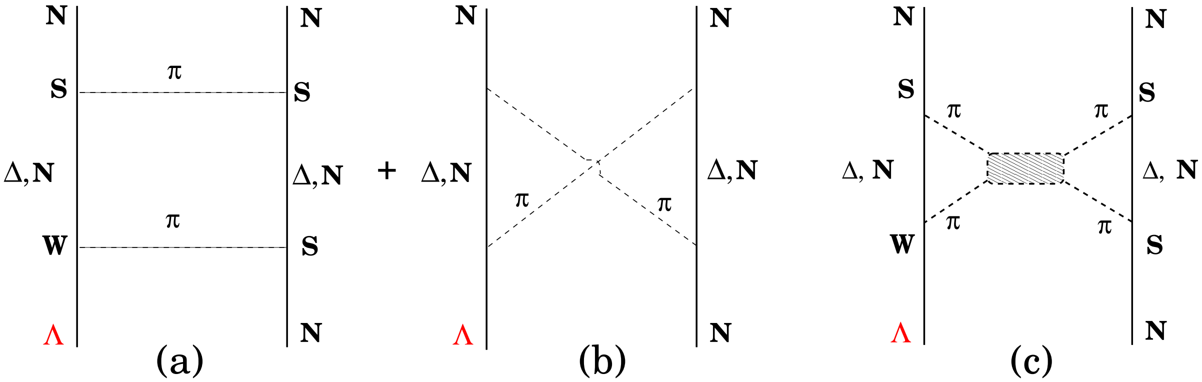
One–Meson–Exchange + Two–Pion–Exchange

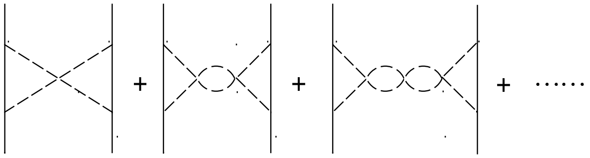
[C. Chumillas, G. G, A. Parreño and A. Ramos, PLB 657, 180 (2007)]

- Uncorrelated (2π) and Correlated ($2\pi/\sigma$) Two–Pion–Exchange (TPE)

  [D. Jido, E. Oset and J.E. Palomar, NPA 694, 525 (2001)]

- $2\pi/\sigma$ motivated by Chiral Unitary Theory





- 2π: dominated by the isoscalar channel
- $2\pi/\sigma$ reproduces $\pi\pi$ scattering data in the scalar sector
- No Free Parameter: couplings determined from chiral meson–meson and meson–baryon Lagrangians

Model	$\Gamma_{\rm NM} = \Gamma_n + \Gamma_p$	${}^{5}_{\Lambda}$He Γ_n/Γ_p	a_Λ
OME	0.379	0.474	-0.590
OME+TPE	0.388	0.415	$+0.041$
OME+TPE+FSI			$+0.028$
KEK–E462	0.424 ± 0.024	0.40 ± 0.11 $(1N)$ 0.27 ± 0.11 $(1N + 2N)$	$+0.07 \pm 0.08^{+0.08}_{-0.00}$

Model	$\Gamma_{\rm NM} = \Gamma_n + \Gamma_p$	${}^{12}_{\Lambda}$C Γ_n/Γ_p	a_Λ
OME	0.667	0.357	-0.698
OME+TPE	0.722	0.366	-0.207
OME+TPE+FSI			-0.126
KEK–E508	0.940 ± 0.035	0.38 ± 0.14 $(1N)$ 0.29 ± 0.14 $(1N + 2N)$	$-0.16 \pm 0.28^{+0.18}_{-0.00}$
KEK–E307	0.828 ± 0.087		

- Moderate change of the Decay Rates, huge influence on the Asymmetries!
- Agreement with *both* Asymmetry and Decay Rate data for *both* ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C!

${}^{5}_{\Lambda}\mathrm{He}$	OME	OME + TPE		OME	OME + TPE
$A:\ {}^1S_0 \rightarrow {}^1S_0$	-0.1044	$+0.0835$	AE	-0.2854	$+0.2112$
$B:\ {}^1S_0 \rightarrow {}^3P_0$	$+0.0057$	$+0.0057$	BC	$+0.0027$	-0.0033
$C:\ {}^3S_1 \rightarrow {}^3S_1$	-0.1399	$+0.1480$	BD	-0.0029	-0.0027
$D:\ {}^3S_1 \rightarrow {}^3D_1$	-0.1814	-0.1814	CF	-0.0856	$+0.0405$
$E:\ {}^3S_1 \rightarrow {}^1P_1$	$+0.3833$	$+0.3833$	DF	-0.2186	-0.2046
$F:\ {}^3S_1 \rightarrow {}^3P_1$	$+0.2234$	$+0.2234$			
$\Gamma_p = \sum_{\alpha=A\ldots F} \|\alpha\|^2$	0.257	0.275	a_Λ	-0.590	$+0.041$

- Spectroscopic notation: $\Lambda p\,({}^{2S+1}L_J) \rightarrow np\,({}^{2S'+1}L'_J)$
- OME → OME + TPE:
  - Drastic change of the Scalar–Isoscalar amplitudes A and C
  - AE interference changes sign and cancels the DF contribution

Perspectives: “Exotic” Hypernuclei

- ✤ Neutron– and Proton–Rich ($^6_\Lambda$H, $^9_\Lambda$He; $^7_\Lambda$Be, $^8_\Lambda$C)
  - Γ_n/Γ_p for extreme N/Z
  - Effects of (low–density) Neutron and Proton Halos on NMWD
  - Present and Future searches:

    KEK and FINUDA: formation probability studies (upper limits)

    HypHI@GSI: in–flight decays, no surrounding target ($T_N^{\rm th} \to 0$)

    J–PARC: E10

    Nuclotron@JINR (Dubna): relativistic hypernuclei

- ✤ Medium and Heavy: $A > 11$ (saturation property of $\Gamma_{\rm NM}$)
  - KEK: saturation at $\Gamma_{\rm NM}(^{28}_{\Lambda}{\rm Si} -^{56}_{\Lambda}{\rm Fe}) \simeq 1.2$, in agreement with Theory
  - COSY–13@Juelich: $p + A$, $A =$ Au, Bi and U targets, measurement of fragments from fission induced by NMWD, no direct identification of hypernuclear formation $\Gamma_{\rm NM}(A \simeq 180 - 225) = 1.81 \pm 0.14$
  - CEBAF@JLAB: proposal for high–precision measurement of lifetime of heavy hypernuclei?