Asymmetric Weak Decay of Hypernuclei: Two–Pion–Exchange Mechanism

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OUTLINE

- ✦ Weak Decay of Λ–Hypernuclei
  - Mesonic and Non–Mesonic Modes
- ✦ Framework for Calculation
  - Non–Mesonic Decay Rates
  - Decay Asymmetries of Polarized Hypernuclei
- ✦ Results
- ✦ Conclusions

References

[1] C. Chumillas, G. G., A. Parreño and A. Ramos, Phys. Lett. **B 657**, 180 (2007); Nucl. Phys. **A 804**, 162 (2008)

WEAK DECAY OF Λ–HYPERNUCLEI

MESONIC

$$\Lambda \rightarrow \pi^0 n \qquad \Gamma_{\pi^0}$$
$$\Lambda \rightarrow \pi^- p \qquad \Gamma_{\pi^-}$$

- $Q_{\rm M} = m_\Lambda - m_N - m_\pi \simeq 40$ MeV $\Longrightarrow p_N \simeq 100\,{\rm MeV} < k_F^0 \simeq 270\,{\rm MeV} \Longrightarrow$ 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

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

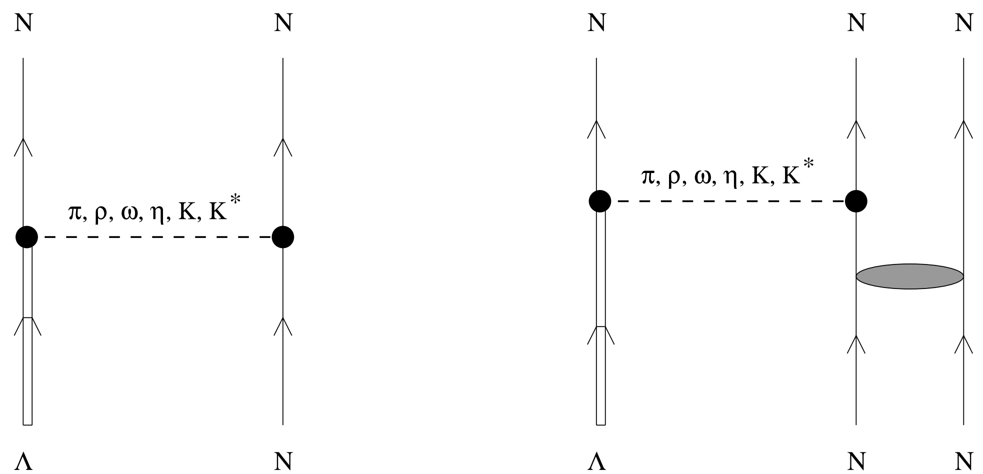
One–nucleon induced

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

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

Two–nucleon induced

$$\Lambda NN \rightarrow nNN \qquad \Gamma_2$$



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

- Only possible in nuclei (the only practical way to get information on baryon–baryon weak interactions)

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

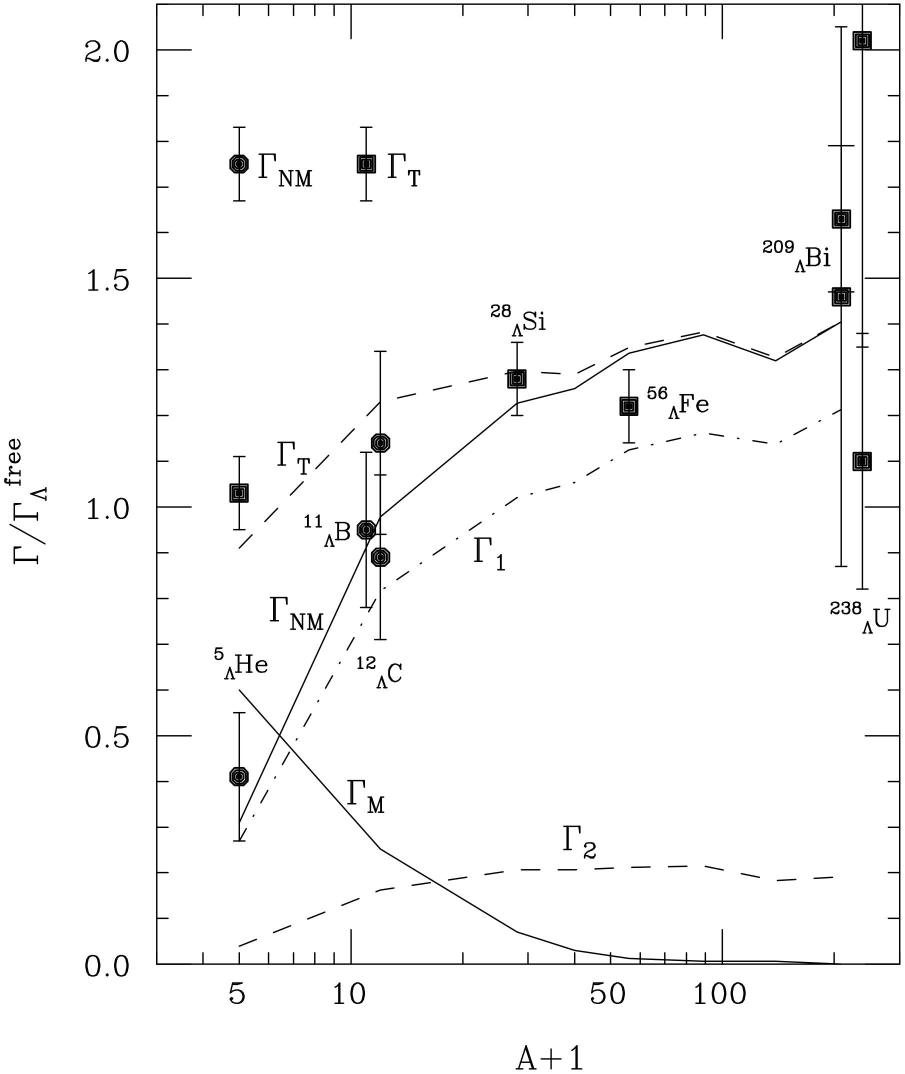
  – overcoming the Pauli blocking $\Longrightarrow$ the non–mesonic weak decay dominates over the mesonic one for all but the s–shell hypernuclei

  – nuclear structure details do not have substantial influence, but ΛN and NN (strong) Short Range Correlations are very important

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

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

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



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

FRAMEWORK FOR CALCULATION

✦ Finite Nucleus Approach supplemented by an IntraNuclear Cascade Model

Non–Mesonic Decay Rates

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

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

$$\Gamma_{n(p)} = \int \frac{d\vec{p}_1}{(2\pi)^3} \int \frac{d\vec{p}_2}{(2\pi)^3} 2\pi\, \delta\left(m_H - E_R - E_1 - E_2\right) \frac{1}{2J+1} \sum_{\substack{M_J\{R\} \\ \{1\}\{2\}}} \left| \mathcal{M}_{n(p)}(\vec{p}_1, \vec{p}_2) \right|^2$$

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

✦ Weak–Coupling scheme: $\mathcal{M}_N \Longrightarrow \langle nN | V_{\mathrm{ME}} | \Lambda N \rangle$

$$\Gamma_{n(p)} = \frac{1}{2J+1} \sum_{M_J} \sigma_{n(p)}(J, M_J)$$

$$\begin{aligned}
\sigma_N(J, M_J) \quad = \quad & \int \frac{d^3 P_T}{(2\pi)^3} \int \frac{d^3 p_r}{(2\pi)^3} (2\pi)\, \delta(M_H - E_R - E_1 - E_2) \\
& \times \sum_{S M_S} \sum_{J_R M_R} \sum_{T_R T_{3_R}} \left| \langle T_R T_{3_R}, \frac{1}{2} t_{3_N} \mid T_I T_{3_I} \rangle \right|^2 \\
& \times \Bigg| \sum_{T T_3} \langle T T_3 \mid \frac{1}{2} - \frac{1}{2}, \frac{1}{2} t_{3_N} \rangle \sum_{m_\Lambda M_C} \langle j_\Lambda m_\Lambda, J_C M_C \mid J M_J \rangle \\
& \times \sum_{j_N} S^{1/2}(J_C\, T_I\, ; J_R\, T_R\, , j_N\, t_{3_N}) \sum_{M_R m_N} \langle J_R M_R, j_N m_N \mid J_C M_C \rangle \\
& \times \sum_{m_{l_N} m_{s_N}} \langle j_N m_N \mid l_N m_{l_N}, \frac{1}{2} m_{s_N} \rangle \sum_{m_{l_\Lambda} m_{s_\Lambda}} \langle j_\Lambda m_\Lambda \mid l_\Lambda m_{l_\Lambda}, \frac{1}{2} m_{s_\Lambda} \rangle \\
& \times \sum_{S_0 M_{S_0}} \langle S_0 M_{S_0} \mid \frac{1}{2} m_{s_\Lambda}, \frac{1}{2} m_{s_N} \rangle \sum_{T_0 T_{3_0}} \langle T_0 T_{3_0} \mid \frac{1}{2} - \frac{1}{2}, \frac{1}{2} t_{3_N} \rangle \\
& \times \frac{1 - (-1)^{(L+S+T)}}{\sqrt{2}} t_{\Lambda N \to nN}(S, M_S, T, T_3, S_0, M_{S_0}, T_0, T_{3_0}, l_\Lambda, l_N, \vec{P}_T, \vec{p}_r) \Bigg|^2
\end{aligned}$$

$$\vec{P}_T = \vec{p}_1 + \vec{p}_2 \qquad \vec{p}_r = \frac{\vec{p}_1 - \vec{p}_2}{2}$$

✦ Two–Body Transition Amplitudes (decomposition into center–of–mass and relative quantum numbers):

$$t_{\Lambda N \to nN}(S, M_S, T, T_3, S_0, M_{S_0}, T_0, T_{3_0}, l_\Lambda, l_N, \vec{P}_T, \vec{p}_r)$$

$$= \frac{1}{\sqrt{2}} \sum_{N_r L_r N_R L_R} X(N_r L_r, N_R L_R, l_\Lambda l_N) \chi^{\dagger\, S}_{M_S}\, \chi^{\dagger\, T}_{T_3}\, \chi^{S_0}_{M_{S_0}}\, \chi^{T_0}_{T_{3_0}}$$

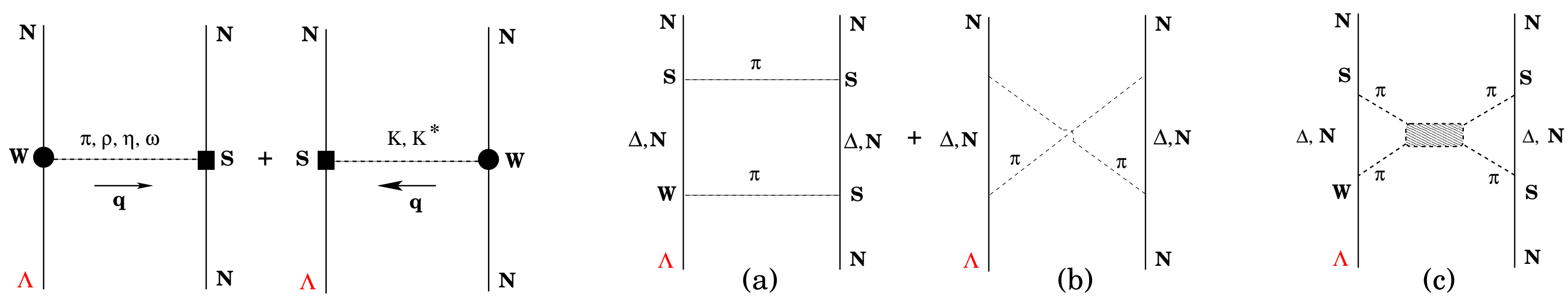
$$\times \int d^3R \int d^3r\, \mathrm{e}^{-i\vec{P}_T \cdot \vec{R}} \Psi^*_{\vec{p}_r}(\vec{r}) V_{ME}(\vec{r})\, \Phi^{\mathrm{CM}}_{N_R L_R}\left(\frac{\vec{R}}{b/\sqrt{2}}\right) \Phi^{\mathrm{rel}}_{N_r L_r}\left(\frac{\vec{r}}{\sqrt{2}b}\right)$$

$$\vec{R} = \frac{\vec{r}_1 + \vec{r}_2}{2} \qquad \vec{r} = \vec{r}_1 - \vec{r}_2$$

✦ V_{ME}: Meson–Exchange $\Lambda N \to nN$ transition potential

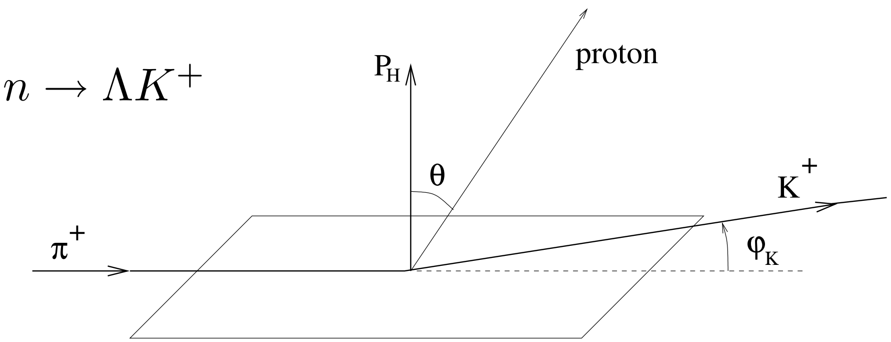
– Pseudoscalar (π, η, K) and Vector (ρ, ω, K^*) Meson Octets

– Two–Pion–Exchange: uncorrelated (2π) and correlated ($2\pi/\sigma$)



Decay Asymmetries of Polarized Hypernuclei

$$\pi^+ n \to \Lambda K^+$$



Weak Decay Proton Intensity from $\vec{\Lambda} p \to np$

$$I(\theta, J) = I_0(J)\,[1 + \mathcal{A}(\theta, J)] \;\; = I_0(J)\,[1 + P(J) A(J) \cos\theta]$$

$$I_0(J) = \frac{1}{2J+1} \sum_{M_J} \sigma_p(J, M_J) \equiv \Gamma_p$$

- ✦ P = Hypernuclear Polarization (kinematics and dynamics of production reaction)
- ✦ $A(J) = \dfrac{3}{J+1} \dfrac{\sum_{M_J} M_J\, \sigma_p(J, M_J)}{\sum_{M_J} \sigma_p(J, M_J)}$ = Hypernuclear Asymmetry Parameter

Asymmetry Parameter $\Longleftrightarrow$ interference among PC and PV $\vec{\Lambda}p \to np$ amplitudes

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

✦ Shell Model Weak–Coupling scheme: $\mathcal{A}(\theta, J) = p_\Lambda(J)\, a_\Lambda\, \cos\theta$

– Λ Polarization : $p_\Lambda(J) = \begin{cases} -\dfrac{J}{J+1}P(J) & \text{if} \quad J = J_C - \frac{1}{2} \\ P(J) & \text{if} \quad J = J_C + \frac{1}{2} \end{cases}$

– Intrinsic Λ Asymmetry Parameter : $a_\Lambda = \begin{cases} -\dfrac{J+1}{J}A(J) & \text{if} \quad J = J_C - \frac{1}{2} \\ A(J) & \text{if} \quad J = J_C + \frac{1}{2} \end{cases}$

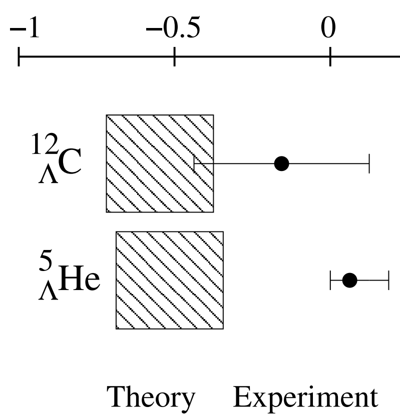
✦ Nucleon Final State Interactions $\Longrightarrow$ Experimentally accessible quantity:
[A. Ramos, M. J. Vicente-Vacas and E. Oset, PRC 55, 735 (1997); PRC 66, 039903(E) (2002)]

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

Observable Λ asymmetry parameter: $a_\Lambda^{\rm M}(J) = \dfrac{1}{p_\Lambda(J)} \dfrac{I^{\rm M}(0^\circ, J) - I^{\rm M}(180^\circ, J)}{I^{\rm M}(0^\circ, J) + I^{\rm M}(180^\circ, J)}$

	$^{5}_{\Lambda}$He	$^{12}_{\Lambda}$C
Sasaki et al. a_Λ		
$\pi + K + \mathrm{DQ}$	-0.68	
Parreño et al.		
$\pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
Itonaga et al.		
$\pi + K + \omega + 2\pi/\rho + 2\pi/\sigma$	-0.33	
Barbero et al.		
$\pi + \rho + K + K^* + \omega + \eta$	-0.54	-0.53
Alberico et al. a_Λ^{M}		
$\pi + \rho + K + K^* + \omega + \eta + \mathrm{FSI}$	-0.46	-0.37
KEK–E508 a_Λ^{M}		$-0.16 \pm 0.28^{+0.18}_{-0.00}$
KEK–E462	$+0.07 \pm 0.08^{+0.08}_{-0.00}$	

KEK–E508/E462: 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 $a_\Lambda({}^{5}_{\Lambda}\text{He})$
  - 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 $\Gamma_{\rm NM}({}^{5}_{\Lambda}\text{He})$ and $\Gamma_n/\Gamma_p({}^{5}_{\Lambda}\text{He})$
  - Improved overall agreement with experiment for ${}^{12}_{\Lambda}$C and ${}^{5}_{\Lambda}$He but data for $a_\Lambda({}^{5}_{\Lambda}\text{He})$ could not be reproduced

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

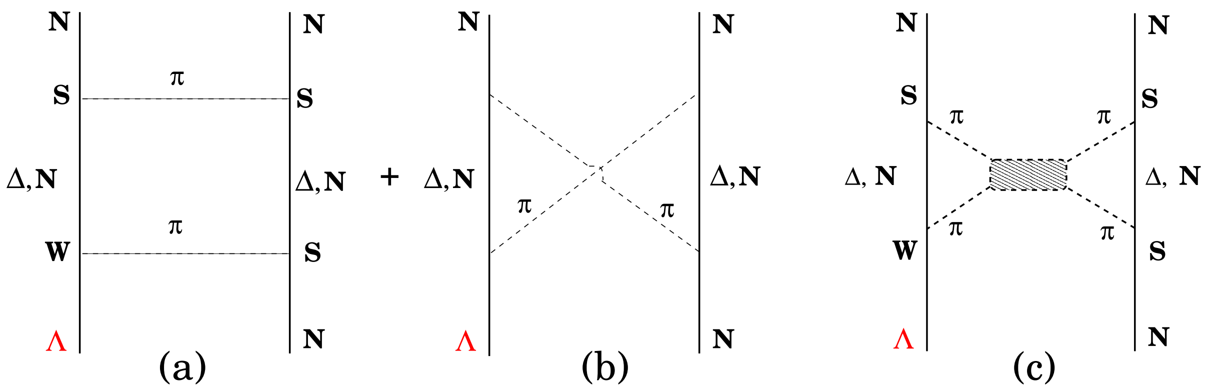
One–Meson–Exchange + Two–Pion–Exchange

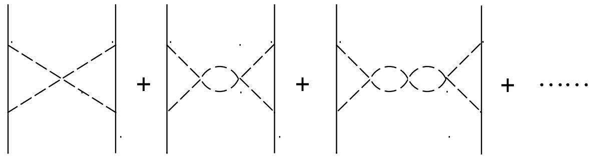
[C. Chumillas, G. G, A. Parreño and A. Ramos, PLB 657, 180 (2007)]

- 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

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

Model	$\Gamma_{\rm NM} = \Gamma_n + \Gamma_p$	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	$0.45 \pm 0.11 \pm 0.03$	$+0.07 \pm 0.08^{+0.08}_{-0.00}$

$^{12}_{\Lambda}$C

Model	$\Gamma_{\rm NM} = \Gamma_n + \Gamma_p$	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	$0.51 \pm 0.13 \pm 0.05$	$-0.16 \pm 0.28^{+0.18}_{-0.00}$
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!

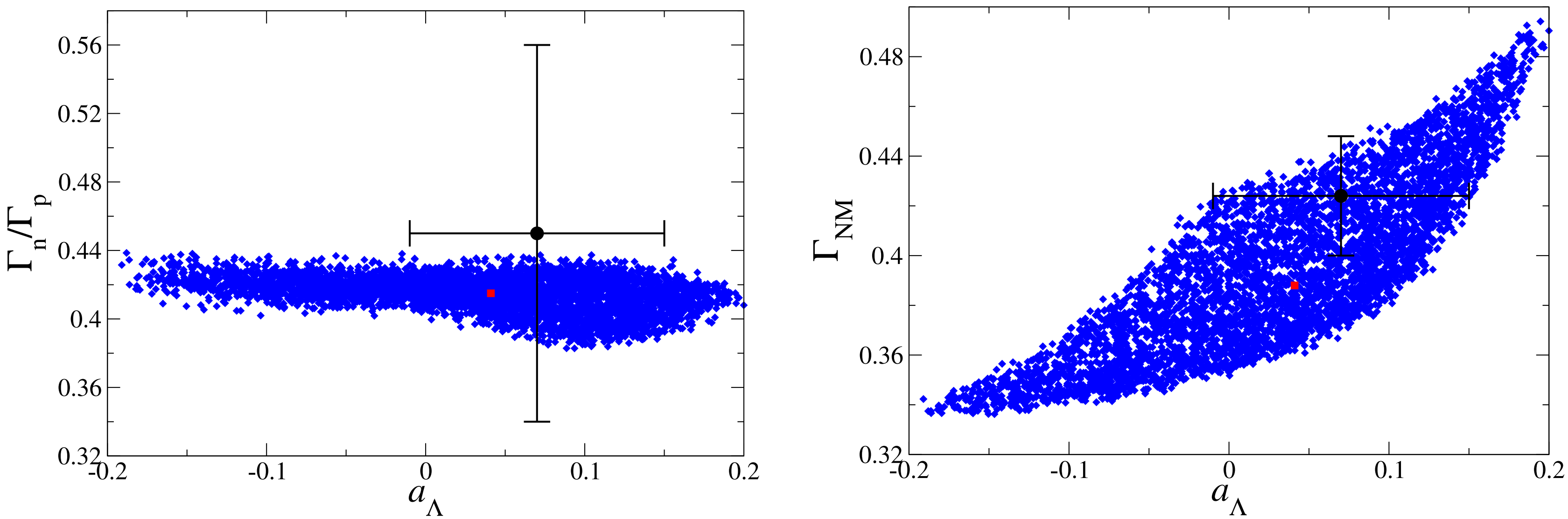
${}^{5}_{\Lambda}$He	OME	OME + TPE		OME	OME + TPE
$A:\ {}^1S_0 \rightarrow {}^1S_0$	-0.1044	$+0.0835$	AE	-0.2854	$+0.2112$
$B:\ {}^1S_0 \rightarrow {}^3P_0$	$+0.0057$	$+0.0057$	BC	$+0.0027$	-0.0033
$C:\ {}^3S_1 \rightarrow {}^3S_1$	-0.1399	$+0.1480$	BD	-0.0029	-0.0027
$D:\ {}^3S_1 \rightarrow {}^3D_1$	-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 $\rightarrow$ OME + TPE:
  - Drastic change of the Scalar–Isoscalar amplitudes A and C
  - AE interference changes sign and cancels the DF contribution

✦ Model–dependencies in OME+TPE results

– Phenomenologically unknown weak Meson–Baryon–Baryon couplings are calculated from $\Lambda N \pi$ ones by $SU(3)$ and $SU(6)$ symmetries

– By introducing a 30% variation in these couplings we obtained:



– a_Λ: -0.2 to 0.2 $\quad\quad$ $\Delta(\Gamma_n/\Gamma_p) \simeq 8\%$ $\quad\quad$ $\Delta\Gamma_{\rm NM} \simeq 20\%$

– Agreement with data is maintained

CONCLUSIONS

✦ Non–Mesonic Weak Decay of Polarized Hypernuclei

– Finite Nucleus approach

– OME supplemented by a chirally motivated TPE $(2\pi + 2\pi/\sigma)$

– IntraNuclear Cascade collisions

✦ OME: reproduces the measured $\Gamma_{\rm NM}$ and Γ_n/Γ_p but not the Asymmetries

✦ OME + TPE:

– Moderate effect on the Decay Rates

– Huge influence on the Asymmetries

– For the first time *all* ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C decay data are reproduced
(pure $\Delta I = 1/2$ $\Lambda N \to nN$ transitions; new info from four–body hypernuclei)

✦ Axial vector a_1–meson exchange: $\pi + K + \omega + 2\pi/\sigma + 2\pi/\rho + \pi\sigma/a_1 + \pi\rho/a_1$

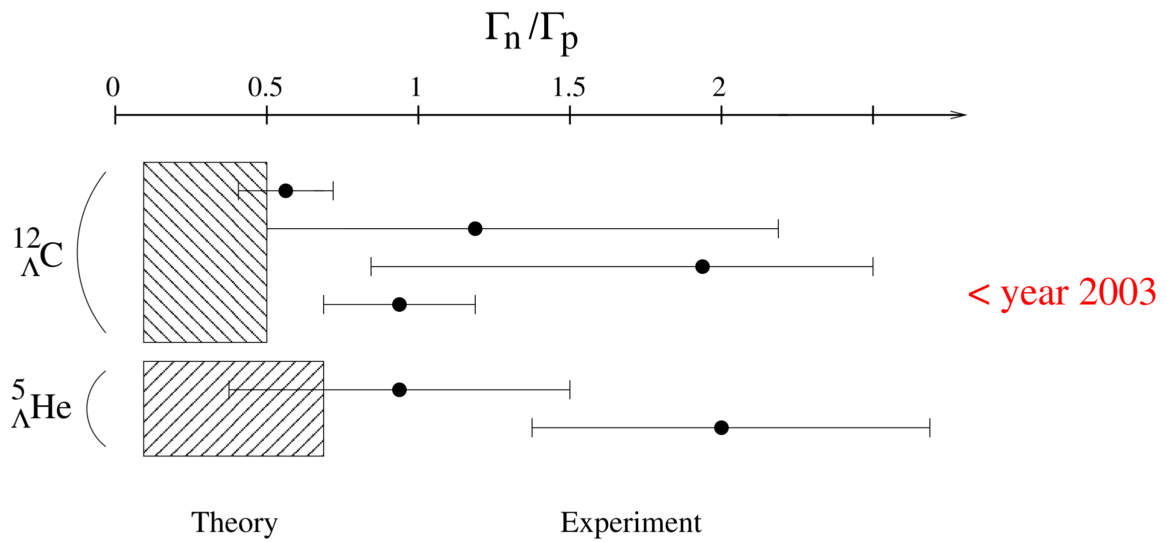
[K. Itonaga, T. Motoba, T. Ueda and Th. A. Rijken, PRC 77, 044605 (2008)]

Improvement: $a_\Lambda({}^{5}_{\Lambda}\mathrm{He}) = -0.833 \to +0.083$, $a_\Lambda({}^{12}_{\Lambda}\mathrm{C}) = -0.755 \to +0.045$

ADDITIONAL SLIDES

THE Γ_n/Γ_p PUZZLE

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



Theory strongly underestimated data!

[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 $\frac{\Gamma_n}{\Gamma_p}$ from $\frac{N_n}{N_p}$ ratio
- KEK–E462/E508: Nucleon–Nucleon Coincidence Spectra (years 2003–2006) [2]
  - more direct (but model–dependent) determination of $\frac{\Gamma_n}{\Gamma_p}$ from $\frac{N_{nn}}{N_{np}}$ ratio
- First data from FINUDA@DAΦNE [3], experiments planned at J–PARC and HypHI@GSI

[1] S. Okada et al., PLB 597, 249 (2004)
[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)

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 the OPE 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.]
- Direct Quark Mechanism [Oka et al.]
- Two–Nucleon Induced Mechanism [Alberico et al., Ramos et al.]
- Nucleon Final State Interactions [Ramos et al., Garbarino et al.]

Heavy Meson Exchange (especially Kaons) [1] and Direct Quark contributions [2] improved the situation:

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

[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]:

- inclusion of Two–Nucleon Induced Decays, $\Lambda NN \to nNN$, (experimental identification expected in NNN coincidence measurements, J–PARC)
- accurate evaluation of the Nucleon FSI inside the residual nucleus

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

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)