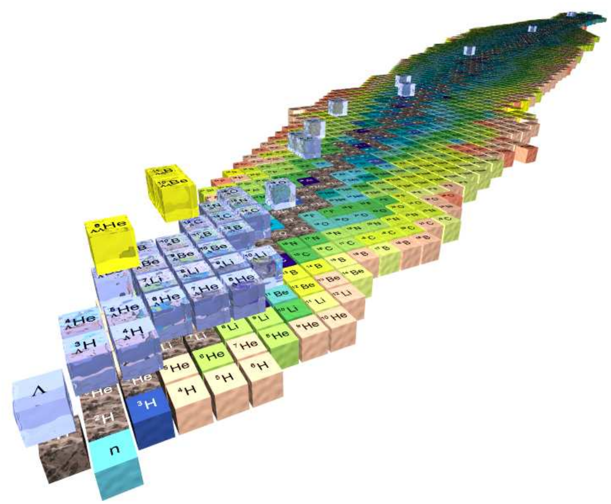
Exchange Terms and Ground State Correlations in Non–Mesonic Weak Decay of Hypernuclei

G. Garbarino
University of Torino

Electroweak interactions with nuclei: superscaling and connections between electron and neutrino scattering
ECT*, October 26–30, 2009



OUTLINE

- Introducing Hypernuclei
- Weak Decay of Hypernuclei
  - Mesonic vs Non–Mesonic
  - $S = -1$ and $S = -2$ Hypernuclei
- Framework for Calculation
  - Non–Relativistic Nuclear Matter in LDA
  - One– and Two–Nucleon Induced Decay
- Results
- Conclusions

E. Bauer and G. G., Nucl. Phys. **A 828**, 29 (2009); arXiv:0907.4199 [nucl-th]

INTRODUCING HYPERNUCLEI

- **Hyperons** (Strange Baryons): $Y = \Lambda,\ \Sigma,\ \Xi,\ \Omega$ $\tau_Y \simeq 10^{-10}$ s $c\,\tau_Y = \mathcal{O}(10\,\mathrm{cm})$

- **Hypernuclei**: bound systems of neutrons, protons and hyperon(s)

- ${}^{A}_{Y}Z$: Z protons, $A - Z$ neutrons and a hyperon Y

- Only the lightest hyperon, the Λ, is stable with respect to esoenergetic strong and electromagnetic processes in nuclear systems
  $\Longrightarrow$ ground state of ${}^{A+1}_{\Lambda}Z$: Λ in the $1s$ level of the Λ–nucleus potential

- Hypernuclear phenomena allows us to investigate important questions:
  - YN and YY strong and weak interactions (YN and YY scattering experiments are very difficult due to the very small τ_Y);
  - in–medium properties of hyperons and mesons;
  - nuclear structure and many–body nuclear dynamics;
  - role played by quark degrees of freedom, flavour symmetry and chiral models in nuclei and hypernuclei

G. Garbarino
University of Torino

WEAK DECAY OF 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

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

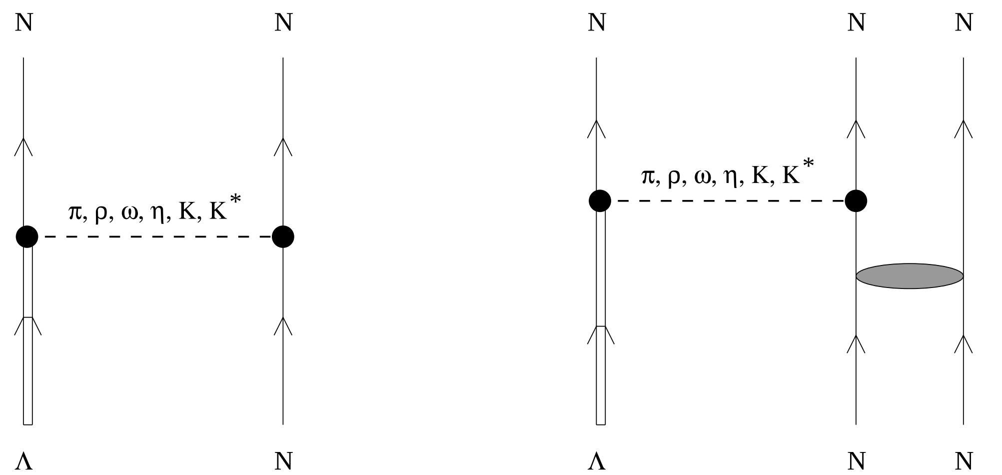
One–nucleon induced

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

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

Two–nucleon induced

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



$$\Gamma_{\rm T} = \Gamma_{\rm M} + \Gamma_{\rm NM} \qquad \Gamma_{\rm NM} = \Gamma_n + \Gamma_p + \Gamma_{nn} + \Gamma_{pp} + \Gamma_{np}$$

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

- $Q_{\rm NM} = m_\Lambda - m_N \simeq 176$ 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

  – 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 $\Gamma_p \equiv \Gamma(\Lambda p \to np)$: Spin– and Isospin–dependence (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

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: $\Lambda\Lambda \to \Lambda n$, $\Lambda\Lambda \to \Sigma N$ $(\Delta S = -1)$, $\Lambda\Lambda \to nn$ $(\Delta S = -2)$

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

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

FRAMEWORK FOR CALCULATION

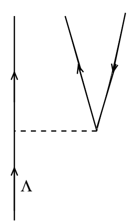
Non–Relativistic Nuclear Matter in LDA

Nuclear Matter

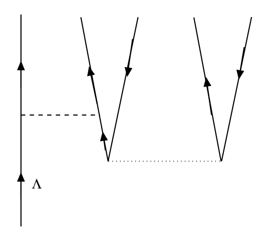
$$\Gamma_{\rm NM}(k,k_F)=\sum_f |\langle f|V^{\Lambda N\to NN}|0\rangle_{k,k_F}|^2\delta(E_f-E_0)$$

- k_F: Fermi momentum
- $k=(k_0,\boldsymbol{k})$: Λ four–momentum
- $|0\rangle_{k,k_F}$: hypernuclear ground state, with energy E_0
- $|f\rangle$: final states, with energy E_f
  - $|f\rangle=|2p1h\rangle$ for Γ_1
  - $|f\rangle=|3p2h\rangle$ for Γ_2
- $V^{\Lambda N\to nN}$: two–body weak transition potential
  - One–Meson–Exchange: π, η, K, ρ, ω, K^*

Γ_1: $\langle 2p1h|V^{\Lambda N\to NN}|0\rangle$



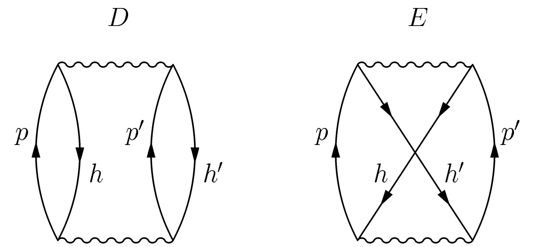
Γ_2: $\langle 3p2h|V^{\Lambda N\to NN}|0\rangle$



Normalization:

$$|0\rangle_{k,k_F} = \mathcal{N}(k_F) \left(|\,\rangle - \sum_{p,p',h,h'} \frac{\langle pp'hh'|V^{NN}|\,\rangle_{D+E}}{\varepsilon_p + \varepsilon_{p'} - \varepsilon_h - \varepsilon_{h'}} |pp'hh'\rangle \right) \otimes |\Lambda\rangle$$

$$\mathcal{N}(k_F) = \left(1 + \sum_{p,p',h,h'} \left| \frac{\langle pp'hh'|V^{NN}|\,\rangle_{D+E}}{\varepsilon_p + \varepsilon_{p'} - \varepsilon_h - \varepsilon_{h'}} \right|^2 \right)^{-1/2}$$



- $|\,\rangle$: uncorrelated nuclear ground state
- $|\Lambda\rangle$: normalized state of the Λ
- V^{NN}: residual strong interaction $\Longrightarrow$ Ground state correlations (GSC)

  Bonn potential: π, ρ, σ, ω

LDA

Local Fermi See of nucleons:

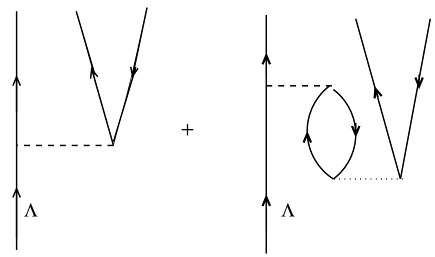
$$k_F(r) = \left\{ \frac{3}{2} \pi^2 \rho(r) \right\}^{1/3}$$

$$\Gamma_{\rm NM} = \int d\boldsymbol{k}\, |\tilde{\psi}_\Lambda(\boldsymbol{k})|^2 \int d\boldsymbol{r}\, |\psi_\Lambda(\boldsymbol{r})|^2\, \Gamma_{\rm NM}(\boldsymbol{k}, k_F(r))$$

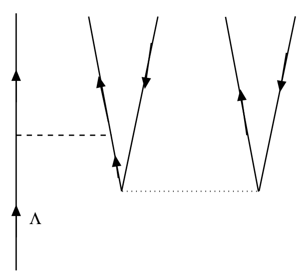
G. Garbarino
University of Torino

At leading order in GSC:

$$\Gamma_1(\boldsymbol{k}, k_F) = \mathcal{N}^2(k_F) \sum_{f \in 2p1h} \delta(E_f - E_0) \left| \langle f | V^{\Lambda N \to NN} | \Lambda \rangle_{D+E} - \sum_{p,h,p',h'} \langle f | V^{\Lambda N \to NN} | php'h';\, \Lambda \rangle_{D+E} \frac{\langle php'h';\, \Lambda | V^{NN} | \Lambda \rangle_{D+E}}{\varepsilon_p - \varepsilon_h + \varepsilon_{p'} - \varepsilon_{h'}} \right|^2$$



$$\Gamma_2(\boldsymbol{k}, k_F) = \mathcal{N}^2(k_F) \sum_{f \in 3p2h} \delta(E_f - E_0) \times \left| \sum_{p,h,p',h'} \langle f | V^{\Lambda N \to NN} | php'h';\, \Lambda \rangle_{D+E} \frac{\langle php'h';\, \Lambda | V^{NN} | \Lambda \rangle_{D+E}}{\varepsilon_p - \varepsilon_h + \varepsilon_{p'} - \varepsilon_{h'}} \right|^2$$



G. Garbarino
University of Torino

Potentials

$$V^{\Lambda N\to NN}(q) = \sum_{\tau_\Lambda=0,1} \mathcal{O}_{\tau_\Lambda} \mathcal{V}_{\tau_\Lambda}^{\Lambda N\to NN}(q)$$

$$V^{NN}(q) = \sum_{\tau_N=0,1} \mathcal{O}_{\tau_N} \mathcal{V}_{\tau_N}^{NN}(q)$$

$$\mathcal{O}_{\tau_{\Lambda(N)}} = \begin{cases} 1 & \text{for} \quad \tau_{\Lambda(N)} = 0 \\ \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 & \text{for} \quad \tau_{\Lambda(N)} = 1 \end{cases}$$

$$\begin{aligned} \mathcal{V}_{\tau_\Lambda}^{\Lambda N\to NN}(q) = & (G_F m_\pi^2) \{P_{C,\tau_\Lambda}(q) + S_{\tau_\Lambda}(q)\, \boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{q}} + S'_{\tau_\Lambda}(q)\, \boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{q}} \\ & + P_{L,\tau_\Lambda}(q) \boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{q}}\, \boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{q}} + P_{T,\tau_\Lambda}(q)(\boldsymbol{\sigma}_1 \times \hat{\boldsymbol{q}}) \cdot (\boldsymbol{\sigma}_2 \times \hat{\boldsymbol{q}}) \\ & + i S_{V,\tau_\Lambda}(q)(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \hat{\boldsymbol{q}}\} \end{aligned}$$

$(\pi + \eta + K + \rho + \omega + K^*)$

$$\begin{aligned} \mathcal{V}_{\tau_N}^{NN}(q) = & \frac{f_\pi^2}{m_\pi^2} \{\mathcal{V}_{C,\,\tau_N}(q) + \mathcal{V}_{L,\,\tau_N}(q) \boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{q}}\, \boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{q}} \\ & + \mathcal{V}_{T,\,\tau_N}(q)(\boldsymbol{\sigma}_1 \times \hat{\boldsymbol{q}}) \cdot (\boldsymbol{\sigma}_2 \times \hat{\boldsymbol{q}})\} \end{aligned}$$

(Bonn: $\pi + \rho + \sigma + \omega$)

One–Nucleon Induced: $\Gamma_1 = \Gamma_n + \Gamma_p$

$$\Gamma_{n\,(p)}(\boldsymbol{k},k_F) = \Gamma^0_{n\,(p)}(\boldsymbol{k},k_F) + \Gamma^{0-\mathrm{GSC}}_{n\,(p)}(\boldsymbol{k},k_F) + \Gamma^{\mathrm{GSC}}_{n\,(p)}(\boldsymbol{k},k_F)$$

$$\begin{aligned}
\Gamma^0_{n\,(p)}(\boldsymbol{k},k_F) &= \sum_{P,Q=D,\,E} \Gamma^{PQ}_{n\,(p)}(\boldsymbol{k},k_F) \qquad \longleftarrow \text{UGS} \\
&= \sum_{P,Q=D,\,E}\ \sum_{\tau_{\Lambda'},\tau_\Lambda=0,1} \mathcal{T}^{PQ}_{\tau_{\Lambda'}\tau_\Lambda,\,n\,(p)}\ \Gamma^{PQ}_{\tau_{\Lambda'}\tau_\Lambda}(\boldsymbol{k},k_F) \\
\Gamma^{0-\mathrm{GSC}}_{n\,(p)}(\boldsymbol{k},k_F) &= \sum_{P,Q,Q'=D,\,E} \Gamma^{PQQ'}_{n\,(p)}(\boldsymbol{k},k_F) \qquad \longleftarrow \text{UGS–CGS Interference} \\
&= \sum_{P,Q,Q'=D,\,E}\ \sum_{\tau_{\Lambda'},\tau_\Lambda,\tau_N=0,1} \mathcal{T}^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N,\,n\,(p)}\ \Gamma^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) \\
\Gamma^{\mathrm{GSC}}_{n\,(p)}(\boldsymbol{k},k_F) &= \sum_{P',P,Q,Q'=D,\,E} \Gamma^{P'PQQ'}_{n\,(p)}(\boldsymbol{k},k_F) \qquad \longleftarrow \text{GSC} \\
&= \sum_{P',P,Q,Q'=D,\,E}\ \sum_{\tau_{N'},\tau_{\Lambda'},\tau_\Lambda,\tau_N=0,1} \mathcal{T}^{P'PQQ'}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N,\,n\,(p)}\ \Gamma^{P'PQQ'}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F)
\end{aligned}$$

(D =Direct, E =Exchange)

G. Garbarino
University of Torino

Isospin factors:

$$\mathcal{T}^{PQ}_{\tau_{\Lambda'}\tau_{\Lambda},\, n\,(p)} = \sum_{f,\,\text{isospin}} \langle t_\Lambda | \mathcal{O}_{\tau_{\Lambda'}} | f \rangle_P \langle f | \mathcal{O}_{\tau_\Lambda} | t_\Lambda \rangle_Q$$

$$\mathcal{T}^{PQQ'}_{\tau_{\Lambda'}\tau_{\Lambda}\tau_N,\, n\,(p)} = \sum_{f,\,\text{isospin}} \langle t_\Lambda | \mathcal{O}_{\tau_{\Lambda'}} | f \rangle_P \langle f | \mathcal{O}_{\tau_\Lambda} | t_p t_h t_{p'} t_{h'}, t_\Lambda \rangle_Q \times \langle t_p t_h t_{p'} t_{h'}, t_\Lambda | \mathcal{O}_{\tau_N} | t_\Lambda \rangle_{Q'}$$

$$\mathcal{T}^{P'PQQ'}_{\tau_{N'}\tau_{\Lambda'}\tau_{\Lambda}\tau_N,\, n\,(p)} = \sum_{f,\,\text{isospin}} \langle t_\Lambda | \mathcal{O}_{\tau_{N'}} | t_{\tilde{p}} t_{\tilde{h}} t_{\tilde{p}'} t_{\tilde{p}'}, t_\Lambda \rangle_{P'} \langle t_{\tilde{p}} t_{\tilde{h}} t_{\tilde{p}'} t_{\tilde{p}'}, t_\Lambda | \mathcal{O}_{\tau_{\Lambda'}} | f \rangle_P \times \langle f | \mathcal{O}_{\tau_\Lambda} | t_p t_h t_{p'} t_{h'}, t_\Lambda \rangle_Q \langle t_p t_h t_{p'} t_{h'}, t_\Lambda | \mathcal{O}_{\tau_N} | t_\Lambda \rangle_{Q'}$$

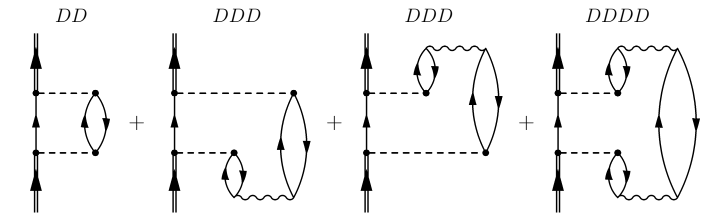
G. Garbarino
University of Torino

$$\Gamma^{PQ}_{\tau_{\Lambda'}\tau_\Lambda}(\boldsymbol{k},k_F) = \mathcal{N}^2(k_F)\,(-1)^n \sum_f \delta(E_f - E_0) \times \langle p_\Lambda|(\mathcal{V}^{\Lambda N\to NN}_{\tau_{\Lambda'}}(q'))^\dagger|f\rangle_P \langle f|\mathcal{V}^{\Lambda N\to NN}_{\tau_\Lambda}(q)|p_\Lambda\rangle_Q$$

$$\Gamma^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) = -2\,\mathcal{N}^2(k_F)\,(-1)^n \sum_f \sum_{p,h,p',h'} \delta(E_f - E_0) \times \langle p_\Lambda|(\mathcal{V}^{\Lambda N\to NN}_{\tau_{\Lambda'}}(q'))^\dagger|f\rangle_P \langle f|\mathcal{V}^{\Lambda N\to NN}_{\tau_\Lambda}(q)|php'h';\,p_\Lambda\rangle_Q \times \frac{\langle php'h';\,p_\Lambda|\mathcal{V}^{NN}_{\tau_N}(t)|p_\Lambda\rangle_{Q'}}{\varepsilon_p - \varepsilon_h + \varepsilon_{p'} - \varepsilon_{h'}}$$

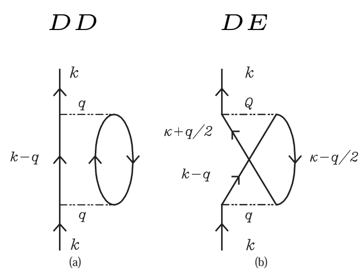
$$\Gamma^{P'PQQ'}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) = \mathcal{N}^2(k_F)\,(-1)^n \sum_f \sum_{\tilde p,\tilde h,\tilde p',\tilde h'} \sum_{p,h,p',h'} \delta(E_f - E_0) \times \frac{\langle p_\Lambda|(\mathcal{V}^{NN}_{\tau_{N'}}(t'))^\dagger|\tilde p,\tilde h,\tilde p',\tilde h';\,p_\Lambda\rangle_{P'}}{\varepsilon_{\tilde p} - \varepsilon_{\tilde h} + \varepsilon_{\tilde p'} - \varepsilon_{\tilde h'}} \times \langle \tilde p,\tilde h,\tilde p',\tilde h';\,p_\Lambda|(\mathcal{V}^{\Lambda N\to NN}_{\tau_{\Lambda'}}(q'))^\dagger|f\rangle_P \times \langle f|\mathcal{V}^{\Lambda N\to NN}_{\tau_\Lambda}(q)|php'h';\,p_\Lambda\rangle_Q \times \frac{\langle php'h';\,p_\Lambda|\mathcal{V}^{NN}_{\tau_N}(t)|p_\Lambda\rangle_{Q'}}{\varepsilon_p - \varepsilon_h + \varepsilon_{p'} - \varepsilon_{h'}}$$

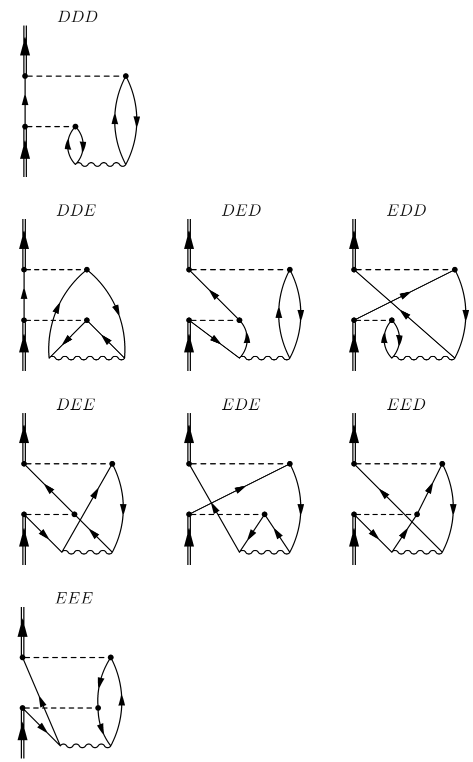
Direct Diagrams $(P', P, Q, Q' = D)$:



Γ_1^0 $\Gamma_1^{0-\mathrm{GSC}}$ Γ_1^{GSC}

Antisymmetrization:





G. Garbarino
University of Torino

UGS:

$$
\begin{aligned}
\Gamma^{DD}_{\tau_{\Lambda'}\tau_\Lambda}(\boldsymbol{k},k_F) &= -\mathcal{N}^2(k_F)\frac{4}{\pi(2\pi)^2}(G_F m_\pi^2)^2 \int d\boldsymbol{q}\,\theta(q_0)\theta(|\boldsymbol{k}-\boldsymbol{q}|-k_F) \\
&\times[S_{\tau_\Lambda}(q)S_{\tau_{\Lambda'}}(q) + S'_{\tau_\Lambda}(q)S'_{\tau_{\Lambda'}}(q) + P_{L,\tau_\Lambda}(q)P_{L,\tau_{\Lambda'}}(q) \\
&+P_{C,\tau_\Lambda}(q)P_{C,\tau_{\Lambda'}}(q) + 2P_{T,\tau_\Lambda}(q)P_{T,\tau_{\Lambda'}}(q) \\
&+2S_{V,\tau_\Lambda}(q)S_{V,\tau_{\Lambda'}}(q)]\mathcal{I}(q_0,\boldsymbol{q})
\end{aligned}
$$

$$
\begin{aligned}
\Gamma^{DE}_{\tau_{\Lambda'}\tau_\Lambda}(\boldsymbol{k},k_F) &= \mathcal{N}^2(k_F)\frac{4}{\pi(2\pi)^2}(G_F m_\pi^2)^2 \int d\boldsymbol{q} \int d\boldsymbol{h}\,\theta(q_0)\theta(|\boldsymbol{k}-\boldsymbol{q}|-k_F) \\
&\times[(\boldsymbol{q}\cdot\boldsymbol{Q})S_{\tau_\Lambda}(q)S_{\tau_{\Lambda'}}(Q) + (2(\boldsymbol{q}\cdot\boldsymbol{Q})^2-1)P_{L\tau_\Lambda}(q)P_{L,\tau_{\Lambda'}}(Q) \\
&+P_{C,\tau_\Lambda}(q)P_{C,\tau_{\Lambda'}}(Q) + 2((\boldsymbol{q}\cdot\boldsymbol{Q})^2-1)P_{T,\tau_\Lambda}(q)P_{T\tau_{\Lambda'}}(Q) \\
&-(2\boldsymbol{q}\cdot\boldsymbol{Q})^2(P_{L,\tau_\Lambda}(q)P_{T\tau_{\Lambda'}}(Q) + P_{L,\tau_\Lambda}(Q)P_{T,\tau_{\Lambda'}}(q))]|_{\boldsymbol{Q}=\boldsymbol{k}-\boldsymbol{q}-\boldsymbol{h}} \\
&\times\Theta(|\boldsymbol{h}+\boldsymbol{q}|-k_F)\Theta(k_F-|\boldsymbol{h}|)\delta(q_0-\varepsilon_{\boldsymbol{h}+\boldsymbol{q}}+\varepsilon_{\boldsymbol{h}})
\end{aligned}
$$

- $q_0 = k_0 - \varepsilon_{\boldsymbol{k}-\boldsymbol{q}} - V_N$

G. Garbarino
University of Torino

UGS–CGS Interference:

$$\Gamma^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) = \mathcal{N}^2(k_F)\frac{1}{4}\frac{(-1)^n}{(2\pi)^8}(G_F m_\pi^2)^2\frac{f_\pi^2}{m_\pi^2}$$
$$\times\int\int\int d\boldsymbol{q}\,d\boldsymbol{h}\,d\boldsymbol{h}'\,\mathcal{W}^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(q,q',t)$$
$$\times\Theta^{PQQ'}(k,q,q',t,h,h',k_F)\frac{1}{-\varepsilon^{PQQ'}_{2p2h}}\,\delta(q_0-(\varepsilon_{\boldsymbol{h}'+\boldsymbol{q}}-\varepsilon_{\boldsymbol{h}'}))$$

- $q_0 = k_0 - \varepsilon_{\boldsymbol{k}-\boldsymbol{q}} - V_N$
- $\mathcal{W}^{PQQ'}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(q,q',t)$: momentum dependence given by $V^{\Lambda N\to NN}$ and V^{NN} and spin summation
- $\Theta^{PQQ'}(k,q,q',t,h,h',k_F)$: product of step functions (phase space of particles and holes)
- $\varepsilon^{PQQ'}_{2p2h}$: energy denominator
- n: number of crossing between fermionic lines

$$\Gamma^{DDD}_{\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) = -\frac{\mathcal{N}^2(k_F)}{(2\pi)^3}(G_F m_\pi^2)^2\frac{f_\pi^2}{m_\pi^2}\int d\boldsymbol{q}\,\theta(q_0)\theta(|\boldsymbol{k}-\boldsymbol{q}|-k_F)$$
$$\times\{[S'_{\tau_{\Lambda'}}(q)S'_{\tau_\Lambda}(q)+P_{C,\tau_{\Lambda'}}(q)P_{C,\tau_\Lambda}(q)]\mathcal{V}_{C,\,\tau_N}(q)$$
$$+[S_{\tau_{\Lambda'}}(q)S_{\tau_\Lambda}(q)+P_{L,\tau_{\Lambda'}}(q)P_{L,\tau_\Lambda}(q)]\mathcal{V}_{L,\,\tau_N}(q)$$
$$+2\,[S_{V,\tau_{\Lambda'}}(q)S_{V,\tau_\Lambda}(q)+P_{T,\tau_{\Lambda'}}(q)P_{T,\tau_\Lambda}(q)]\mathcal{V}_{T,\,\tau_N}(q)\}$$
$$\times\mathcal{R}(-q_0,\boldsymbol{q})\mathcal{I}(q_0,\boldsymbol{q})$$

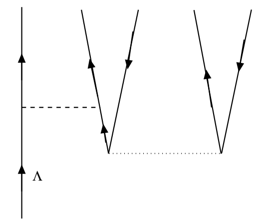
GSC:

$$\Gamma^{DDDD}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) = -\frac{\mathcal{N}^2(k_F)}{(2\pi)^2}(G_F m_\pi^2)^2\left(\frac{f_\pi^2}{m_\pi^2}\right)^2\int d\boldsymbol{q}\,\theta(q_0)\theta(|\boldsymbol{k}-\boldsymbol{q}|-k_F)$$
$$\times\{[S'_{\tau_{\Lambda'}}(q)S'_{\tau_\Lambda}(q)+P_{C,\tau_{\Lambda'}}(q)P_{C,\tau_\Lambda}(q)]\mathcal{V}^2_{C,\,\tau_N}(q)$$
$$+[S_{\tau_{\Lambda'}}(q)S_{\tau_\Lambda}(q)+P_{L,\tau_{\Lambda'}}(q)P_{L,\tau_\Lambda}(q)]\mathcal{V}^2_{L,\,\tau_N}$$
$$+2\,[S_{V,\tau_{\Lambda'}}(q)S_{V,\tau_\Lambda}(q)+P_{T,\tau_{\Lambda'}}(q)P_{T,\tau_\Lambda}(q)]\mathcal{V}^2_{T,\,\tau_N}(q)\}$$
$$\times\mathcal{R}^2(-q_0,\boldsymbol{q})\mathcal{I}(q_0,\boldsymbol{q})$$

- $\Gamma^{P'PQQ'}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}$ exchange terms are neglected: $\Gamma^{P'PQQ'}_{n(p)} < \Gamma^{DDDD}_{n(p)} \simeq 10^{-2}\Gamma_{n(p)}$

G. Garbarino
University of Torino

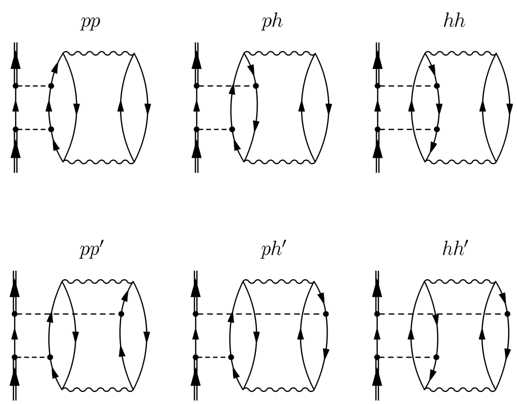
Two–Nucleon Induced: $\Gamma_2 = \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}$



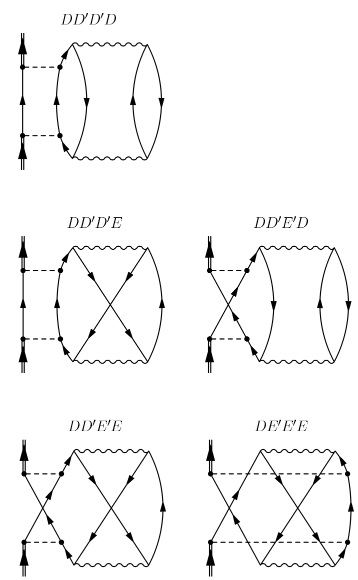
$$\Gamma_2(\boldsymbol{k}, k_F) = \mathcal{N}^2(k_F) \sum_{f \in 3p2h} \delta(E_f - E_0)$$

$$\times \left| \sum_{p,h,p',h'} \langle f | V^{\Lambda N \to NN} | php'h'; \Lambda \rangle_{D+E} \frac{\langle php'h'; \Lambda | V^{NN} | \Lambda \rangle_{D+E}}{\varepsilon_p - \varepsilon_h + \varepsilon_{p'} - \varepsilon_{h'}} \right|^2$$

Direct Diagrams



Antisymmetrization



$$\Gamma_2^{\rm pp} = \Gamma_2^{{\rm pp}\,D} + \Gamma_2^{{\rm pp}\,E} = \Gamma_2^{dd'd'd} + (\Gamma_2^{dd'd'e} + \Gamma_2^{dd'e'd} + \Gamma_2^{dd'e'e} + \Gamma_2^{de'e'e})$$

$$\begin{aligned}
\Gamma_2^{dd'd'd} &\equiv \frac{1}{4}(\Gamma_2^{DD'D'D} + \Gamma_2^{DE'E'D} + \Gamma_2^{ED'D'E} + \Gamma_2^{EE'E'E}) = \Gamma_2^{DD'D'D} \\
\Gamma_2^{dd'd'e} &\equiv \frac{1}{4}(\Gamma_2^{DD'D'E} + \Gamma_2^{ED'D'D}) = \frac{1}{2}\Gamma_2^{DD'D'E} \\
\Gamma_2^{dd'e'd} &\equiv \frac{1}{4}(\Gamma_2^{DD'E'D} + \Gamma_2^{DE'D'D} + \Gamma_2^{ED'E'E} + \Gamma_2^{EE'D'E}) = \Gamma_2^{DD'E'D} \\
\Gamma_2^{dd'e'e} &\equiv \frac{1}{4}(\Gamma_2^{DD'E'E} + \Gamma_2^{DE'D'E} + \Gamma_2^{ED'E'D} + \Gamma_2^{EE'D'D}) = \Gamma_2^{DD'E'E} \\
\Gamma_2^{de'e'e} &\equiv \frac{1}{4}(\Gamma_2^{DE'E'E} + \Gamma_2^{EE'E'D}) = \frac{1}{2}\Gamma_2^{DE'E'E}
\end{aligned}$$

$$\begin{aligned}
\Gamma_2 &= \Gamma_2^{\rm pp} + \Gamma_2^{\rm ph} + \Gamma_2^{\rm hh} + \Gamma_2^{\rm pp'} + \Gamma_2^{\rm ph'} + \Gamma_2^{\rm hh'} \\
&= (\Gamma_2^{{\rm pp}\,D} + \Gamma_2^{{\rm pp}\,E}) + (\Gamma_2^{{\rm ph}\,D} + \Gamma_2^{{\rm ph}\,E}) + (\Gamma_2^{{\rm hh}\,D} + \Gamma_2^{{\rm hh}\,E}) \\
&\quad + (\Gamma_2^{{\rm pp'}\,D} + \Gamma_2^{{\rm pp'}\,E}) + (\Gamma_2^{{\rm ph'}\,D} + \Gamma_2^{{\rm ph'}\,E}) + (\Gamma_2^{{\rm hh'}\,D} + \Gamma_2^{{\rm hh'}\,E})
\end{aligned}$$

$$\Gamma_2^{{\rm ij}\,P} = \Gamma_{nn}^{{\rm ij}\,P} + \Gamma_{np}^{{\rm ij}\,P} + \Gamma_{pp}^{{\rm ij}\,P} \qquad (P = D \,{\rm or}\, E)$$

$$\Gamma_2^{\rm pp}(\boldsymbol{k},k_F) = \sum_{\tau_{N'},\tau_{\Lambda'},\tau_\Lambda,\tau_N=0,1} \mathcal{T}^{PQ'R'S}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N,\, n\,(p)} \, \Gamma^{PQ'R'S}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F)$$

$$\begin{aligned}
\Gamma^{PQ'R'S}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{k},k_F) \quad = \quad & \mathcal{N}^2(k_F)\frac{1}{2}\frac{(-1)^n}{(2\pi)^9} f_{pq'r's}(G_F m_\pi^2)^2(\frac{f_\pi^2}{m_\pi^2})^2 \\
& \times \int d\,\boldsymbol{q} \int d\,\boldsymbol{t} \int d\,\boldsymbol{h} \int d\boldsymbol{h}' \,\theta(q_0) \\
& \times \theta(|\boldsymbol{k}-\boldsymbol{q}|-k_F)\,\theta(|\boldsymbol{h}-\boldsymbol{t}|-k_F)\,\theta(|\boldsymbol{h}-\boldsymbol{t}+\boldsymbol{q}|-k_F) \\
& \times \theta(k_F-|\boldsymbol{h}|)\theta(|\boldsymbol{t}+\boldsymbol{h}'|-k_F)\theta(k_F-|\boldsymbol{h}'|) \\
& \times \delta(k_0-(\varepsilon_{\boldsymbol{k}-\boldsymbol{q}}+\varepsilon_{\boldsymbol{h}-\boldsymbol{t}+\boldsymbol{q}}+\varepsilon_{\boldsymbol{t}+\boldsymbol{h}'}-\varepsilon_{\boldsymbol{h}}-\varepsilon_{\boldsymbol{h}'})) \\
& \times \mathcal{W}^{PQ'R'S}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{q},\boldsymbol{q}',\boldsymbol{t},\boldsymbol{t}')\,\frac{1}{\prod \epsilon_{2p2h}}
\end{aligned}$$

Specific of each diagram are:

- $\mathcal{W}^{PQ'R'S}_{\tau_{N'}\tau_{\Lambda'}\tau_\Lambda\tau_N}(\boldsymbol{q},\boldsymbol{q}',\boldsymbol{t},\boldsymbol{t}')$: momentum dependence introduced by $V^{\Lambda N\to NN}$ and V^{NN} and spin summation
- Energy denominator $\prod \epsilon_{2p2h}$
- $f_{pq'r's}$ and n

G. Garbarino
University of Torino

RESULTS

One–Nucleon Induced: $\Gamma_1 = \Gamma_n + \Gamma_p$

$$\Gamma_{n\,(p)} = \Gamma^0_{n\,(p)} + \Gamma^{0-\mathrm{GSC}}_{n\,(p)} + \Gamma^{\mathrm{GSC}}_{n\,(p)}$$

$$\equiv \sum_{P,Q=D,E} \Gamma^{PQ}_{n\,(p)} + \sum_{P,Q,Q'=D,E} \Gamma^{PQQ'}_{n\,(p)} + \sum_{P',P,Q,Q'=D,E} \Gamma^{P'PQQ'}_{n\,(p)}$$

UGS | UGS–CGS Interference | GSC

Table 1: $\Gamma^{PQ}_{n(p)}$ terms for ${}^{12}_{\Lambda}$C in units of the free Λ decay rate, $\Gamma^0 = 2.52 \cdot 10^{-6}$ eV. Note that $\Gamma^{DD}_{n\,(p)} = \Gamma^{EE}_{n\,(p)}$ and $\Gamma^{DE}_{n\,(p)} = \Gamma^{ED}_{n\,(p)}$.

Channel	$2\,\Gamma^{DD}$	$2\,\Gamma^{DE}$	Γ^0
$\Lambda n \to nn$	0.146	0.008	0.154
$\Lambda p \to np$	0.469	0.002	0.470
sum	0.615	0.009	0.624

- Exchange terms: 5.1% (0.3%) of Γ^0_n (Γ^0_p)
- Slight increase of Γ_n/Γ_p and Γ_1

Table 2: $\Gamma_{n(p)}^{PQQ'}$ terms for ${}^{12}_{\Lambda}$C.

Channel	Γ^{DDD}	Γ^{DDE}	Γ^{DED}	Γ^{EDD}	
$\Lambda n \to nn$	0.022	-0.002	-0.009	-0.004	
$\Lambda p \to np$	0.071	0.005	-0.027	-0.011	
sum	0.093	0.003	-0.036	-0.015	
Channel	Γ^{DEE}	Γ^{EDE}	Γ^{EED}	Γ^{EEE}	$\Gamma^{0-\mathrm{GSC}}$
$\Lambda n \to nn$	0.006	0.008	0.006	0.002	0.029
$\Lambda p \to np$	-0.008	0.009	0.025	0.002	0.066
sum	-0.003	0.017	0.031	0.004	0.095

- Antisymmetrization: $\Gamma_n^{0-\mathrm{GSC}}$ increased by 34%, $\Gamma_p^{0-\mathrm{GSC}}$ decreased by 8%
- Increase of Γ_n/Γ_p, Γ_1 unaffected

Table 3: The one–nucleon induced decay rates for ${}^{12}_{\Lambda}$C.

Channel	Γ^0	$\Gamma^{0-\mathrm{GSC}}$	Γ^{GSC}	Γ
$\Lambda n \to nn$	0.154	0.029	0.002	0.185
$\Lambda p \to np$	0.470	0.066	0.008	0.544
sum	0.624	0.095	0.010	0.729

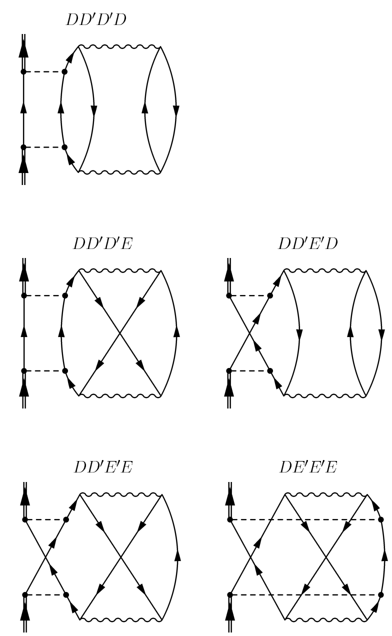
- $\Gamma_1^0 : \Gamma_1^{0-\mathrm{GSC}} : \Gamma_1^{\mathrm{GSC}} = 0.86 : 0.13 : 0.01$ (non–negligible effect of GSC)
- $\Gamma_1^{\mathrm{GSC}} = \Gamma_1^{DDDD} \simeq 0.01$ (exchange terms neglected)

Two–Nucleon Induced: $\Gamma_2 = \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}$

Table 4: Partial contributions to $\Gamma_2^{\rm pp}$ for ${}^{12}_{\Lambda}$C. Values smaller than 0.0005 are represented by ~ 0.

Channel	$\Gamma_2^{dd'd'd}$	$\Gamma_2^{dd'd'e}$	$\Gamma_2^{dd'e'd}$	$\Gamma_2^{dd'e'e}$	$\Gamma_2^{de'e'e}$	$\Gamma_2^{\rm pp}$
$\Lambda nn \to nnn$	0.012	−0.002	−0.002	~ 0	0.001	0.009
$\Lambda np \to nnp$	0.184	−0.047	−0.039	0.009	0.016	0.123
$\Lambda pp \to npp$	0.036	−0.008	−0.007	0.002	0.002	0.025
sum	0.232	−0.057	−0.048	0.011	0.019	0.157

- Antisymmetry: $\Gamma_2^{\rm pp}$ decreased by 32%
- $\Gamma_{np}^{\rm pp} : \Gamma_{pp}^{\rm pp} : \Gamma_{nn}^{\rm pp} = 0.78 : 0.16 : 0.06$
  (quasi–deuteron approximation)



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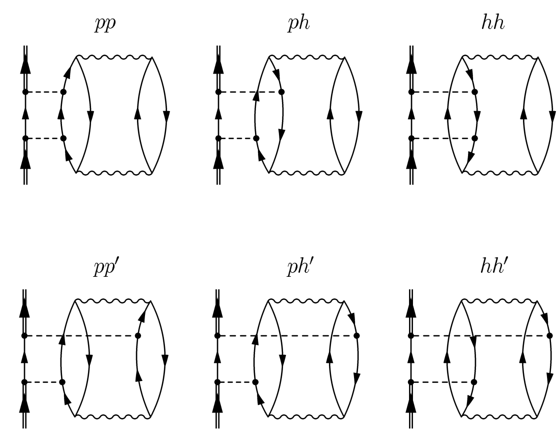
University of Torino

Table 5: Partial contributions to Γ_2 for ${}^{12}_{\Lambda}$C. Values smaller than 0.0005 are represented by ~ 0.

Channel	$\Gamma_2^{\mathrm{pp}\,D}$	$\Gamma_2^{\mathrm{pp}\,E}$	$\Gamma_2^{\mathrm{ph}\,D}$	$\Gamma_2^{\mathrm{ph}\,E}$	$\Gamma_2^{\mathrm{hh}\,D}$	$\Gamma_2^{\mathrm{hh}\,E}$	
$\Lambda nn \to nnn$	0.012	-0.003	~ 0	~ 0	0.002	-0.001	
$\Lambda np \to nnp$	0.184	-0.061	-0.003	0.001	0.027	-0.006	
$\Lambda pp \to npp$	0.036	-0.011	~ 0	~ 0	0.006	-0.001	
sum	0.232	-0.075	-0.003	0.001	0.035	-0.008	
Channel	$\Gamma_2^{\mathrm{pp}'\,D}$	$\Gamma_2^{\mathrm{pp}'\,E}$	$\Gamma_2^{\mathrm{ph}'\,D}$	$\Gamma_2^{\mathrm{ph}'\,E}$	$\Gamma_2^{\mathrm{hh}'\,D}$	$\Gamma_2^{\mathrm{hh}'\,E}$	Γ_2
$\Lambda nn \to nnn$	0.002	-0.001	~ 0	~ 0	~ 0	~ 0	0.011
$\Lambda np \to nnp$	0.081	-0.021	0.010	-0.004	0.004	-0.002	0.210
$\Lambda pp \to npp$	0.001	~ 0	~ 0	~ 0	~ 0	~ 0	0.031
sum	0.084	-0.022	0.010	-0.004	0.004	-0.002	0.252

- $\Gamma_2 = \Gamma_2^{\mathrm{pp}} + \Gamma_2^{\mathrm{ph}} + \Gamma_2^{\mathrm{hh}} + \Gamma_2^{\mathrm{pp}'} + \Gamma_2^{\mathrm{ph}'} + \Gamma_2^{\mathrm{hh}'}$
- $\Gamma_2^{\mathrm{pp}\,D} > \Gamma_2^{\mathrm{pp}'\,D} > |\Gamma_2^{\mathrm{pp}\,E}|$
- $|\Gamma^{\mathrm{ij}\,E}_{N_1N_2}/\Gamma^{\mathrm{ij}\,D}_{N_1N_2}| = 0.2\text{-}0.5.$
- $\Gamma_2^D = 0.36$ vs $\Gamma_2 = 0.25$
- $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$



Comparison with Experiment

Table 6: Non–mesonic weak decay widths of ${}^{12}_{\Lambda}$C.

Ant./GSC	Γ_n	Γ_p	Γ_1	Γ_2	$\Gamma_{\rm NM}$	Γ_n/Γ_p	$\Gamma_2/\Gamma_{\rm NM}$
no/no	0.15	0.47	0.62	0	0.62	0.31	0
yes/no	0.18	0.56	0.74	0	0.74	0.33	0
no/yes	0.15	0.47	0.61	0.31	0.91	0.31	0.50
yes/yes	0.19	0.55	0.73	0.25	0.98	0.34	0.26
KEK–E508	0.23 ± 0.08	0.45 ± 0.10	0.68 ± 0.13	0.27 ± 0.13	0.95 ± 0.04	$0.51 \pm 0.13 \pm 0.05$	0.29 ± 0.13
FINUDA							0.24 ± 0.10

- The four set of results corresponds to different ground state normalization functions
- Similar results for Γ_n/Γ_p for the 4 sets of results
- GSC: unchanged Γ_1, $\Gamma_2 \neq 0 \Longrightarrow$ sizable increase of $\Gamma_{\rm NM}$
- Antisymmetry: increase of Γ_1, reduction of $\Gamma_2 \Longrightarrow$ sizable reduction of $\Gamma_2/\Gamma_{\rm NM}$
- Ant./GSC: yes/yes is the only set reproducing all data

Medium and Heavy Hypernuclei

Table 7: Non–mesonic weak decay rates for medium to heavy hypernuclei.

Hypernucleus	Γ_1	Γ_2	$\Gamma_{\rm NM}$
${}^{11}_{\Lambda}$B	0.64	0.18	0.82
${}^{12}_{\Lambda}$C	0.73	0.25	0.98
${}^{27}_{\Lambda}$Al	0.94	0.28	1.22
${}^{28}_{\Lambda}$Si	0.96	0.29	1.25
${}^{40}_{\Lambda}$Ca	1.03	0.29	1.33
${}^{56}_{\Lambda}$Fe	1.06	0.33	1.39
${}^{89}_{\Lambda}$Y	1.06	0.33	1.39
${}^{139}_{\Lambda}$La	1.04	0.32	1.36
${}^{208}_{\Lambda}$Pb	1.06	0.34	1.40

- Saturation of Γ_1 and Γ_2 with increasing A:
  Saturation when $R(A)$ sensitively larger than $r_{\rm NM} \sim 1/m_\pi \sim 1.4$ fm

- $\Gamma_2/\Gamma_{\rm NM} \simeq 0.22$-$0.26$

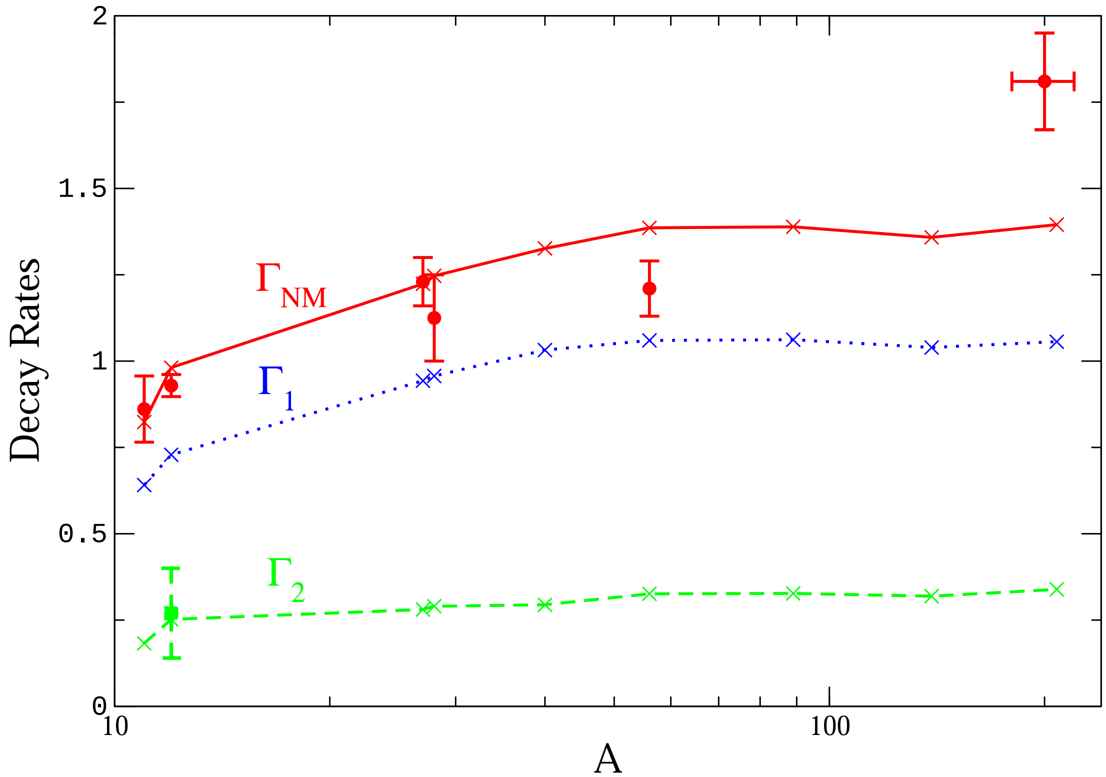


Figure 1: Weak decay rates as a function of the hypernuclear mass number A. Data are from KEK and COSY@Juelich.

- Rather good agreement with data

CONCLUSIONS

- Microscopic Calculation of Hypernuclear Non–Mesonic Weak Decay Rates: Nuclear Matter + LDA ($^{11}_{\Lambda}$B to $^{208}_{\Lambda}$Pb)
- $V^{\Lambda N \to NN}$: OME including PS and V meson octets (π, η, K, ρ, ω, K^*)
- V^{NN}: Bonn potential (π, ρ, σ, ω)
- Exchange terms and GSC (leading order in V^{NN}) introduced on the same footing for one– and two–nucleon induced weak decay channels
  - GSC : unchanged Γ_1, $\Gamma_2 \neq 0 \Longrightarrow$ sizable increase of $\Gamma_{\rm NM}$
  - Antisymmetry : increase of Γ_1 and Γ_n/Γ_p, reduction of $\Gamma_2 \Longrightarrow$ sizable reduction of $\Gamma_2/\Gamma_{\rm NM}$
- Main conclusion: a detailed many–body treatment is important
- Future developments:
  - Inclusion of $\Delta(1232)$–resonance contributions
  - Study of nucleon emission spectra

    New many–body terms accounting for FSI

    Microscopic vs INC
- Present and Future Experiments: J–PARC, FINUDA@DAPHNE, HypHI@GSI

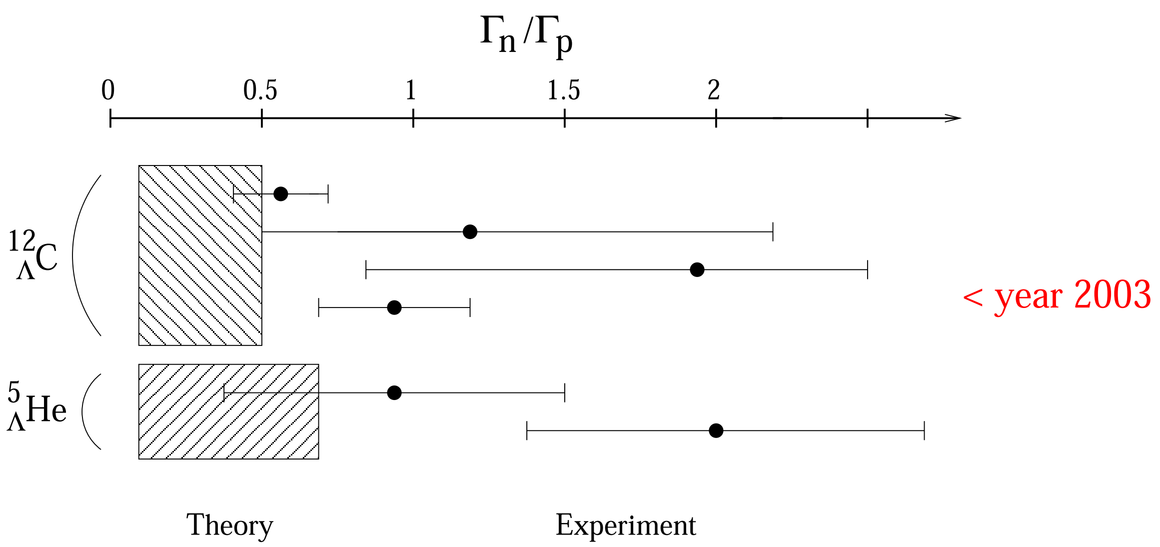
G. Garbarino
University of Torino

ADDITIONAL SLIDES

G. Garbarino
University of Torino

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)]

G. Garbarino
University of Torino

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)

KEK experiments: [Plenary Talk by Outa]

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]

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

[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]:

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

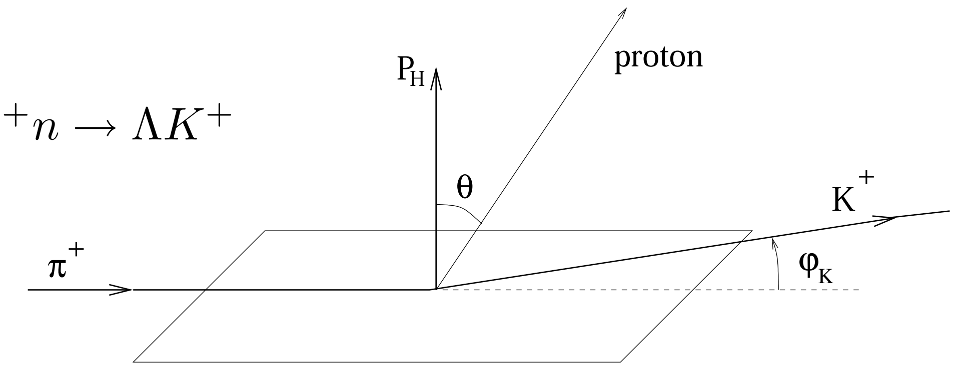
$$\left[\frac{N_{nn}}{N_{np}}\right]^{\rm KEK} \simeq 0.5 \pm 0.1 \quad \Longrightarrow \quad \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{“EXP”}} = (0.3 \div 0.4) \pm 0.1$$

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

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



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

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

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

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

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

G. Garbarino
University of Torino

	${}^{5}_{\Lambda}$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)		
OME + FSI	-0.46	-0.37
Chumillas et al. (2007)		
OME + 2π + $2\pi/\sigma$ + 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

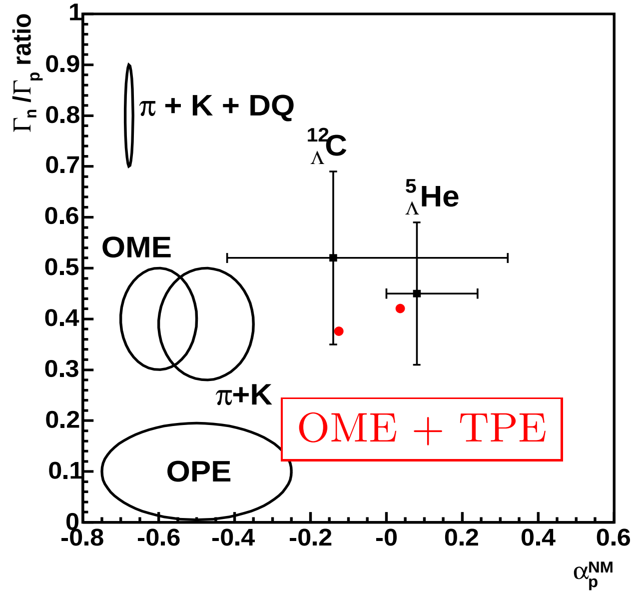
OME + TPE: Agreement also with the Decay Rate data for *both* ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C!

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

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

G. Garbarino
University of Torino

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

$\Delta I = 1/2$ rule — Experiment

$$\Gamma_{\rm NM}({}^4_\Lambda{\rm He}) = 0.25^{+0.04}_{-0.01} \iff 0.177 \pm 0.028 \quad \text{(BNL–E788)}$$

$$\Gamma_{\rm NM}({}^4_\Lambda{\rm H}) = 0.08^{+0.03}_{-0.02} \iff 0.17 \pm 0.11 \quad \text{(KEK)}$$

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

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

[Poster by Ajimura]

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

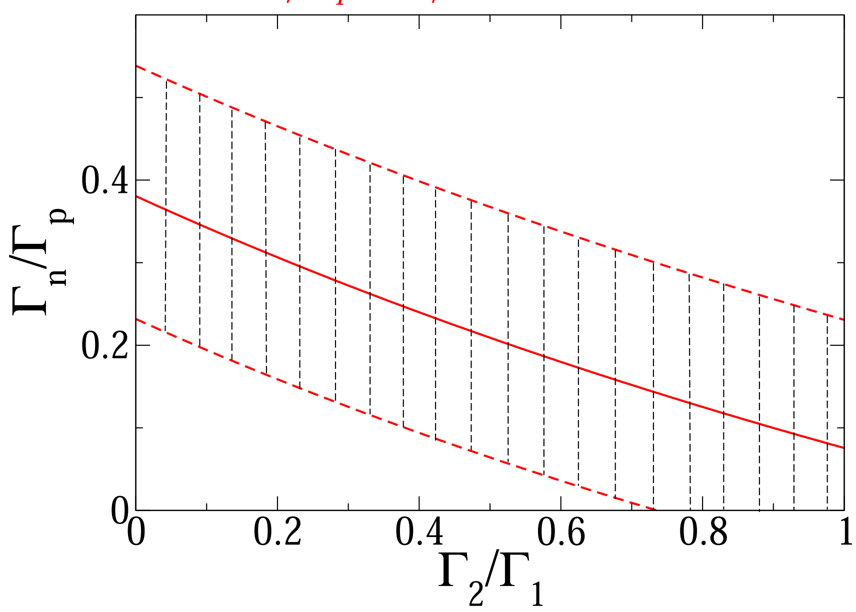
ii) Extraction of $\Gamma_2 = \Gamma(\Lambda NN \to nNN)$ from Data

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)]

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

Γ_n/Γ_p–Γ_2/Γ_1 Correlation



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

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

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

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

  [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]

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University of Torino

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)]

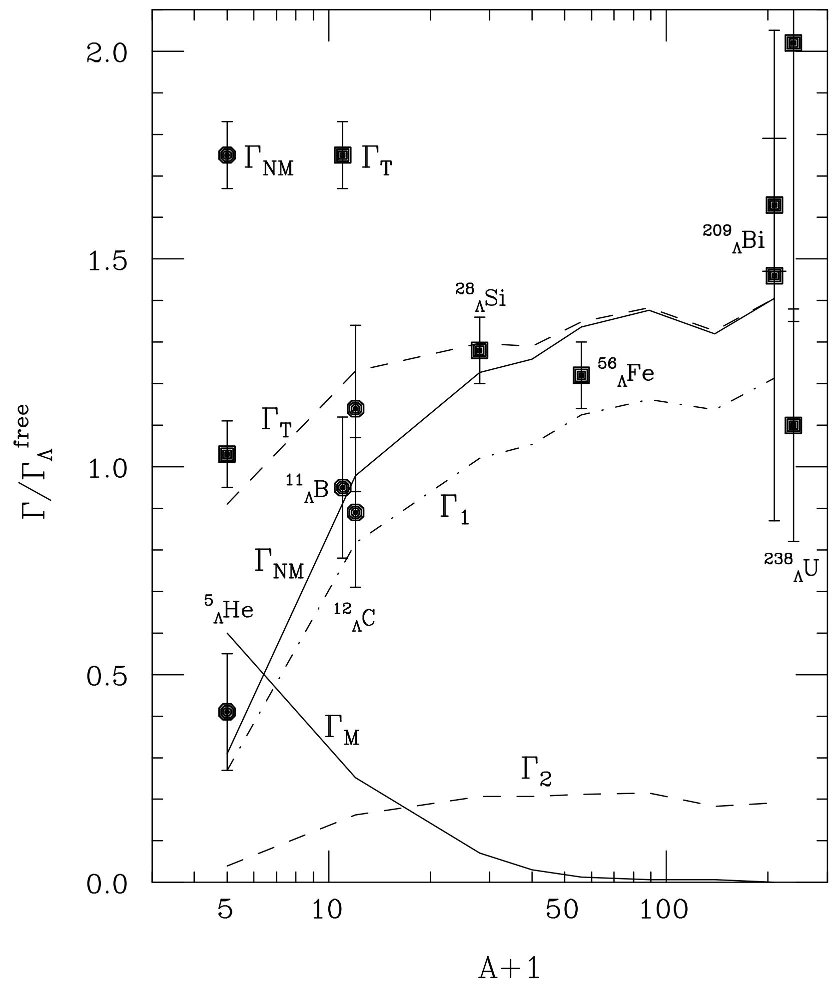
    $\Lambda\Lambda \to \Sigma^- p$ (but $BR^{\mathrm{th}} \simeq 0.001$)

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

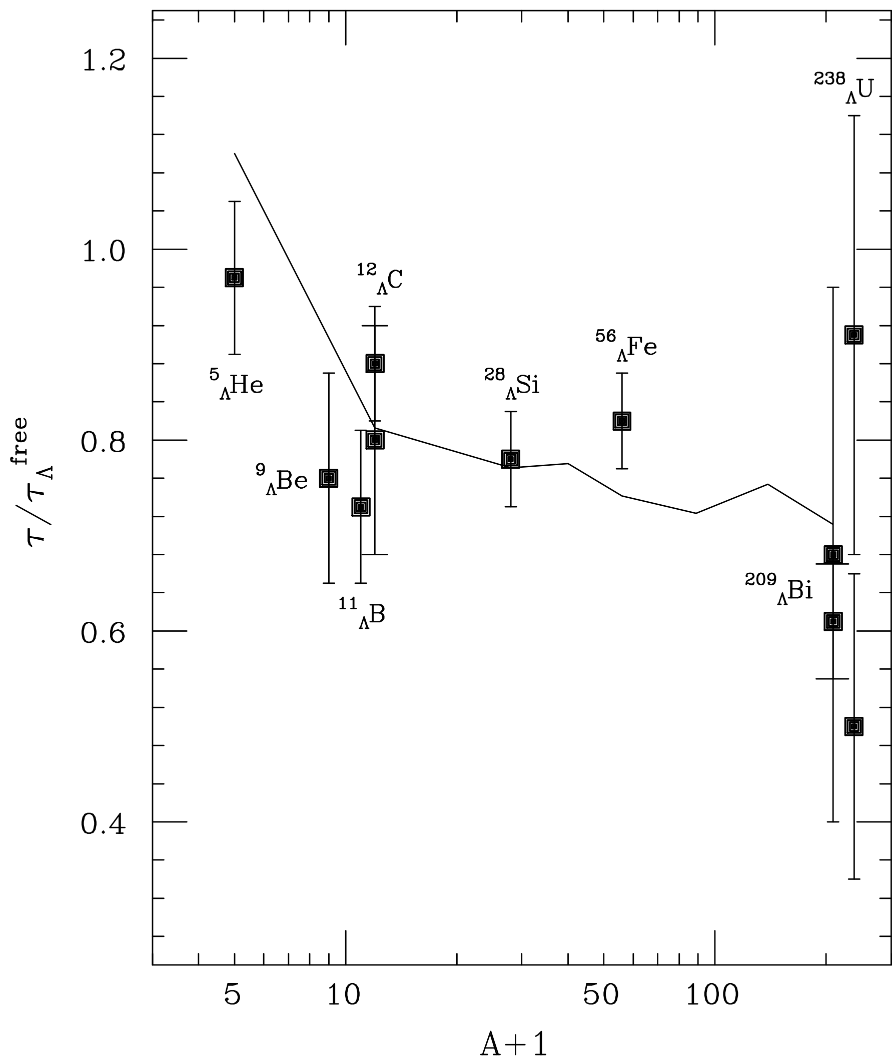
    [J.F. Donoghue, E. Golowich and B.R. Holstein, PRD 34, 3434 (1986)]

    $\Lambda\Lambda \to H \to \Sigma^- p$?
- New investigations: E07@J–PARC, PANDA@FAIR [Plenary Talk by Gianotti]

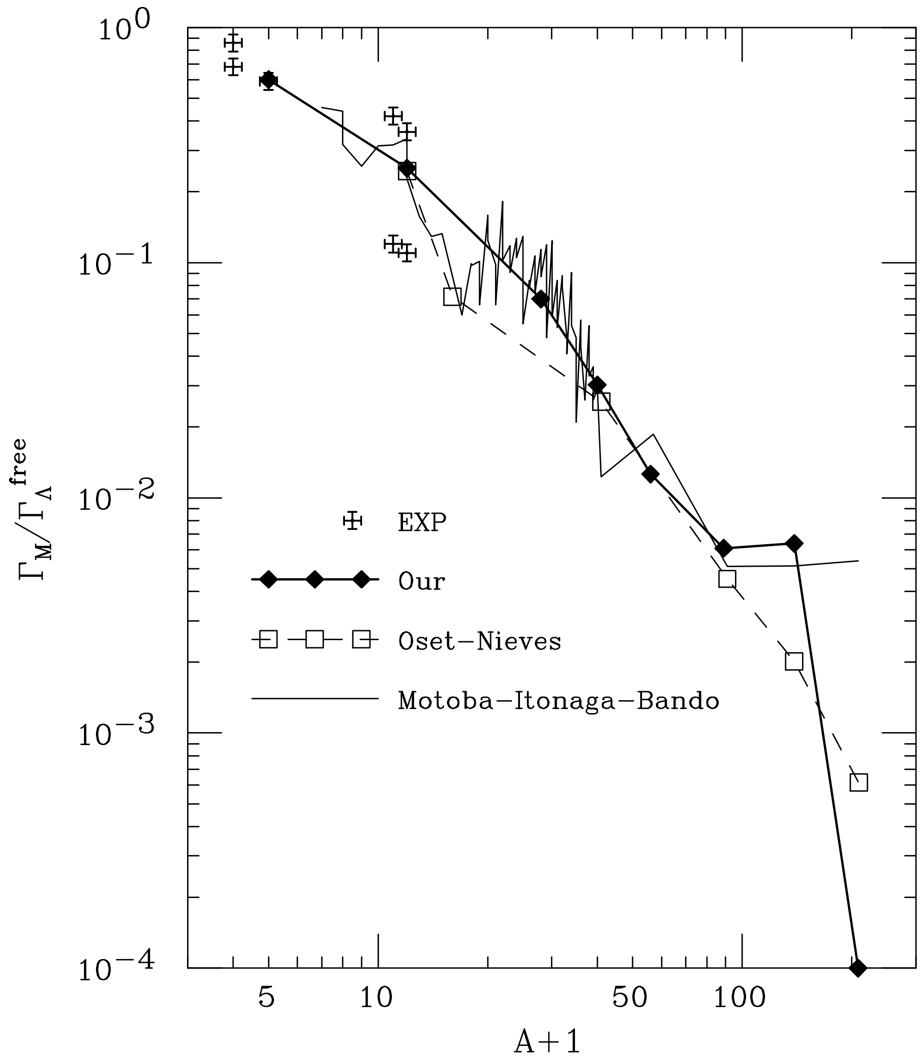
RESULTS



[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)]

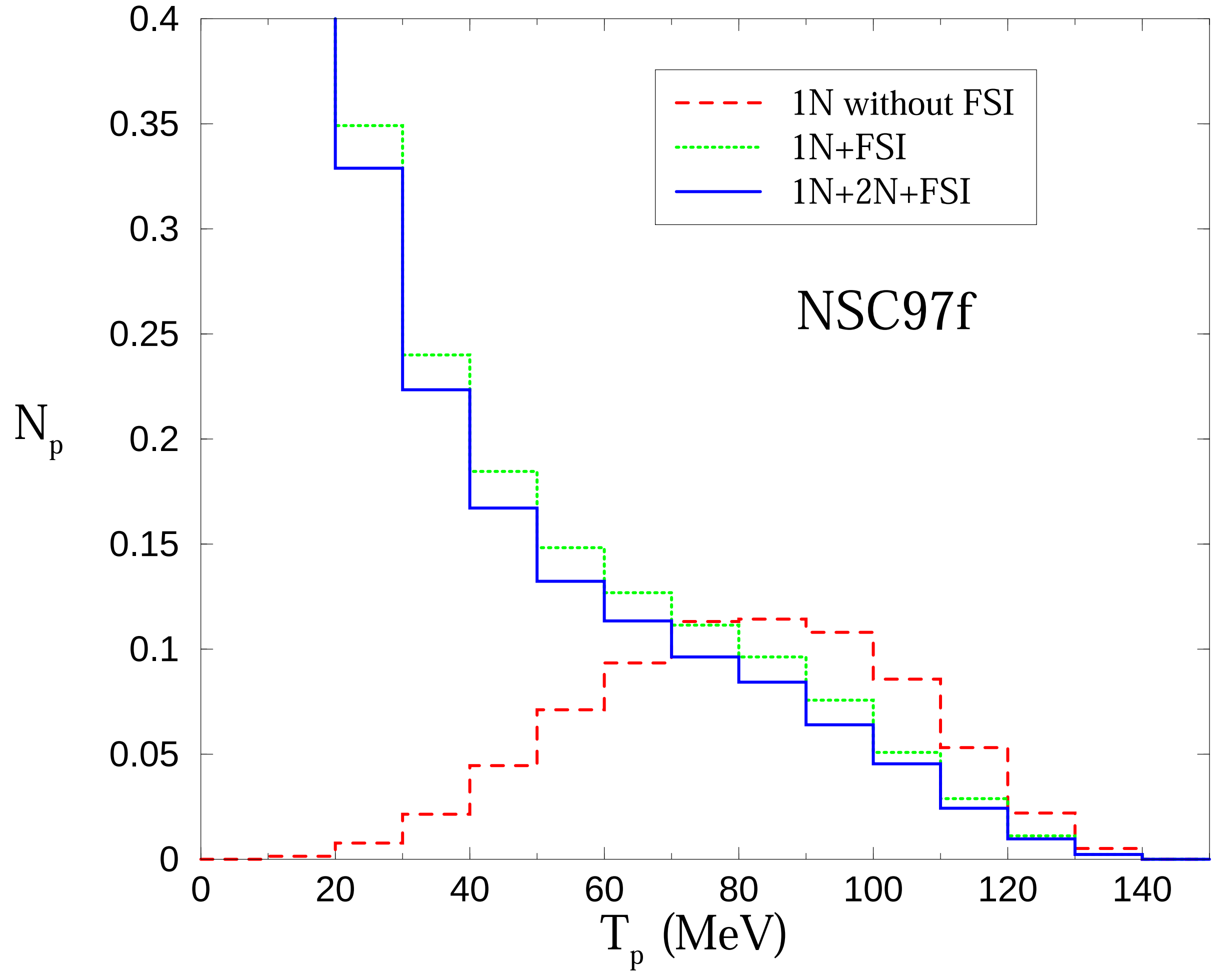


Figure 2: Single–proton kinetic energy spectra per NMWD of ${}^{12}_{\Lambda}C$.

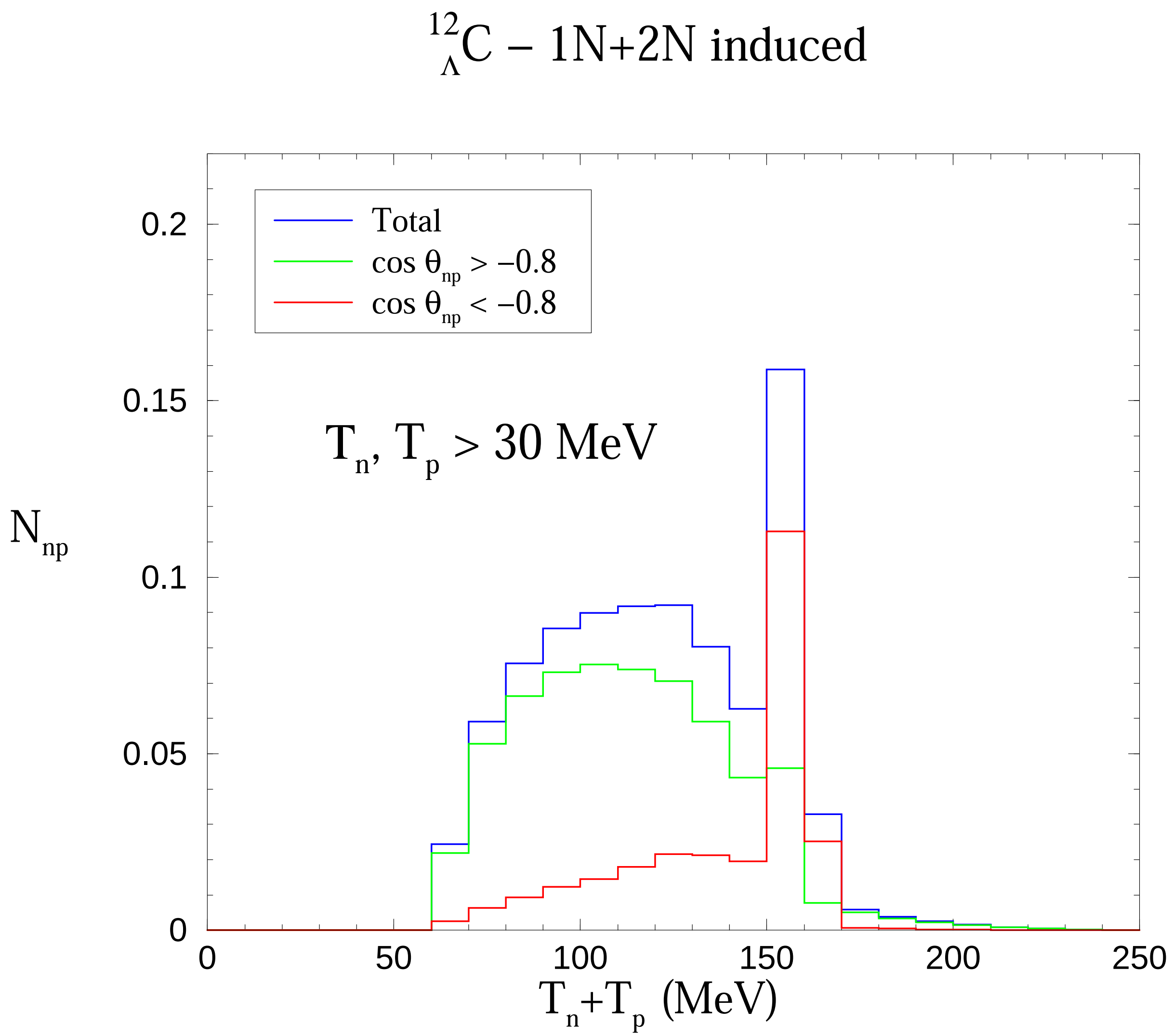


Figure 3: Kinetic energy correlations of np pairs emitted per NMWD of $^{12}_{\Lambda}\mathrm{C}$

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University of Torino

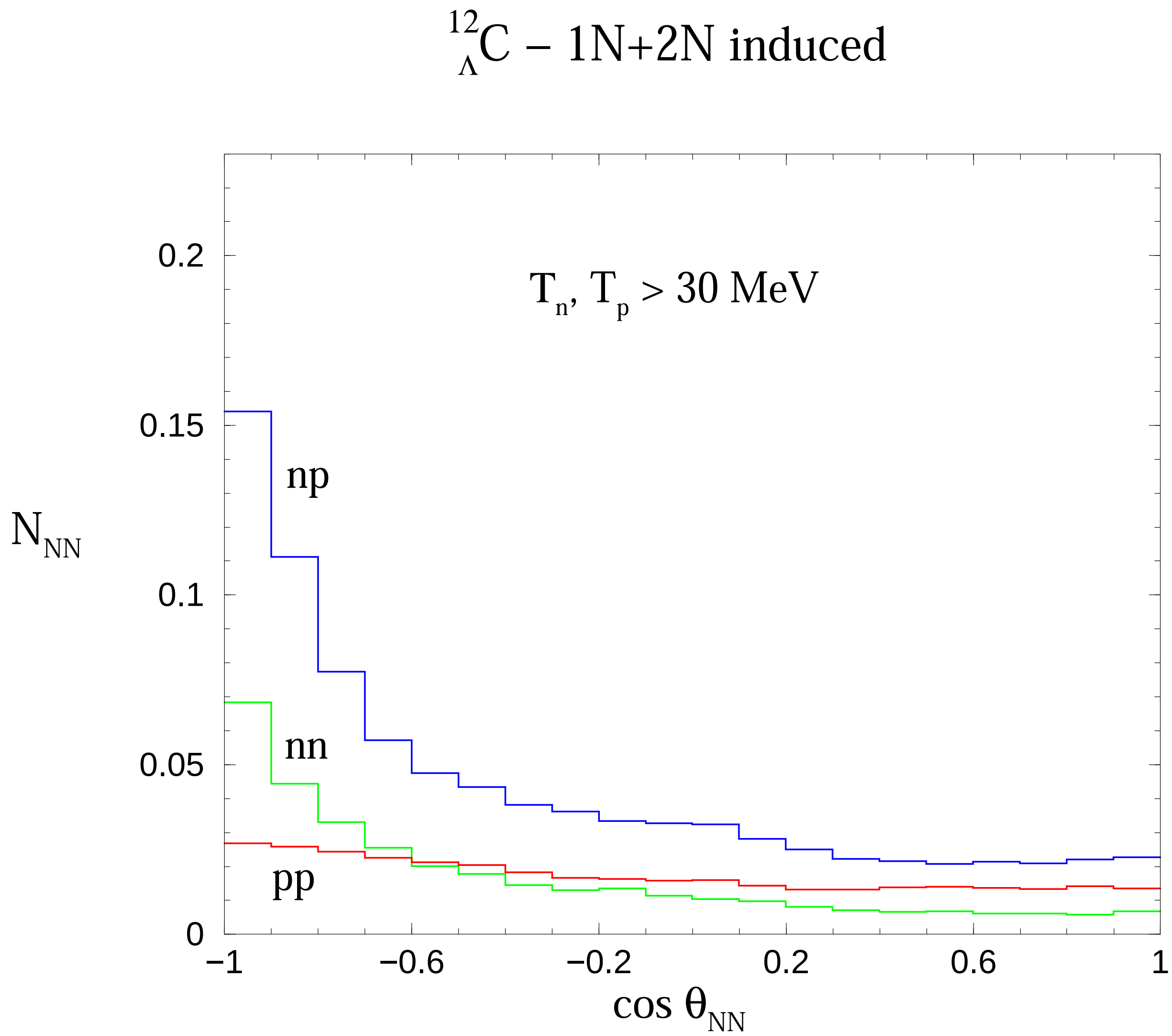


Figure 4: Angular distribution of *nn*, *np* and *pp* pairs emitted per NMWD of $^{12}_{\Lambda}C$

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:

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

Table 8: 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}	${}^5_\Lambda$He Γ_n/Γ_p	${}^{12}_\Lambda$C N_{nn}/N_{np}	${}^{12}_\Lambda$C 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:

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

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

  which define the six weak–decay–model independent quantities: N_{nn}^{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:

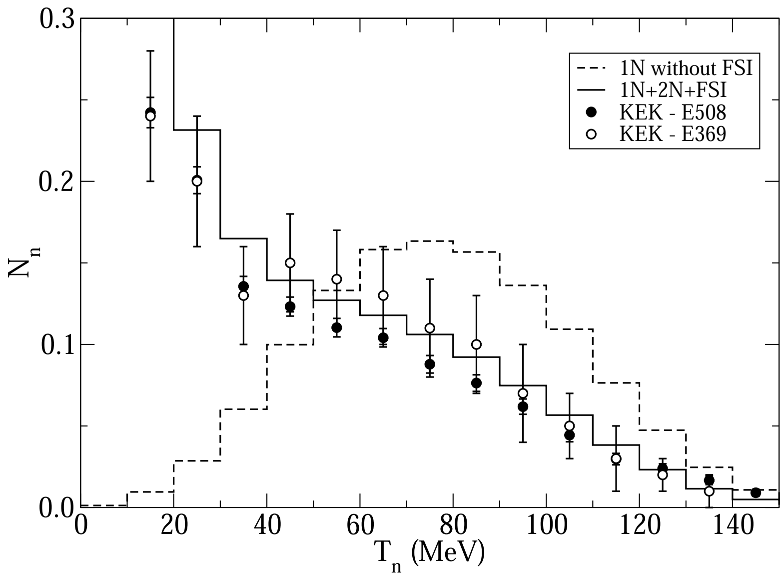
$$\frac{\Gamma_n}{\Gamma_p} = \frac{N_{nn}^{\mathrm{1Bp}} + N_{nn}^{\mathrm{2B}}\frac{\Gamma_2}{\Gamma_1} - \left(N_{np}^{\mathrm{1Bp}} + N_{np}^{\mathrm{2B}}\frac{\Gamma_2}{\Gamma_1}\right)\frac{N_{nn}}{N_{np}}}{\left(N_{np}^{\mathrm{1Bn}} + N_{np}^{\mathrm{2B}}\frac{\Gamma_2}{\Gamma_1}\right)\frac{N_{nn}}{N_{np}}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

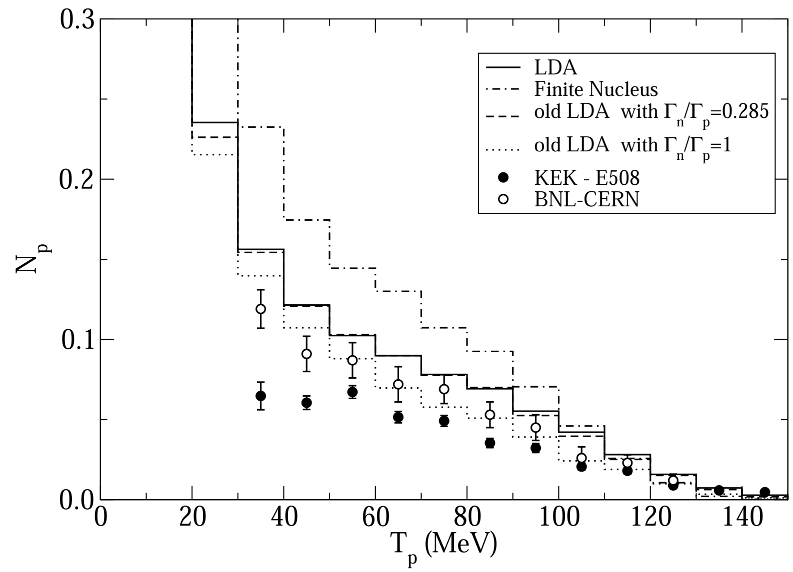
- From KEK data we obtained:

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

Exp–Th disagreement on Proton Spectra

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





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

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

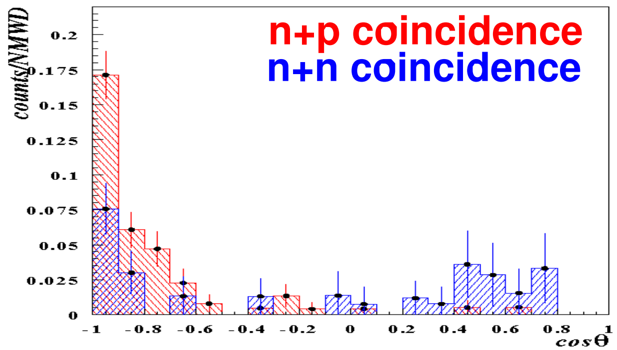
- FINUDA: Proton Spectra for $^{5}_{\Lambda}He$ to $^{16}_{\Lambda}O$:
  peaking structure at $\simeq$ 80 MeV

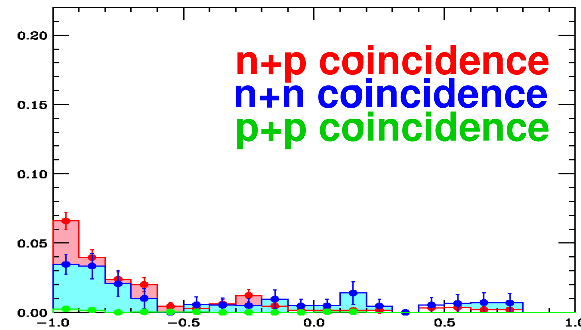
  [M. Agnello et al., NPA 804, 151 (2008)]

Comparison with theoretical calc. for angular correlation

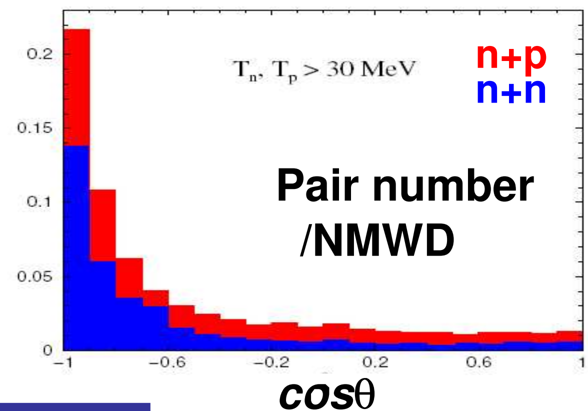
$^{5}_{\Lambda}$He (E462) | $^{12}_{\Lambda}$C (E508)

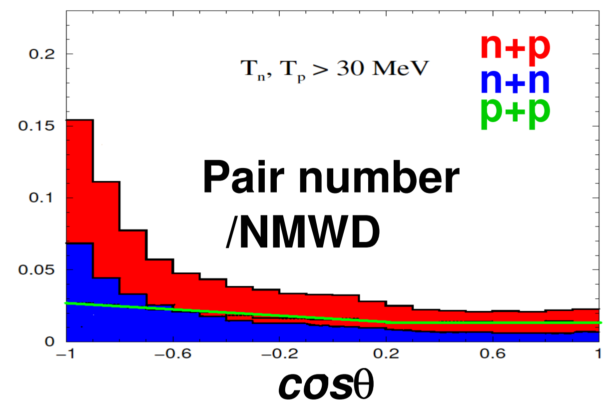
experimental data





theoretical calc.





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

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Asymmetry: OME + Nucleon FSI

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

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

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

	${}^{5}_{\Lambda}\mathrm{He}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$
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 $a_\Lambda({}^{5}_{\Lambda}{\rm He})$

  – 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 + σ, OME$= \pi + \rho + K + K^* + \eta + \omega$

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

  – Unknown σ couplings fixed to reproduce measured $\Gamma_{\rm NM}({}^{5}_{\Lambda}{\rm He})$ and $\Gamma_n/\Gamma_p({}^{5}_{\Lambda}{\rm He})$

  – Improved overall agreement with experiment for ${}^{12}_{\Lambda}$C and ${}^{5}_{\Lambda}$He but data for $a_\Lambda({}^{5}_{\Lambda}{\rm He})$ could not be reproduced

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

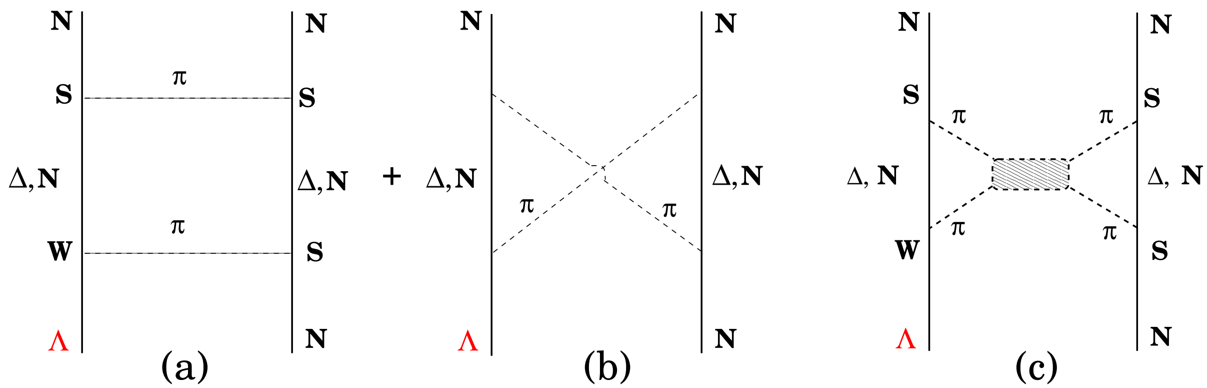
One–Meson–Exchange + Two–Pion–Exchange

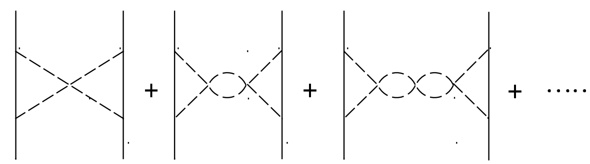
[C. Chumillas, G. G, A. Parreño and A. Ramos, PLB 657, 180 (2007)]

- 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	$\Gamma_{NM}=\Gamma_n+\Gamma_p$	${}^5_\Lambda$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	$\Gamma_{NM}=\Gamma_n+\Gamma_p$	${}^{12}_{\Lambda}$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!

G. Garbarino
University of Torino

${}^5_\Lambda$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
$F:\ {}^3S_1 \rightarrow {}^3P_1$	$+0.2234$	$+0.2234$			
$\Gamma_p = \sum_{\alpha=A\ldots F} \lvert\alpha\rvert^2$	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

G. Garbarino
University of Torino

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?

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

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

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

  $a_\Lambda({}^{5}_{\Lambda}{\rm He}) \sim 0 \div 0.2 \quad a_\Lambda({}^{12}_{\Lambda}{\rm C}) \sim -0.1 \div +0.3$ (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)

G. Garbarino
University of Torino