WEAK DECAY OF HYPERNUCLEI

Àngels Ramos

University of Barcelona

XXIInd Indian-Summer School and SPHERE School on Strangeness Nuclear Physics
September 7-11, 2010, Rez/Prague, Czech Republic

Outline:

1. INTRODUCTORY REMARKS

   What is a hypernucleus?

   How are they produced?

   What can be learned?

2. WEAK DECAY OF HYPERNUCLEI:

   2.1. Mesonic Weak Decay → lecture I

   2.2. Non-Mesonic Weak Decay → lecture II

3. FINAL REMARKS

Some useful references

HYPERNUCLEAR STRUCTURE

T. Motoba and J. Zofka, Int. J. Mod. Phys. A5 (1990) 4021

H. Bando, T. Motoba, Y. Yamamoto, Prog. Theor. Phys. Suppl. No 81 (1981)

R.H. Dalitz and A. Gal, Ann. Phys. (NY) 116 (1978) 167

C. B. Dover and E. Walker, Phys. Reports 89 (1982) 1

C. B. Dover and A. Gal, Prog. Part. Nucl. Phys. 12 (1984) 171

E. Oset, P. Fernández de Córdoba, L.L. Salcedo, R. Brockmann, Phys. Reports 188 (1990) 79

O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564

D.J. Millener, Lecture Notes in Physics 724 (2007) 31

HYPERNUCLEAR DECAY

B.F. Gibson and E.V. Hungerford III, Phys. Reports 257 (1995) 349

E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41 (1998) 191

W.M. Alberico and G. Garbarino, Phys. Reports 369 (2002) 1

A. Parreño, Lecture Notes in Physics 724 (2007) 141

CONVENTIONAL NUCLEAR PHYSICS

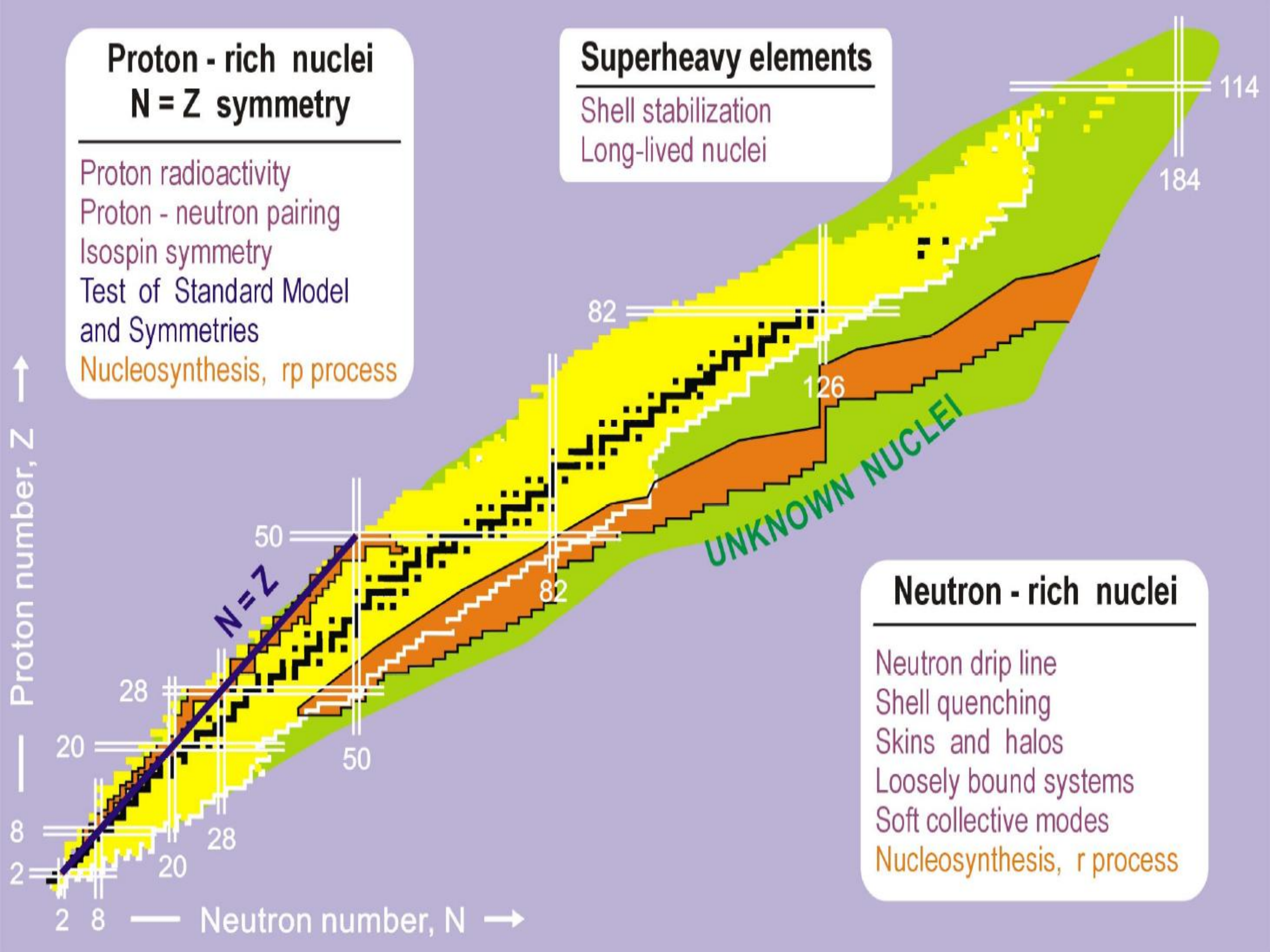
Nuclear Physics aims at the understanding of the structure, dynamics and overall properties of nuclei and nuclear reactions.

Degrees of freedom: baryons (n,p,Δ,…) and mesons (π,ρ,…) made of u,d quarks and antiquarks

Over 60 years much research has been devoted to test and establish the validity of nuclear models (shell-model, liquid drop, pairing …) in explaining a vast variety of nuclear phenomena

In spite of the impressive progress it is still a very active field….

GSI,COSY,MAMI (Germany), ISOLDE-CERN, CRC (Belgium), KVI (The Netherkands), GANIL (France), JYFL (Finland), Dubna (Russia), LNL,Gran Sasso,LNS,LNF (Italy), MSU,ANL,Oak Ridge (USA), RIKEN (Japan), …



Proton - rich nuclei
N = Z symmetry
Proton radioactivity
Proton - neutron pairing
Isospin symmetry
Test of Standard Model
and Symmetries
Nucleosynthesis, rp process
Superheavy elements
Shell stabilization
Long-lived nuclei
Neutron - rich nuclei
Neutron drip line
Shell quenching
Skins and halos
Loosely bound systems
Soft collective modes
Nucleosynthesis, r process
UNKNOWN NUCLEI
N = Z
Proton number, Z
Neutron number, N
2
8
20
28
50
82
114
126
184

STRANGENESS NUCLEAR PHYSICS

Studies nuclear phenomena involving one or more strange particles (containing the s quark or antiquark)

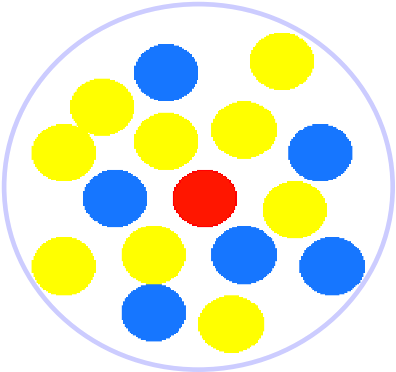
Baryon (Hyperon)	quarks	Isospin	Mass (MeV)
Λ	$u\ d\ s$	0	1115
Σ^+	$u\ u\ s$	1	1189
Σ^0	$u\ d\ s$	1	1193
Σ^-	$d\ d\ s$	1	1197
Ξ^0	$u\ s\ s$	1/2	1315
Ξ^-	$d\ s\ s$	1/2	1321

Meson	quarks	Isospin	Mass (MeV)
$\bar{K}^0$	$\bar{d}\ s$	1/2	498
K^-	$\bar{u}\ s$	1/2	494
K^+	$u\ \bar{s}$	1/2	494
K^0	$d\ \bar{s}$	1/2	498

HYPERNUCLEAR PHYSICS

Hypernuclei are bound systems of conventional baryons (protons, neutrons) plus one or more strange baryons (hyperons → Y)

$^{A}_{Y}Z$



✓ New spectroscopy involving a strange baryon
(hyperon beams are unstable)

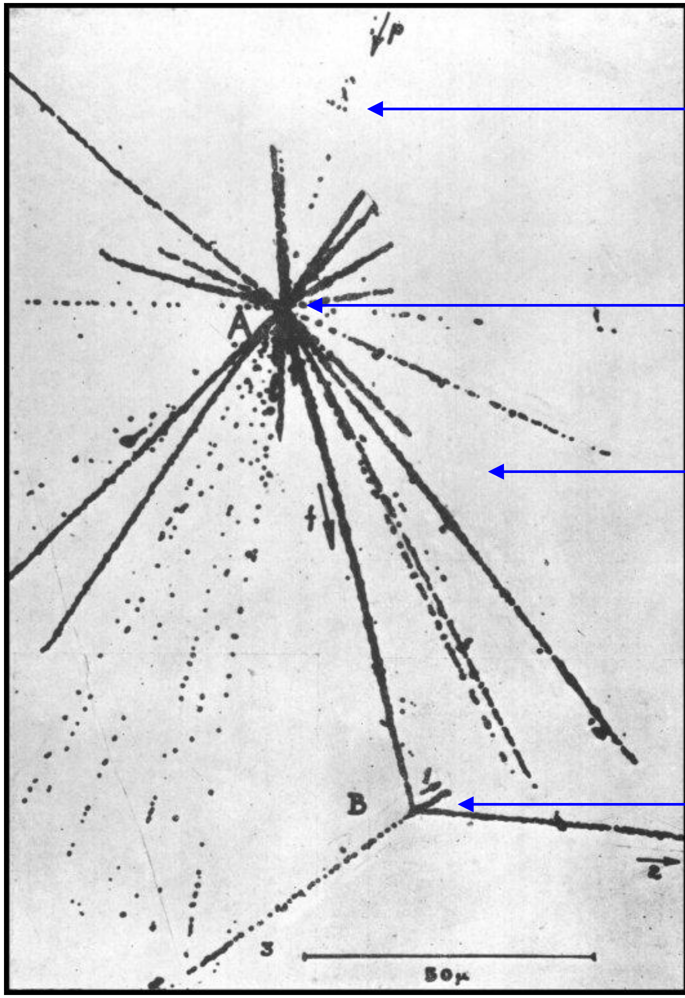
→ Learn about the *strong* YN (and YY) interactions

Is SU(3) enough to understand the new phenomenology?

✓ Unique source of information for studying the *weak* YN → NN interaction

First hyperuclear event observed in a nuclear emulsion

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348



Incoming high energy cosmic ray

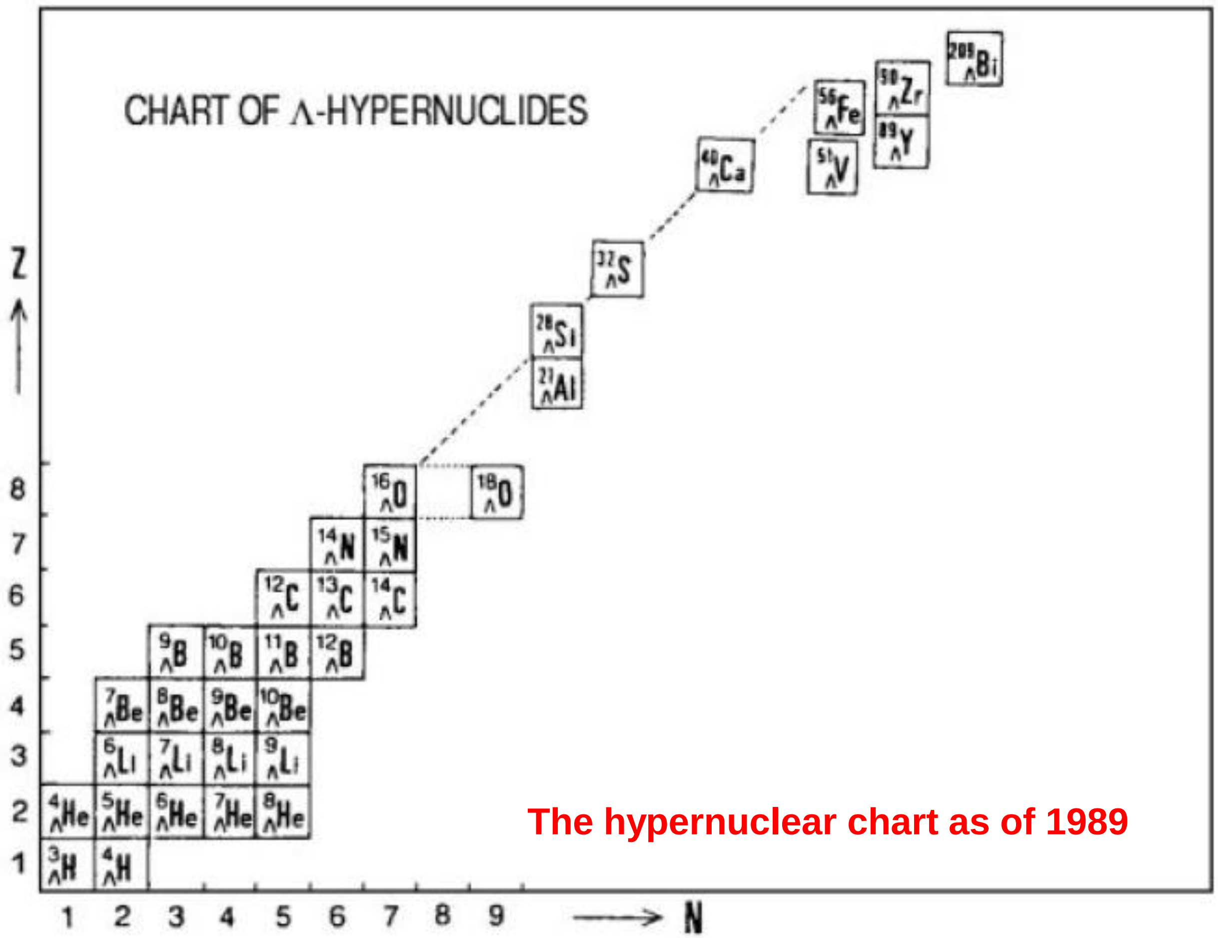
Collision with the nucleus

A “star” of nuclear fragments that eventuallly stop in the emulsion

One fragment disintegrates:
A hyperon (which decays weakly) is inside the fragment:→ hyperfragment or hypernucleus

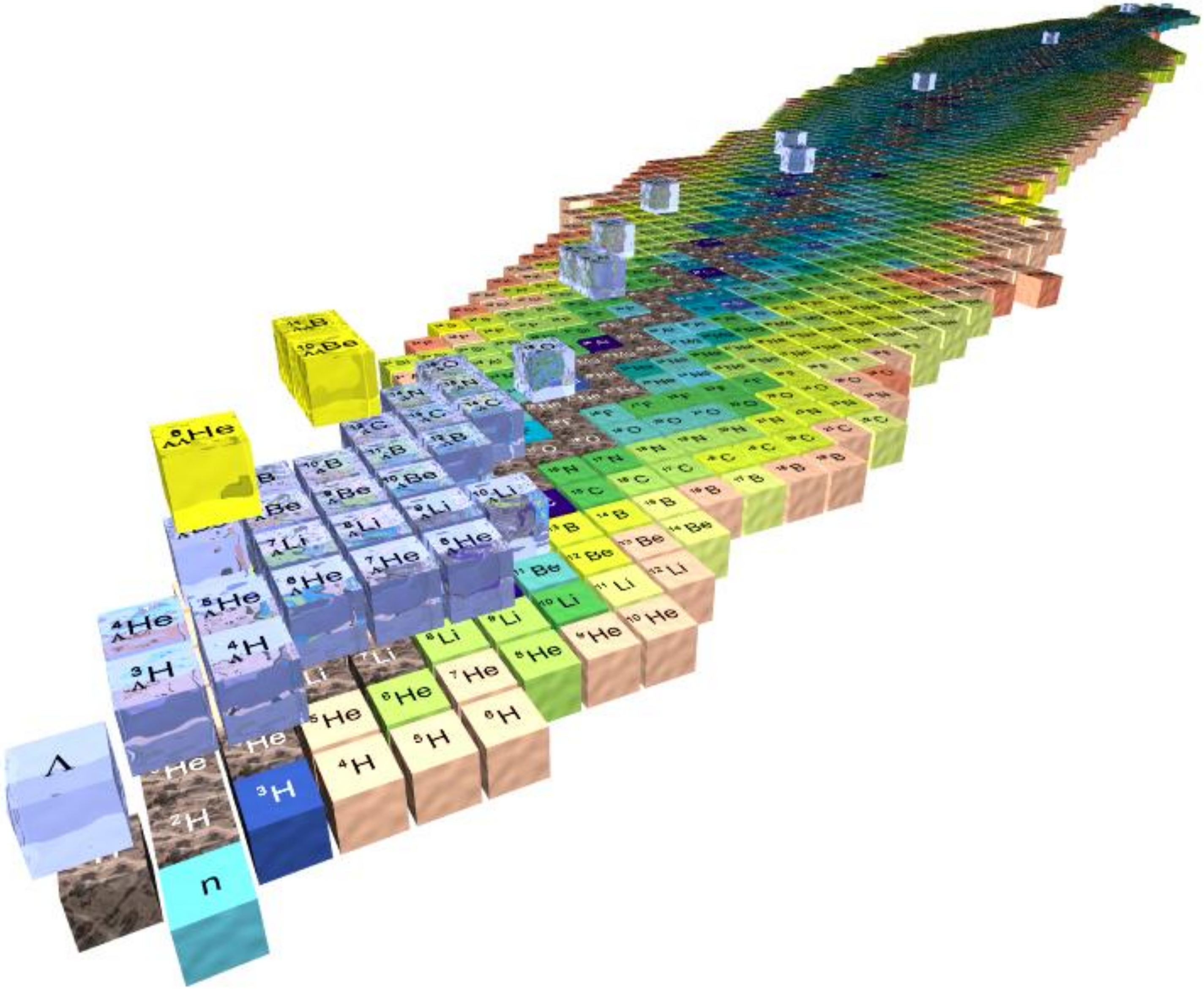
In late 50’s: emulsions were exposed to K-beams and many hypernuclei were produced

Known Λ hypernuclei



15 years later: basically the same hypernuclei … but measured with better statistics and energy resolution
→ excited hypernuclear states are now available!

The 3D nuclear chart



HYP06 conference poster

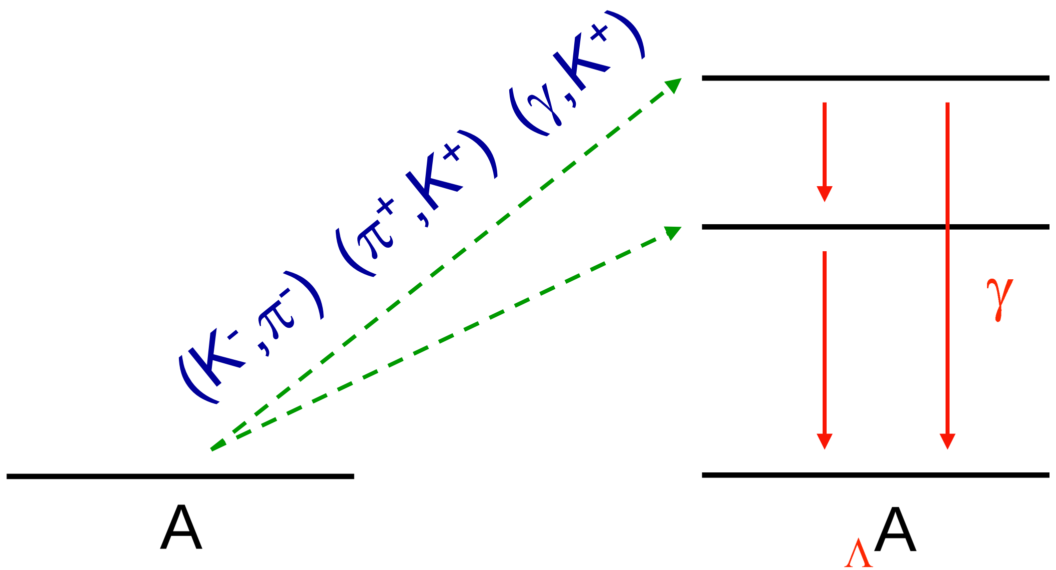
PRODUCTION OF HYPERNUCLEI
(collider era)

Strangeness exchange: $n(K^-, \pi^-)\Lambda$ CERN, BNL, KEK, DAPHNE

$p(K^-, \pi^\pm)\Sigma^\mp$

Associated production: $n(\pi^+, K^+)\Lambda$ BNL, KEK

Electroproduction: $p(e, e'K^+)\Lambda$ Jlab, MAMI

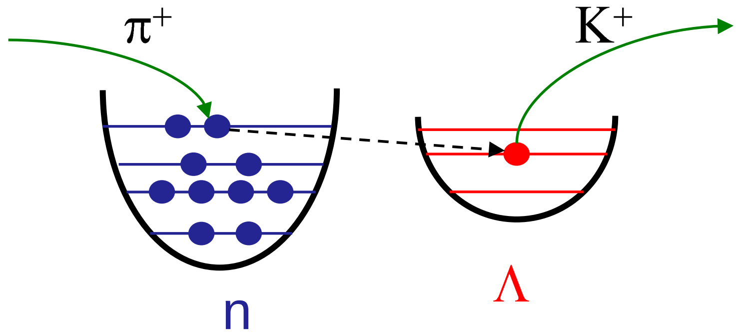


Also:

heavy-ion collisions,
delayed fission, etc..

GSI, Dubna,…

$$\pi^+ + {}^{56}Fe \rightarrow K^+ + {}^{56}_{\Lambda}Fe$$



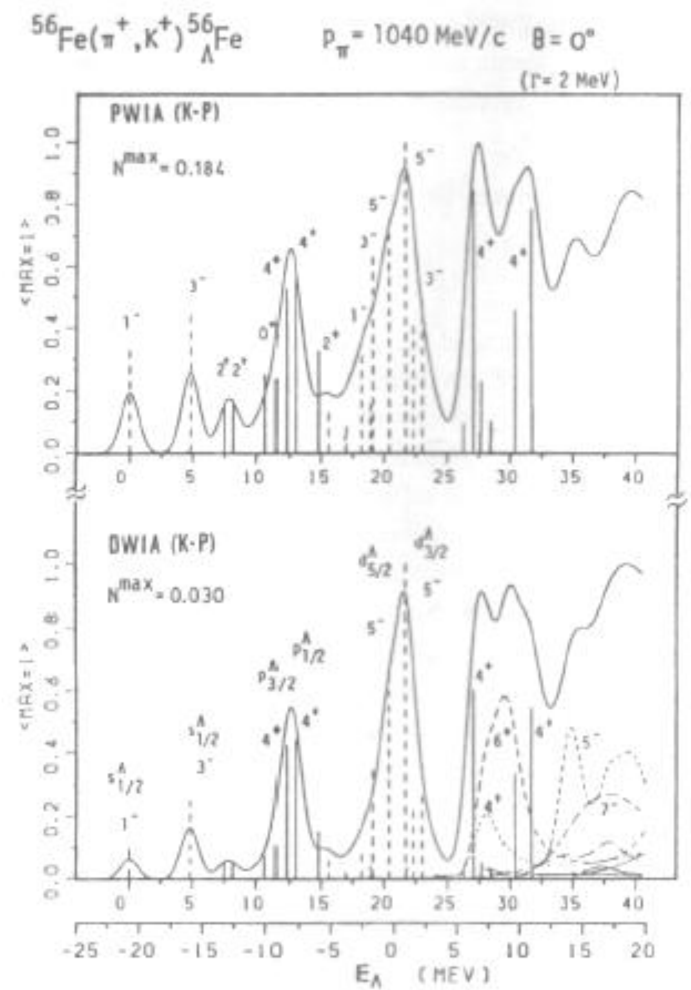
$$[1f^{-1}_{7/2} \otimes 1l^{\Lambda}_{j}]_{J^P}$$

$$E_{\pi^+} + M_A = E_{K^+} + M_{Hy} + \frac{P^2_{Hy}}{2M_{Hy}}$$

$$M_A = M_{A-1} + m_n - B_n$$

$$M_{Hy} = M_{A-1} + m_{\Lambda} - B_{\Lambda}$$

$$E_{K^+} = E_{\pi^+} + m_n - m_{\Lambda} - B_n + B_{\Lambda} - \frac{P^2_{Hy}}{2M_{Hy}}$$

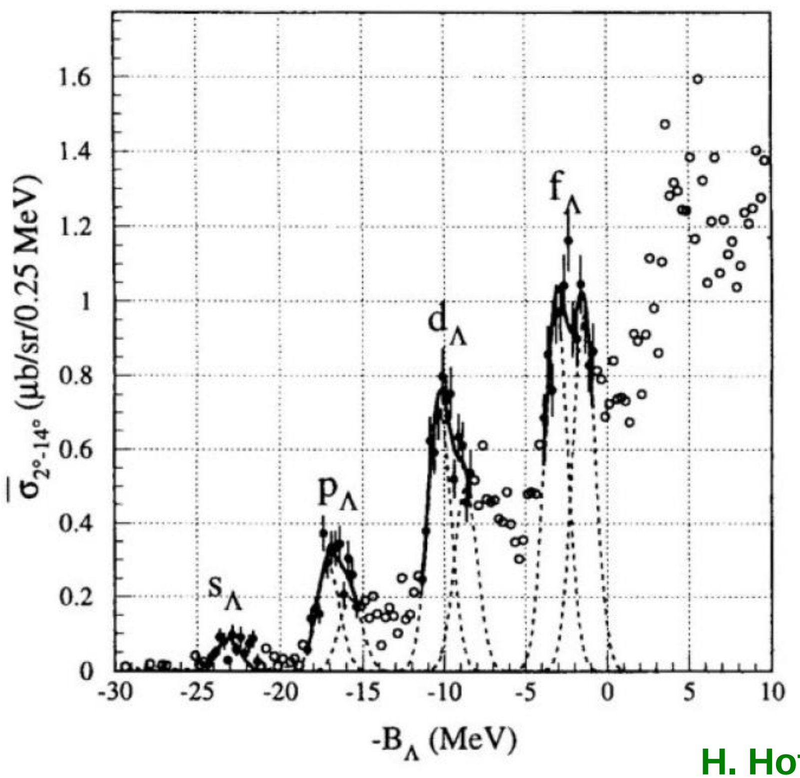


T. Motoba et al, Phys. Rev. C38 (1988) 1322

Fixing the indicent beam energy and the detection angle, the energy of the emitted meson (K^+) is directly related to the Λ binding energy

An example

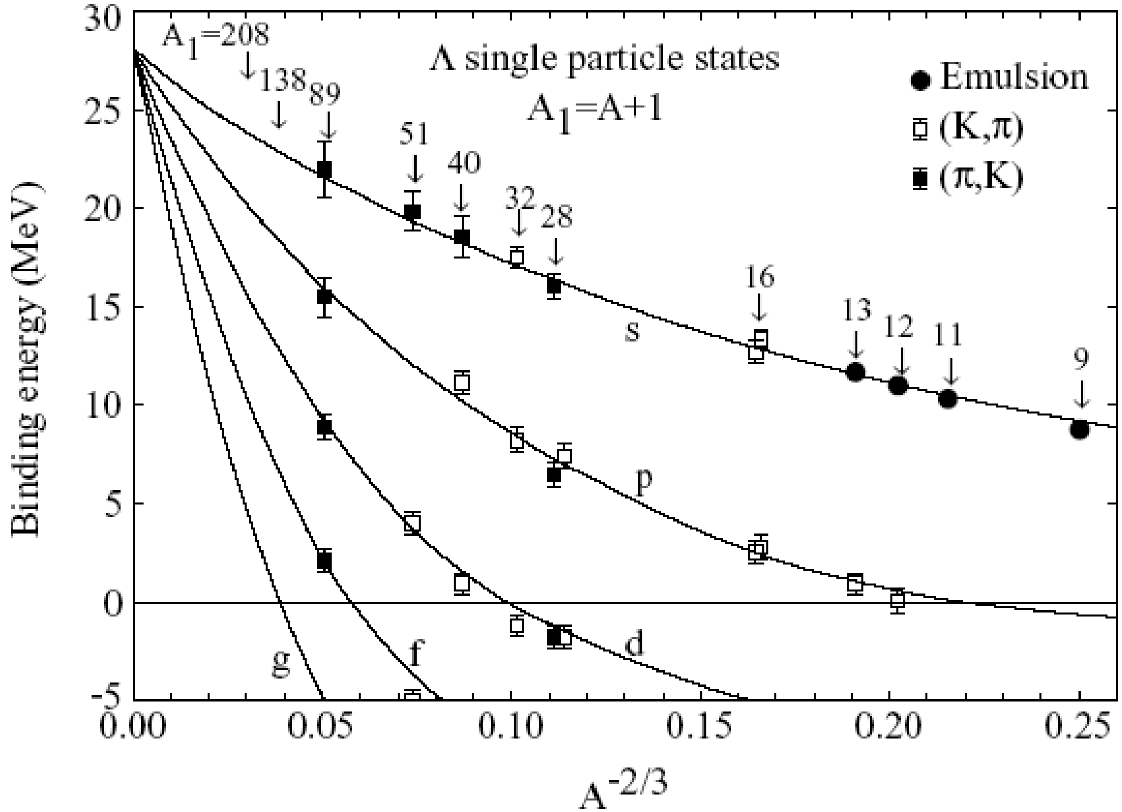
Spectrum of ${}^{89}_{\Lambda}$Y (KEK E369)



H. Hotchi et al., PRC64 (2001) 044302

The (π^+,K^+) reaction selectively populates configurations with a loosely bound neutron hole and a Λ-hyperon in a series of orbits, including the deepest one.

Binding energies of s.p. Λ states

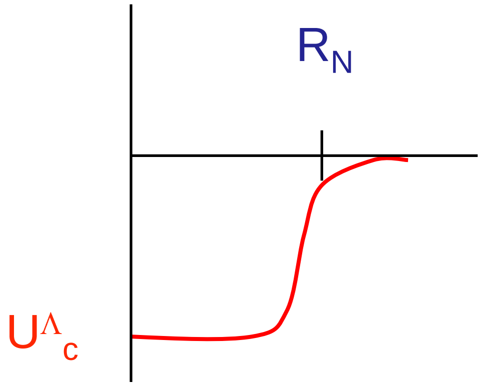


Converges to B_{Λ}=28 MeV

Linear behavior with $A^{-2/3}$ at large A

HYPERNUCLEAR STRUCTURE

These data reflect the single particle behaviour of the Λ in the nucleus



$$U(r) = U_c^{\Lambda} f(r) + U_{s.o.}^{\Lambda} \vec{l} \cdot \vec{s} \frac{1}{r} \frac{df(r)}{dr}$$

$$\left(f(r) = \frac{1}{1 + e^{\frac{r-R}{a}}} \right)$$

The B_Λ data is well fitted with

U^{Λ}_{c}= - 28 MeV $\quad$ (U^{N}_{c}=-55 MeV)

$R = 1.1 A^{1/3} \mathrm{fm}$

$a = 0.6 \ \mathrm{fm}$

See e.g. D.J. Millener, C.B. Dover and A. Gal, Phys. Rev. C38 (1988) 2700

Spin-orbit potential

$b' : \quad [p_{3/2}^{-1}\, s_{1/2}^{\Lambda}]_{J=1}$

$d : \quad [p_{1/2}^{-1}\, s_{1/2}^{\Lambda}]_{J=1}$

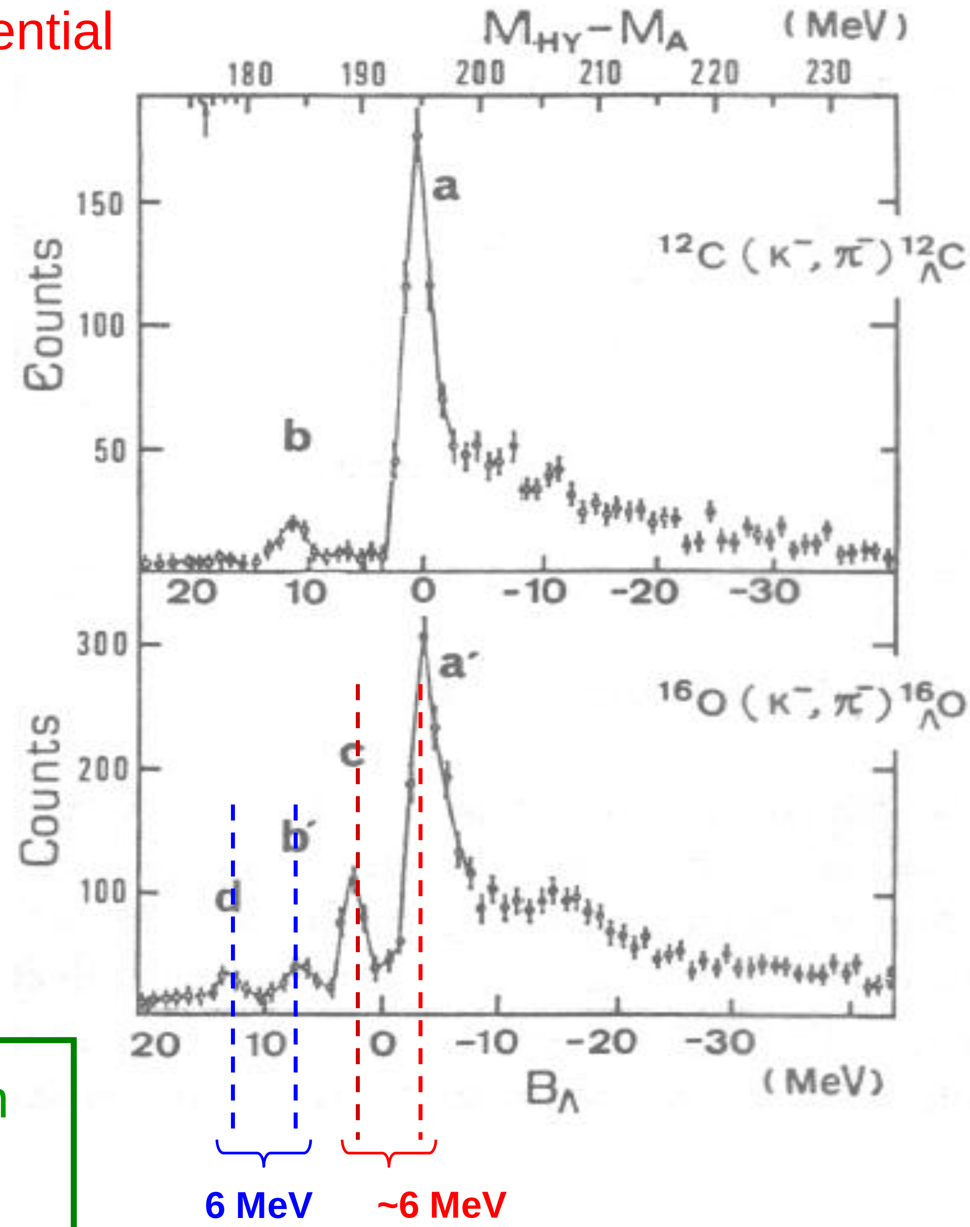
→ neutron spin orbit: 6 MeV

$a' : \quad [p_{3/2}^{-1}\, p_{3/2}^{\Lambda}]_{J=0}$

$c : \quad [p_{1/2}^{-1}\, p_{1/2}^{\Lambda}]_{J=0}$

→neutron PLUS Λ hyperon spin orbit: ~ 6 MeV

$$\varepsilon(p_{1/2}^{\Lambda}) - \varepsilon(p_{3/2}^{\Lambda}) < 0.3\ \text{MeV}$$



Spin-orbit potential for the Λ hyperon is very weak!

$U^{\Lambda}_{s.o.}$=4 MeV $\qquad$ ($U^{N}_{s.o}$=30 MeV)

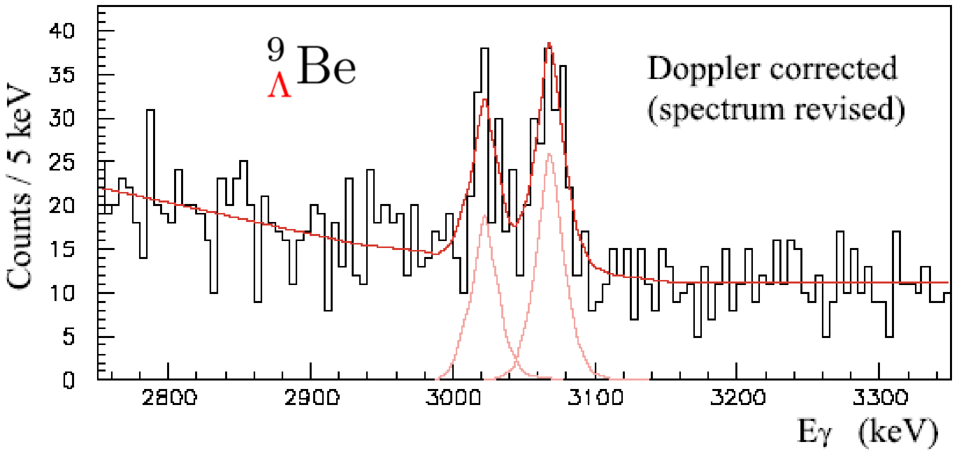
W. Brückner et at, Phys. Lett. 55B(1975)107

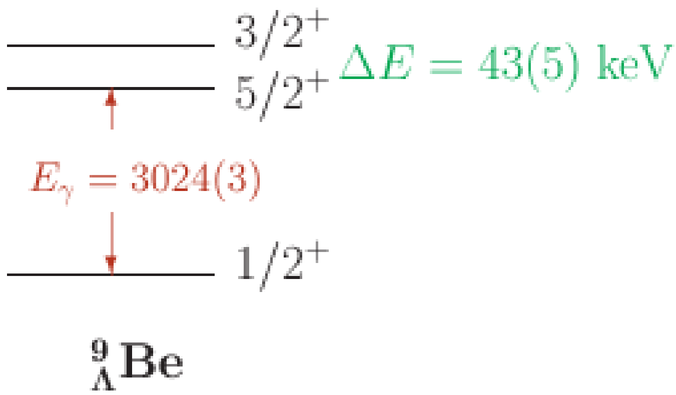
New info from precise γ-ray (coincidence) experiments !

BNL E930

Tamura lectures

H. Akikawa et al, PRL88 (2002) 082501





Nijmegen NSC97f → spin-orbit splitting in $^{9}_{\Lambda}$Be: 150-200 keV

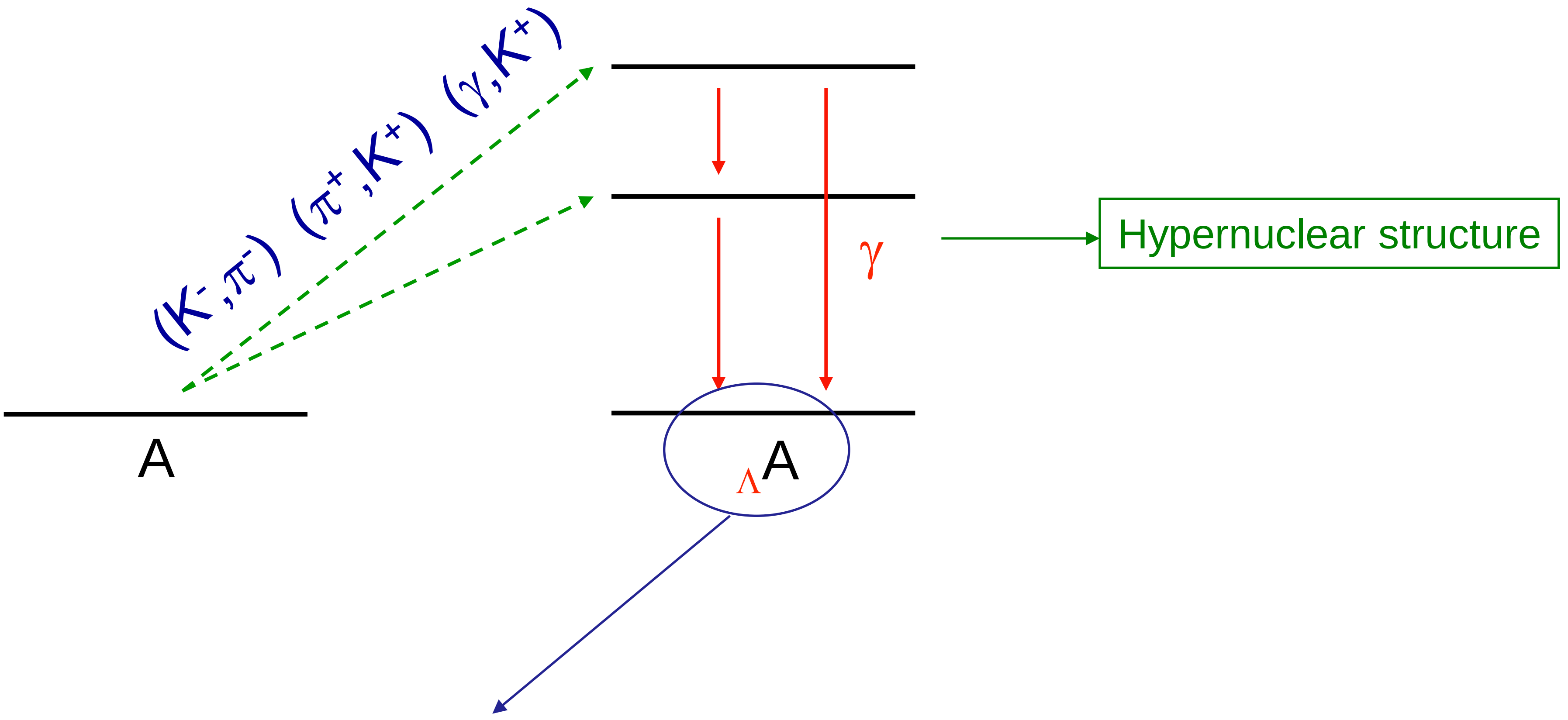
E.Hiyama et al., PRL85 (2000) 270

New! Nijmegen ESC03 → spin-orbit splittings in $^{9}_{\Lambda}$Be: ~ 80 keV

The new generation of experiments performed in the last 5 years have disclosed many interesting aspects of hypernuclear structure

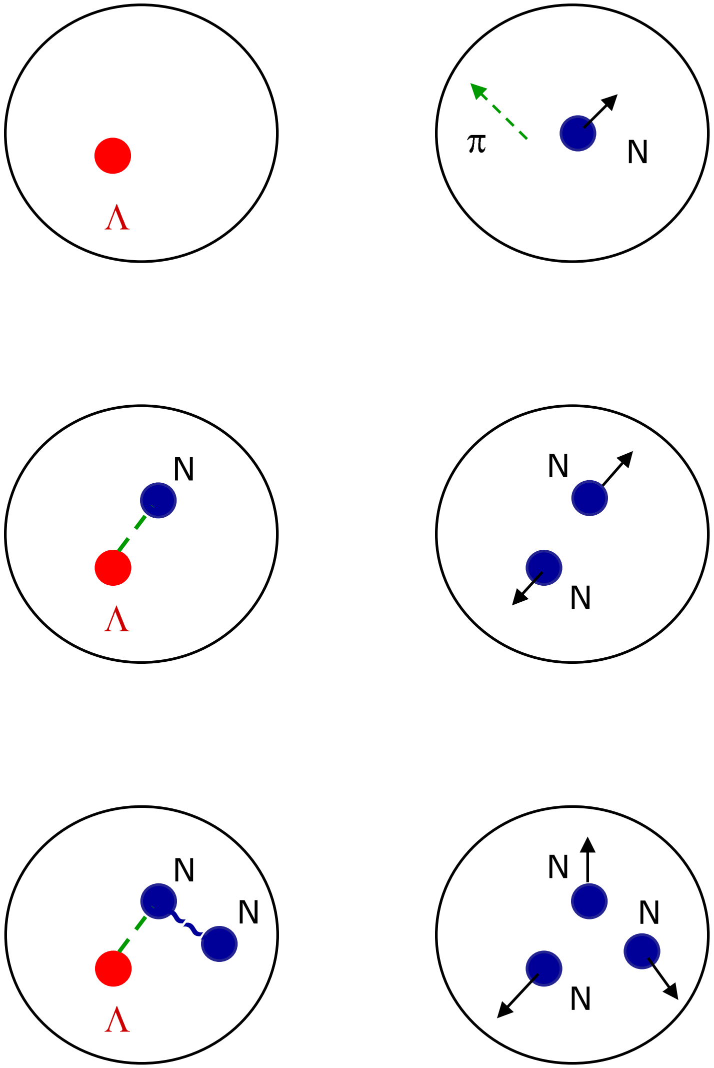
→ crucial information for constraining the YN interaction!

WEAK HYPERNUCLEAR DECAY



Weak decay of hypernuclei allows to obtain new and complementary information on the properties of hypernuclei and the weak YN interaction

WEAK HYPERNUCLEAR DECAY



MESONIC

Γ_{π^-} : $\Lambda \rightarrow \pi^- p$

Γ_{π^0} : $\Lambda \rightarrow \pi^0 n$

k_N~100 MeV/c < k_F

↓

Pauli blocked!

NON-MESONIC

Γ_n: $\Lambda n \rightarrow n n$

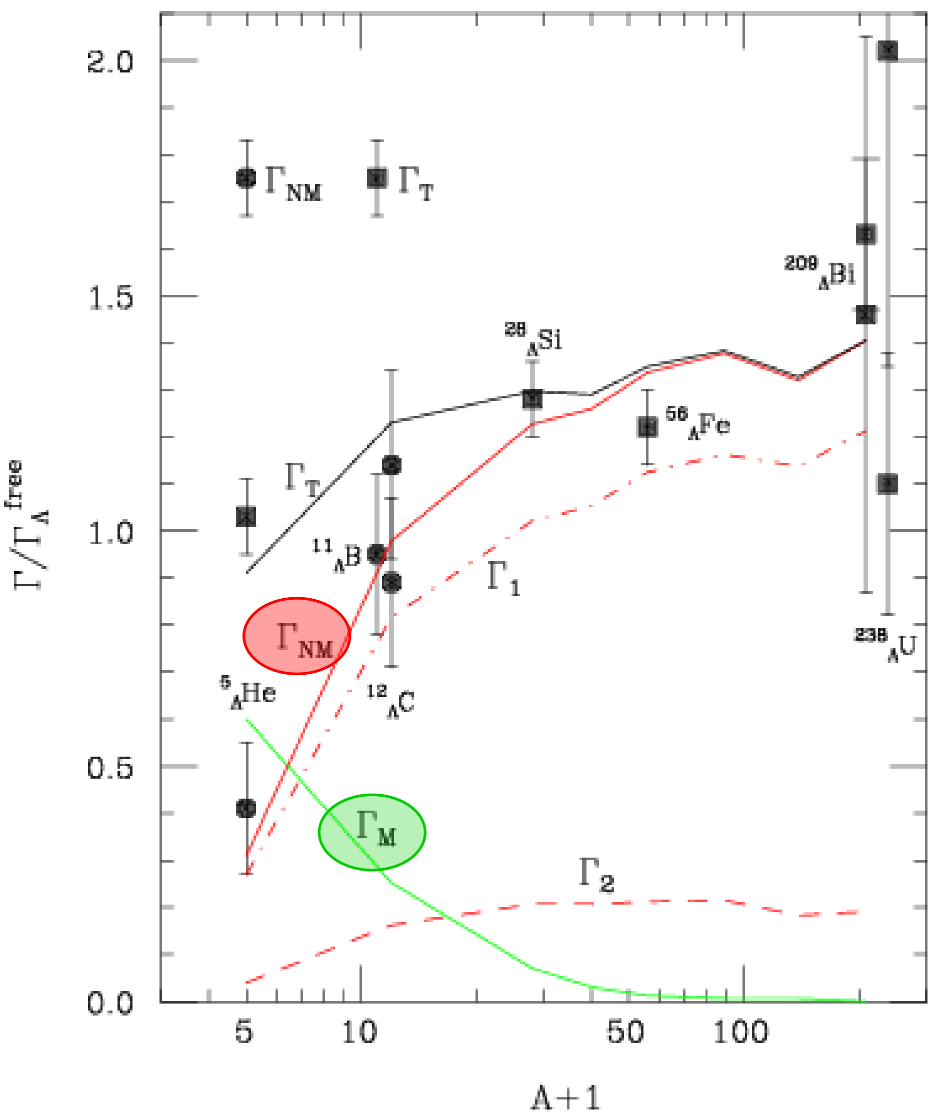
Γ_p: $\Lambda p \rightarrow n p$

k_N~400 MeV/c

Γ_2: $\Lambda N N \rightarrow n N N$ k_N~340 MeV/c

$$\Gamma_T = \Gamma_M + \Gamma_{NM} = \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_n + \Gamma_p + \Gamma_2$$

Observed decay rates



free Λ : $\Gamma_\Lambda^{free} = 3.8\ 10^9\ s^{-1}$

$\Gamma_{\pi-}^{free}$: $\Lambda \rightarrow \pi^- p$

$\Gamma_{\pi 0}^{free}$: $\Lambda \rightarrow \pi^0 n$

$\Gamma_{\pi-}^{free}/\Gamma_{\pi 0}^{free} = 1.78 \sim 2 \rightarrow \Delta I=1/2$!

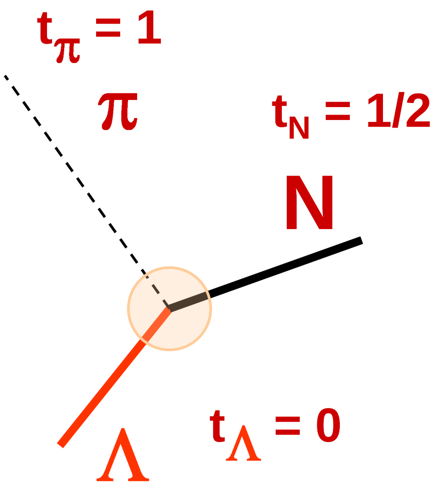
Hypernuclear width: $\Gamma_T \sim \Gamma_\Lambda^{free}$

BNL, 91

KEK, 95, 98

Jülich, 93, 97, 98

ΔI=1/2 rule in free Λ decay



Isospin decomposition

$$\begin{cases} |\pi^- p\rangle = \sqrt{\frac{1}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{2}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle \\ |\pi^0 n\rangle = \sqrt{\frac{2}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle + \sqrt{\frac{1}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle \end{cases}$$

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \approx \frac{|\langle\pi^- p|T_{1/2,-1/2}|\Lambda\rangle|^2}{|\langle\pi^0 n|T_{1/2,-1/2}|\Lambda\rangle|^2} = \left|\frac{\sqrt{2/3}}{\sqrt{1/3}}\right|^2 = 2 \qquad \text{for } \Delta I = 1/2,$$

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \approx \frac{|\langle\pi^- p|T_{3/2,-1/2}|\Lambda\rangle|^2}{|\langle\pi^0 n|T_{3/2,-1/2}|\Lambda\rangle|^2} = \left|\frac{\sqrt{1/3}}{\sqrt{2/3}}\right|^2 = \frac{1}{2} \qquad \text{for } \Delta I = 3/2.$$

$$\text{Experiment} \quad \left\{\frac{\Gamma^{free}_{\Lambda\to\pi^- p}}{\Gamma^{free}_{\Lambda\to\pi^0 n}}\right\}^{Exp} \approx 1.78$$

⇒ ΔI = 1/2 rule

MESONIC DECAY: $\Lambda \rightarrow \pi N$

$Q \sim m_\Lambda - m_N - m_\pi \sim 35$ MeV

$$m_\Lambda = \sqrt{m_N^2 + q^2} + \sqrt{m_\pi^2 + q^2}$$

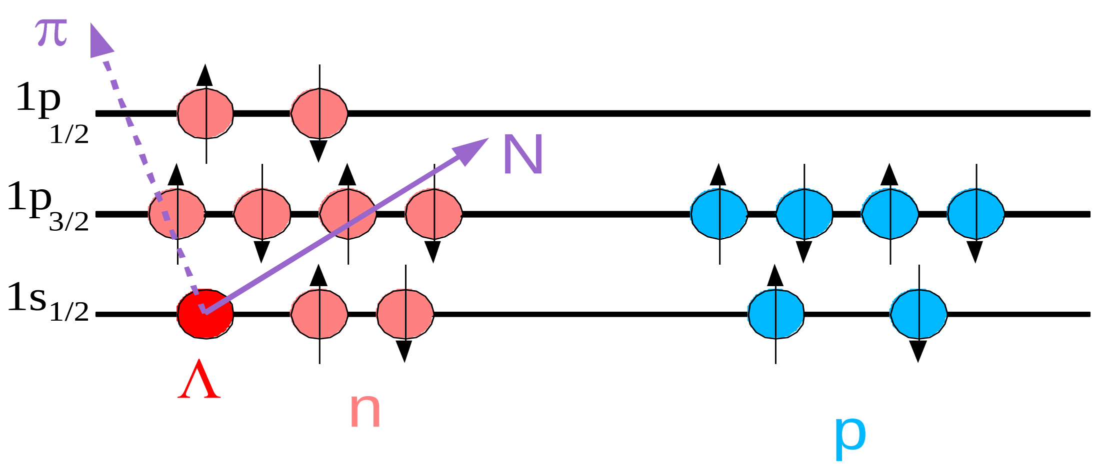
→ $q \sim 100$ MeV/c << p_F=270 MeV/c

strictly forbidden in nuclear matter!

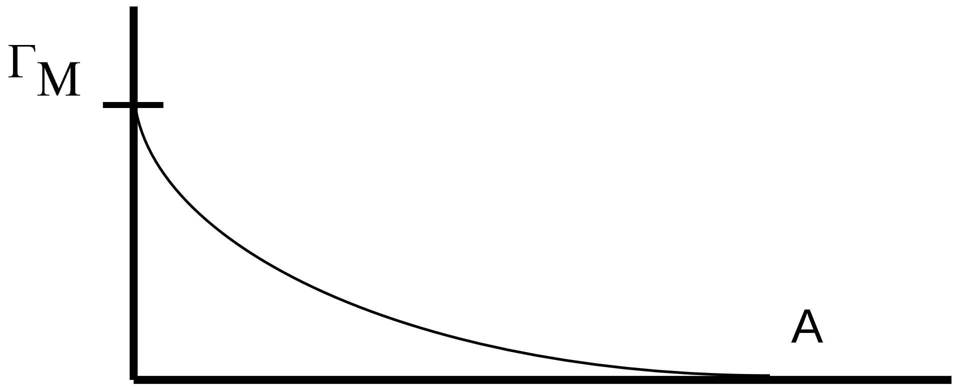
Mesonic Λ decay is supressed in the medium due to:

✓ Bound Λ (smaller initial energy)

✓ Pauli blocking on nucleons (difficult to access unoccupied orbits)



MESONIC DECAY



BUT this drastic reduction is “slowed” by the effect of the attractive pion-nucleus optical potential

$$E_\Lambda = E_N + E_\pi = E_N + \sqrt{m_\pi^2 + q^2} + U_\pi$$

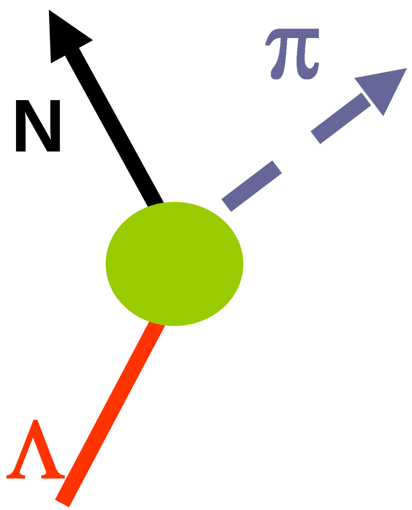
attractive (negative)

“The pion distortion induces high-momentum components in the pion wave-function and, by momentum conservation, the nucleon acquires also higher momenta, hence having more chances to overcome the Fermi momentum”

E. Oset, L.L. Salcedo, Nucl. Phys. A443 (1985) 704

How does one obtain the mesonic decay rate?

Let's first start with the free decay of a Λ:



Lagrangian

$$L^W_{\Lambda\pi N} = -\mathrm{i}\, G m_\pi^2\, \overline{\psi}_N \left(A + B\gamma_5\right) \vec{\tau}\cdot\vec{\phi}_\pi\, \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix} + h.c.$$

$$G m_\pi^2 = 2.21 \times 10^{-7}$$

(weak Fermi constant)

$|\Lambda\rangle = |1/2\ -1/2\rangle$

(isospurion)

→ to enforce $\Delta I=1/2$ rule

$$A = 1.05$$

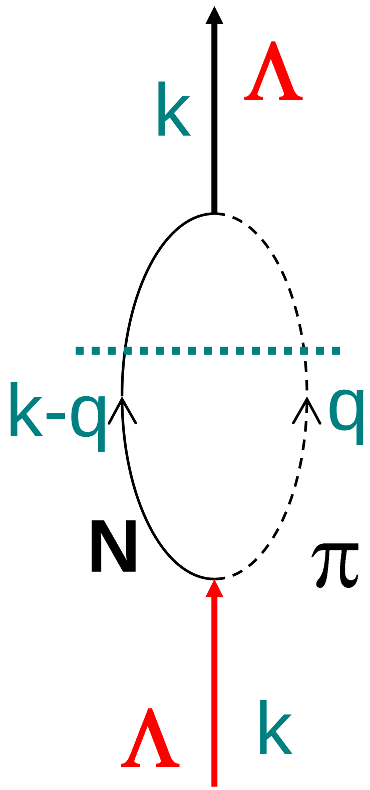
(Parity Violating)

$$B = -7.15$$

(Parity Conserving)

Adjusted to free decay observables

Diagrammatically, one starts computing the Λ self-energy Σ:



$$-\mathrm{i}\,\Sigma(k) = 3\,(G m_\pi^2)^2 \int \frac{d^4 q}{(2\pi)^4}\, G(k-q)\, D(q)\, \left(S^2 + \frac{P^2}{m_\pi^2}\,\vec{q}^{\,2} \right)$$

$$S = A$$

$$P = \frac{m_\pi B}{2 m_N}$$

Free nucleon and pion propagators:

$$G(k) = \frac{1}{k^0 - E(\vec{k}) + \mathrm{i}\varepsilon}$$

$$D(q) = \frac{1}{(q^0)^2 - \vec{q}^{\,2} - m_\pi^{\,2} + \mathrm{i}\varepsilon}$$

Width: $\Gamma_\Lambda^{free} = -2\,\mathrm{Im}\,\Sigma$

→ Free Λ width:

$$\Gamma_\Lambda^{\text{free}} = 3\left(G m_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3\, 2\omega(\vec{q})}$$

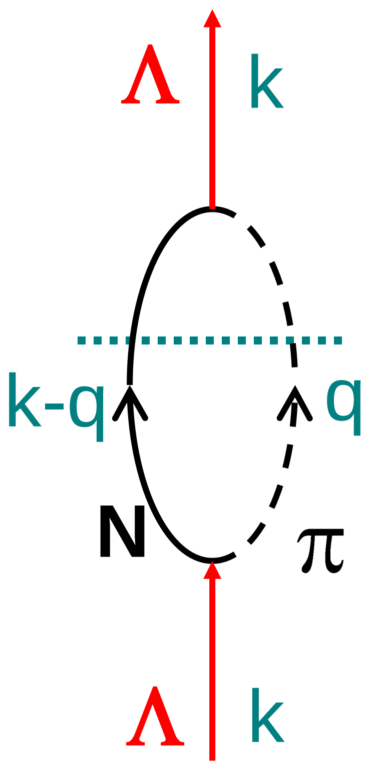
$$\times 2\pi\, \delta\left(E_\Lambda - \omega(\vec{q}) - E_N(\vec{k}-\vec{q})\right)\left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

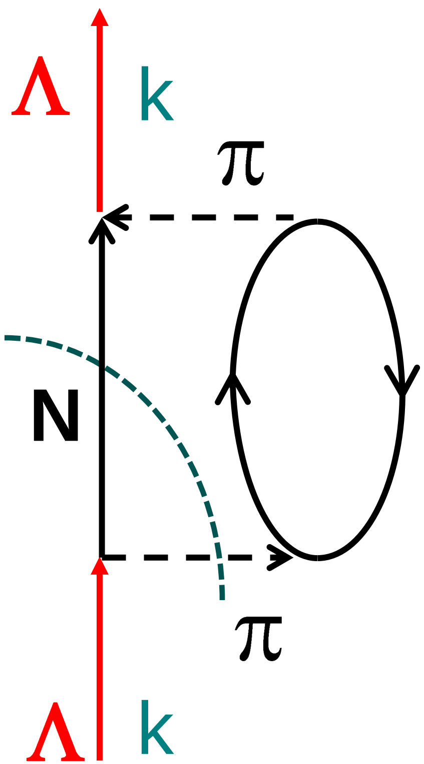
$$\underset{(\vec{k}=0)}{\Gamma_\Lambda^{\text{free}}} = 3\left(G m_\pi^2\right)^2 \frac{1}{2\pi}\frac{m_N q_{c.m.}}{m_\Lambda}\left(S^2 + \frac{P^2}{m_\pi^2} q_{c.m.}^2\right)$$

with $q_{c.m.} \sim 100$ MeV/c

Mesonic decay rate in the medium

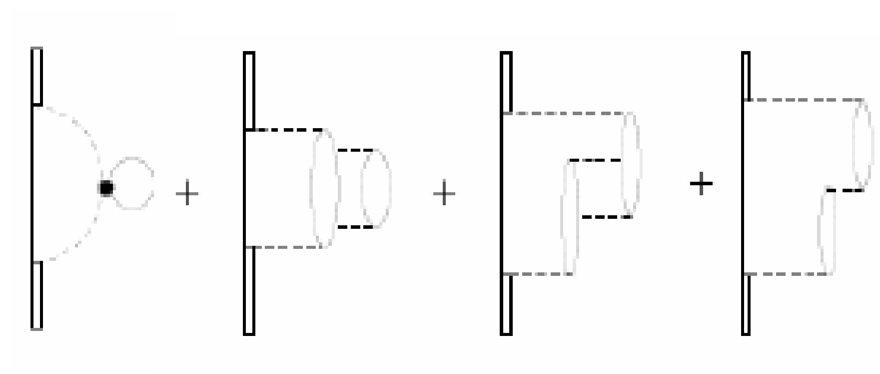
(Simple model: nuclear matter)





The pion can interact with the nucleons of the medium giving rise to a new diagram

+ many others …



→ All these additional contributions are embedded in the pion self-energy!

The mesonic rate is obtained from the mesonic cut!

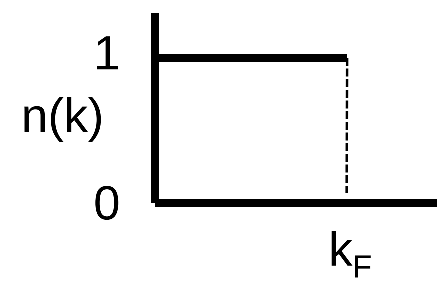
Mesonic decay rate in the medium (nuclear matter)

$$\Sigma_\Lambda(k) = 3\mathrm{i}\,(G m_\pi^2)^2 \int \frac{d^4 q}{(2\pi)^4} \left(S^2 + \frac{P^2}{m_\pi^2} \vec{q}^{\,2} \right) F_\pi^2(q)\, G_N(k-q)\, D_\pi(q)$$

In-medium nucleon and pion propagators:

$$G(p) = \frac{1-n(\vec{p})}{p^0 - E(\vec{p}) - V_N + \mathrm{i}\varepsilon} + \frac{n(\vec{p})}{p^0 - E(\vec{p}) - V_N - \mathrm{i}\varepsilon}$$

Pauli blocking factor



$$D(q) = \frac{1}{(q^0)^2 - \vec{q}^{\,2} - m_\pi^{\,2} + \Pi(q^0, \vec{q})}$$

Pion self-energy

Mesonic decay rate in the medium (nuclear matter)

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

(mesonic cut)

$$\Gamma_\Lambda(k) = -6\left(G m_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3}$$

$$\times \left[1 - n\left(\vec{k}-\vec{q}\right)\right] \theta\left(k^0 - E\left(\vec{k}-\vec{q}\right) - V_N\right) \left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$$\times\,\mathrm{Im} \left.\frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi\left(q^0, q\right)}\right|_{q^0 = k^0 - E\left(\vec{k}-\vec{q}\right) - V_N}$$

Mesonic decay rate in the medium

(finite nucleus model)

Itonaga, Motoba, Bando, 1988
Nieves, Oset, 1993
Motoba, Itonaga, 1994

$$\Gamma_\alpha = c_\alpha \left(G m_\pi^2\right)^2 \sum_{N \notin F} \int \frac{d\vec{q}}{(2\pi)^3 2\omega(\vec{q})} 2\pi\, \delta\left(E_\Lambda - \omega(\vec{q}) - E_N\right)$$

$$\times \left\{ S^2 \left| \int d\vec{r}\, \phi_\Lambda(\vec{r})\, \phi_\pi(\vec{q},\vec{r})\, \phi_N^*(\vec{r}) \right|^2 + \frac{P^2}{m_\pi^2} \left| \int d\vec{r}\, \phi_\Lambda(\vec{r})\, \vec{\nabla} \phi_\pi(\vec{q},\vec{r})\, \phi_N^*(\vec{r}) \right|^2 \right\}$$

$c_\alpha = 1$ for Γ_{π^0}

$c_\alpha = 2$ for Γ_{π^-}

$\Delta I = 1/2$ rule

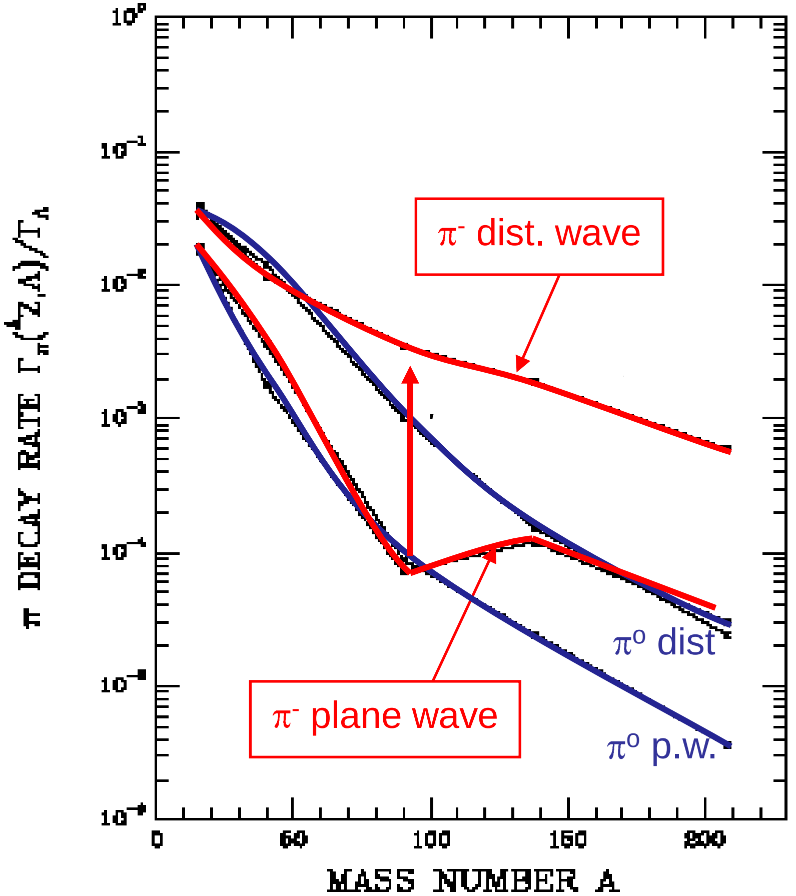
Distorted pion wave-function

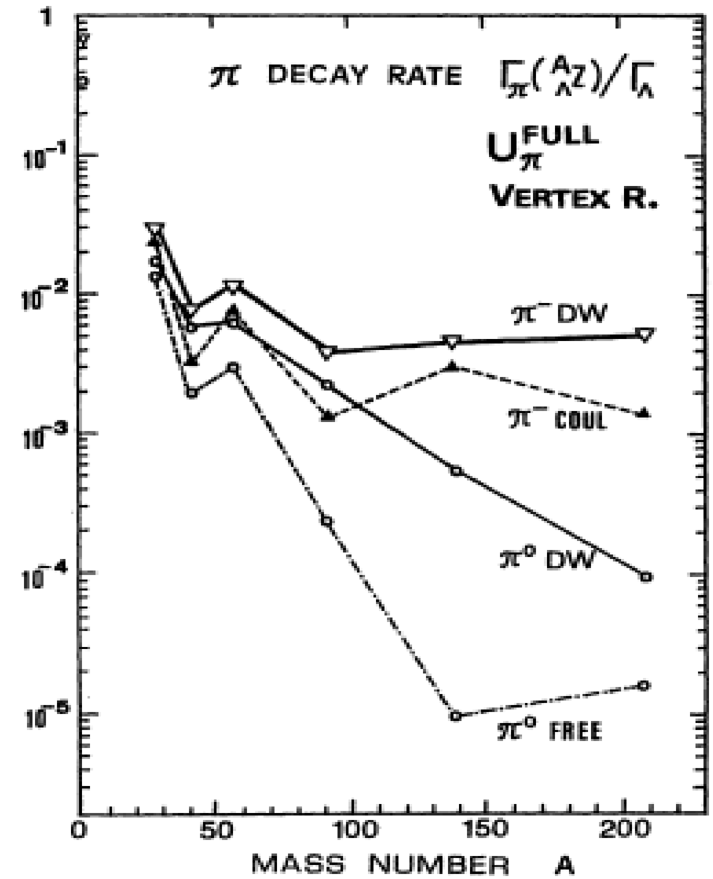
(from Klein-Gordon equation)

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

What can we learn?

→ pion-nucleus optical potential:





T. Motoba, K. Itonaga,
Prog. Theor. Phys. Suppl. 117 (1994) 477

J. Nieves, E. Oset, Phys. Rev. C47 (1993) 1478

Enhancement of up to two orders of magnitude!

→ nuclear and hypernuclear shell structure

$$|{}^{A}_{\Lambda}Z;\ J_i^{P_i}\rangle \rightarrow \pi^- + |{}^{A}(Z+1);\ J_f^{P_f}\rangle$$

- Dalitz and co, from late fifties onwards, used mesonic decay rates of Λ hypernuclei produced in nuclear emulsions to determine their ground state spin-parity J^P

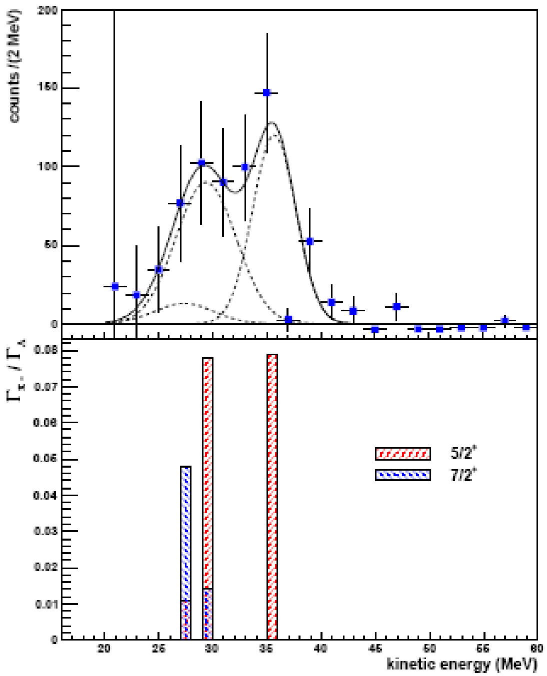
- Itonaga, Motoba, Bando, 1988, pointed the possibility of determining ground state hypernuclear spins on the basis of the pionic decay strength (spectrum of the emitted pion).

- This has been confirmed very recently by the pion spectra obtained for ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B and ${}^{15}_{\Lambda}$N by the **FINUDA collaboration, Agnello et al. PLB681 (2009) 139,** complemented by the revised analysis of pionic branching ratios by **A. Gal, Nucl. Phys. A828 (2009) 72.**

Pion spectra from FINUDA collaboration

Agnello et al. PLB681 (2009) 139

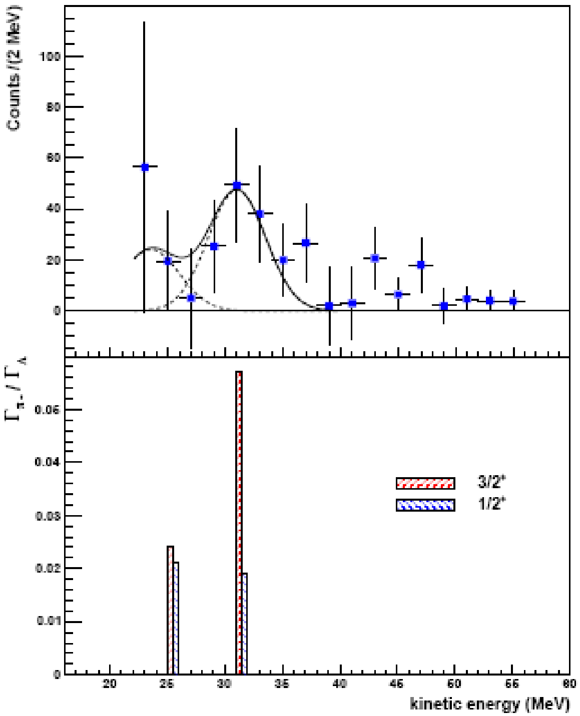
$${}^{11}_{\Lambda}B \rightarrow {}^{11}C + \pi^-$$



Spectral shape confirms the 5/2+ assignment for ${}^{11}_{\Lambda}$B g.s.

(established by an earlier KEK expt, **Y. Sato et al., PRC71 (2005) 025203**)

$${}^{15}_{\Lambda}N \rightarrow {}^{15}O + \pi^-$$



Ratio of peaks is 3:1

(as obtained by calculations of Gal 09, for J^P=3/2+).

Total decay rate is also consistent with this assignment.

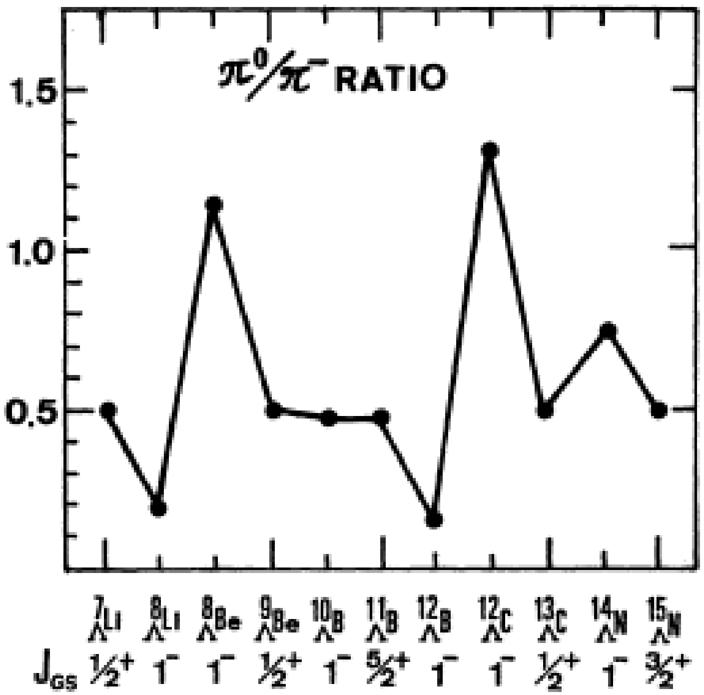
→ Spin-parity 3/2+ for g.s. of ${}^{15}_{\Lambda}$Ni has been determined!

Other nuclear structure effects:

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

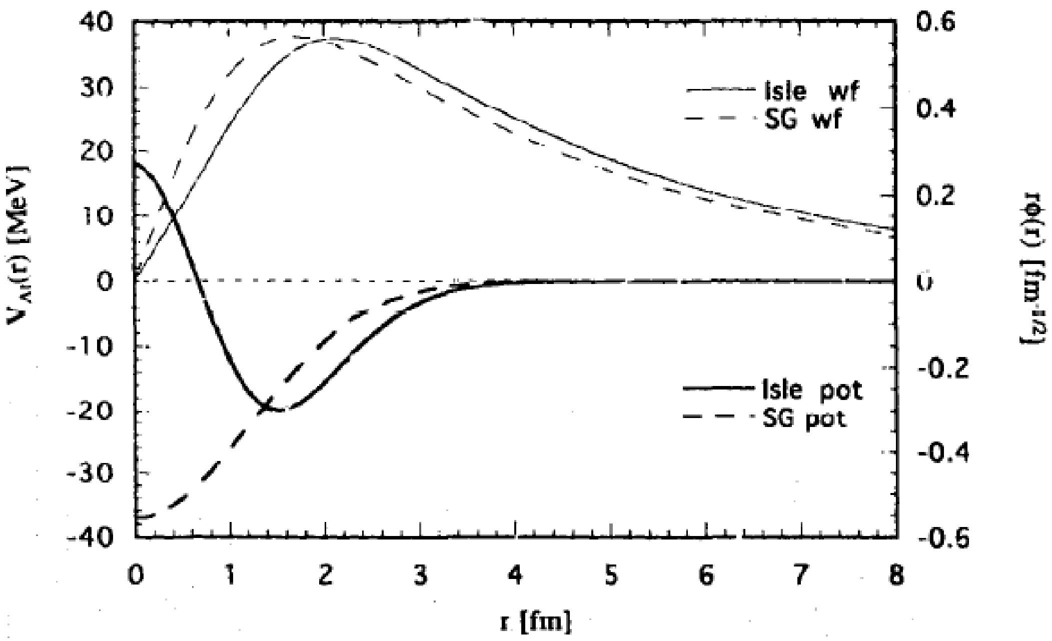
	$\Gamma_{\pi^0}/\Gamma_\Lambda$	$\Gamma_{\pi^-}/\Gamma_\Lambda$	$\Gamma_{\pi^0}/\Gamma_{\pi^-}$
NO-93	0.159	0.086	1.86
MI-94	0.130	0.098	1.32
EXP$^{(*)}$	0.217 ± 0.084	$0.052 \pm^{0.063}_{0.035}$	

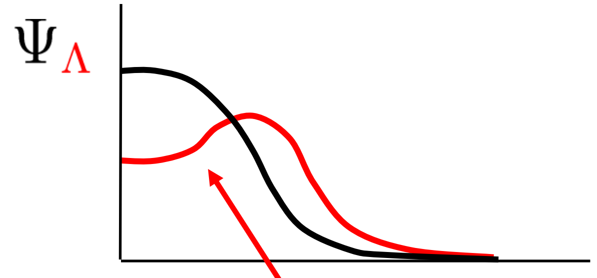
(*) A.Sakaguchi et al., Phys. Rev. C43 (1991) 73



Strong violation fo the $\Delta I=1/2$ rule, $(\Gamma_{\pi^0}/\Gamma_{\pi^-})=0.5$, due to nuclear shell effects!

→ Λ wavefunction in the nucleus:





$^{5}_{\Lambda}He$	$\Gamma_{\pi^0}/\Gamma_\Lambda$	$\Gamma_{\pi^-}/\Gamma_\Lambda$
SG	0.16	0.31
Isle	0.20	0.40
QM	0.239	0.431
EXP(*)	0.18 ± 0.20	0.44 ± 0.11

I.Kumagai-Fuse, S.Okabe,Y.Akaishi, Phys.Lett.B345 (1995) 386

U.Straub,J.Nieves,A.Faessler,E.Oset, Nucl.Phys.A556 (1993) 531

(*) J.J.Szymanski et al., Phys. Rev. C43 (1991) 849

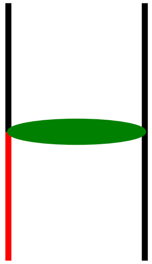
NON-MESONIC DECAY: $\Lambda N \to N N$ $Q \sim m_\Lambda - m_N \sim 175$ MeV

The emerging nucleons are very energetic and this process is not sensitive to nuclear structure details

→ Ideal process to characterize the baryon-baryon *weak* interaction!

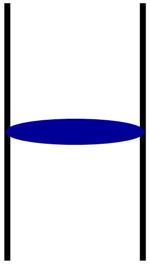
In particular, for processes having $\Delta S=1$ ($\Lambda N \to NN$), the PC amplitude is not masked by the strong interaction like in the case $\Delta S=0$ ($NN \to NN$)

$\Delta S=1$



Both PC and PV weak amplitudes can be studied from hypernuclear weak decay

$\Delta S=0$



Only the PV amplitudes are accessible

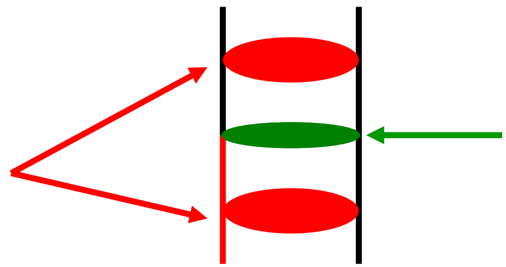
W.M. Alberico and G. Garbarino, Phys. Reports 369 (2002) 1
E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41 (1998) 191

Non-mesonic processes:

Γ_n: Λ n → n n

Γ_p: Λ p → n p

strong interaction
between initial ΛN
and final NN pair



weak interacction:

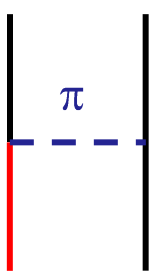
- meson exchange: π,η,K,ρ,ω,K*
- quark models

For many years until recently:

→ Decay width $\Gamma_1=\Gamma_n+\Gamma_p$ well reproduced by all models but…

→ not the ratio Γ_n/Γ_p !

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{theo}} < 0.5 \qquad 0.5 < \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{exp}} < 2$$



OPE mechanism dominated by tensor transitions

$^3S_1$ → $^3D_1$

ΛN → NN

Antisymmetry requires isospin I=0
nn pairs are in isospin I=1
→ Γ_n: Λn → nn supressed in OPE!

Meson exchange model for the nonmesonic weak decay

Channels: $\Lambda n \rightarrow nn\ (\Gamma_n)$, $\Lambda p \rightarrow np\ (\Gamma_p)$

A. Parreño, A. Ramos and C. Bennhold, Phys. Rev. C 56 (1997) 339

Decay rate (neutron or proton incuded)

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

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

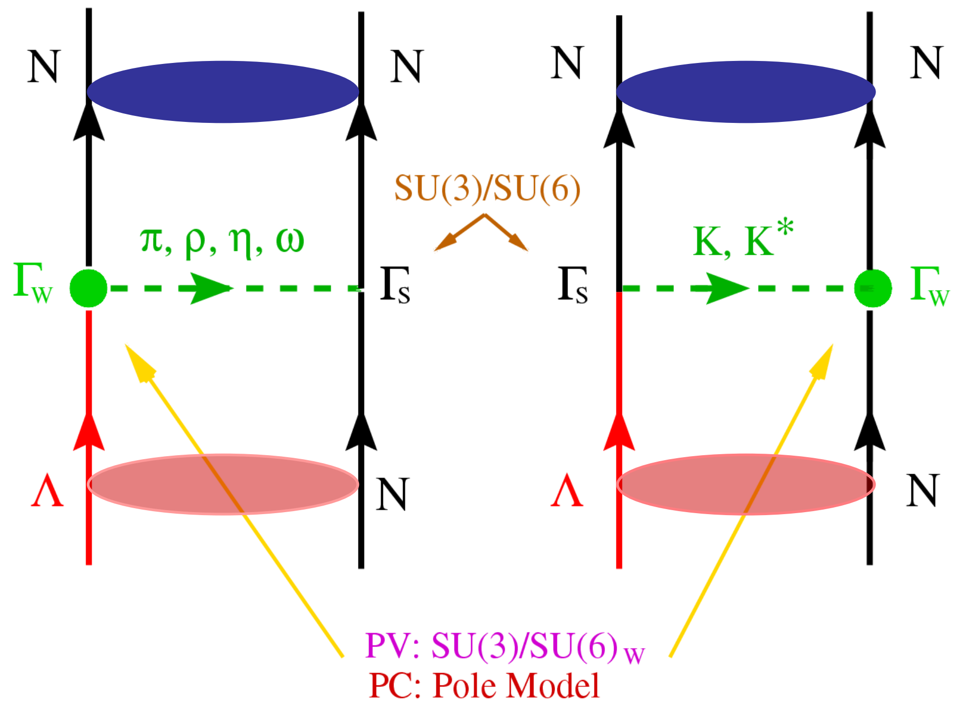
Transition amplitude

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

Ψ_H, Ψ_R: shell-model wave functions

$$\mathcal{M}_N \longrightarrow \langle NN | V_{\mathrm{OME}} | \Lambda N \rangle$$

V_{OME}: meson exchange potential $(\pi, \eta, K, \rho, \omega, K*)$ for the elementary transition $\Lambda N \rightarrow NN$



Weak interaction: $B_1 \rightarrow B_2 M$ ← From the transitions $\Lambda \rightarrow \pi N$, $\Sigma \rightarrow \pi N$, using SU(3)/SU(6)

Strong interaction: $B_1 \rightarrow B_2 M$

Initial state correlations ΛN

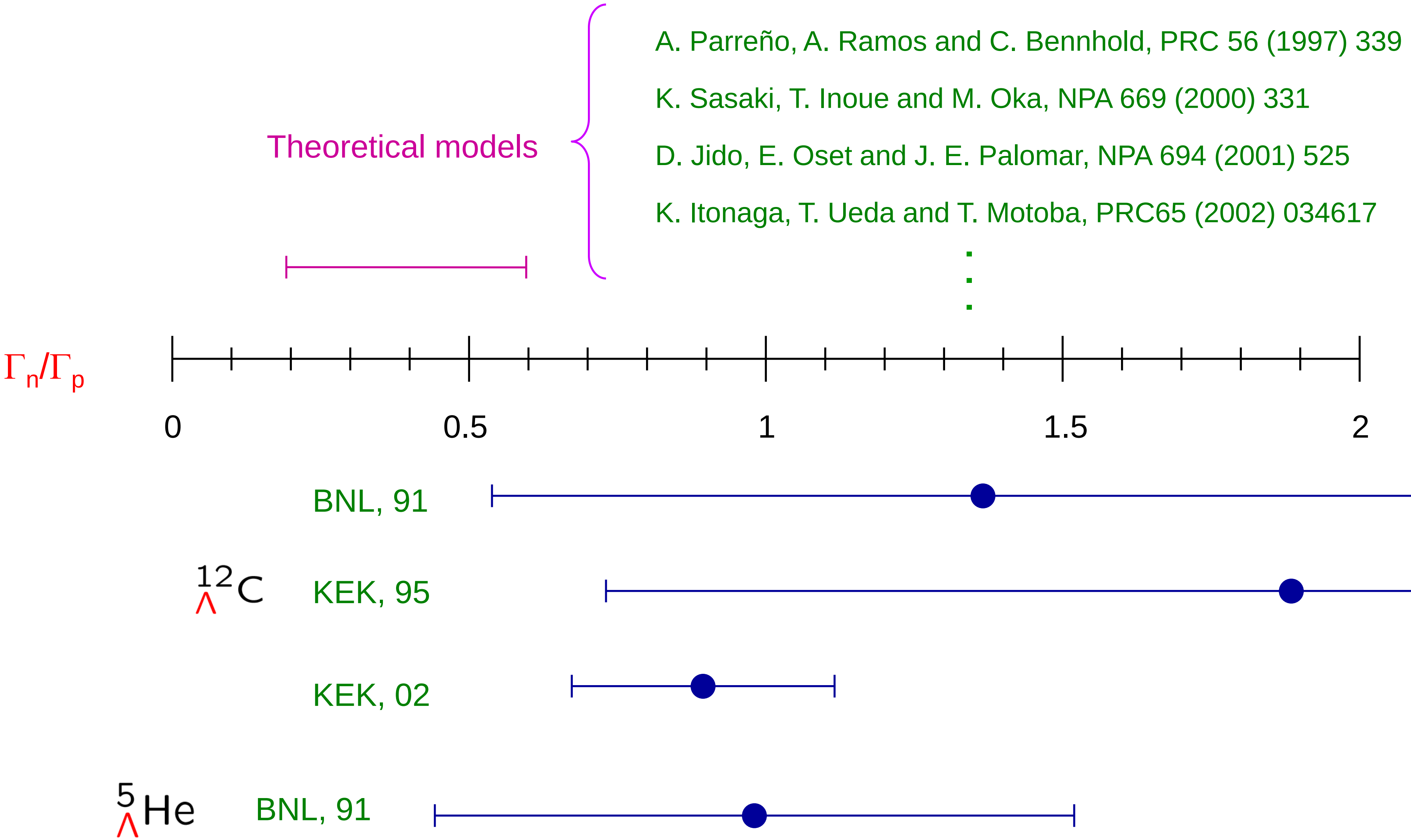
Final state correlations NN

} ← From realistic BB forces: Nijmegen89, Julich89

Model updated: **A. Parreño and A. Ramos, Phys. Rev. C65 (2002) 015204**

- Use of new and improved strong BB interactions: NSC97a,b,c,d,f
- Uncertities tied to the strong interaction have been quantified
- Sign correction in K, K* amplitudes

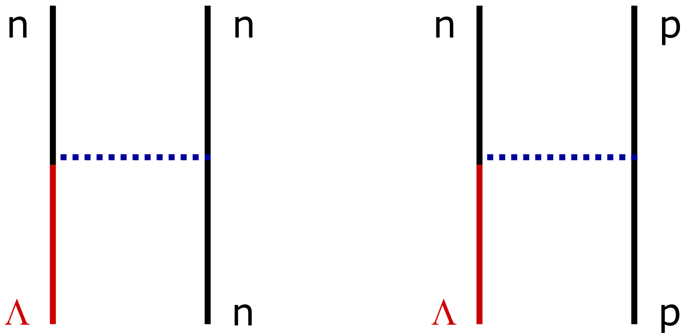
	$\Gamma_n + \Gamma_p$		Γ_n / Γ_p		a_Λ	
	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
OPE	0.43	0.75	0.09	0.08	−0.25	−0.34
OME-a	0.43	0.73	0.34	0.29	−0.68	−0.72
OME-f	0.32	0.55	0.46	0.34	−0.68	−0.73



A challenge in hypernuclear weak decay for many years!

However, we must keep in mind that Γ_n/Γ_p is not really an “observable”.

Essentially, it had been measured *indirectly* through the number of nucleons arriving to the detectors. In a simplistic picture:



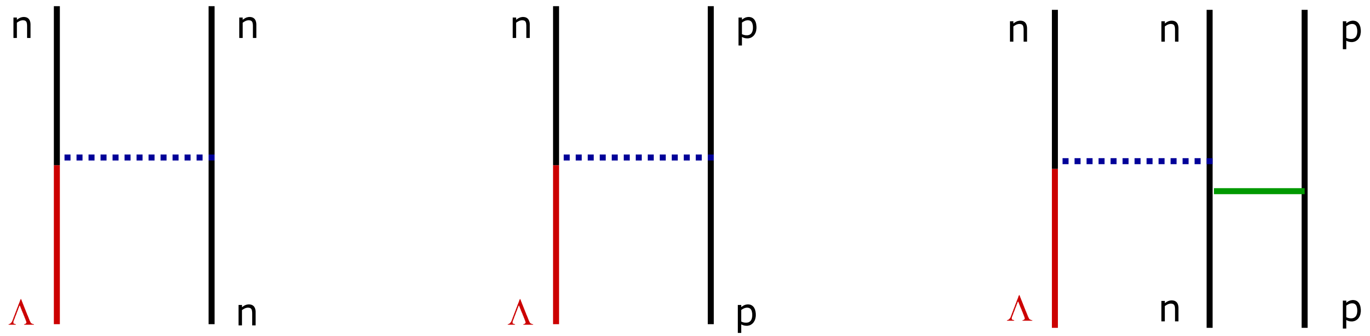
$$N_n = 1\,\Gamma_p + 2\,\Gamma_n$$
$$N_p = 1\,\Gamma_p$$
$$\rightarrow \quad \Gamma_n/\Gamma_p \sim (N_n/N_p - 1)/2$$

BUT a realistic analysis of Γ_n/Γ_p must take into account that some neutrons and protons might come from other sources (and they should not be attributed as being the primary nucleons of the weak decay process).

→ A realistic analysis of Γ_n/Γ_p must consider:

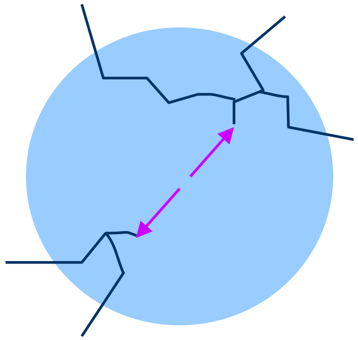
1. The influence of the 2-nucleon induced decay (Γ_2)

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



$$N_n = 1\,\Gamma_p + 2\,\Gamma_n + 2\,\Gamma_2$$
$$N_p = 1\,\Gamma_p + \Gamma_2$$
$$\longrightarrow \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\mathrm{Expt}}$$

2. The final state interaction (FSI) of the primary nucleons

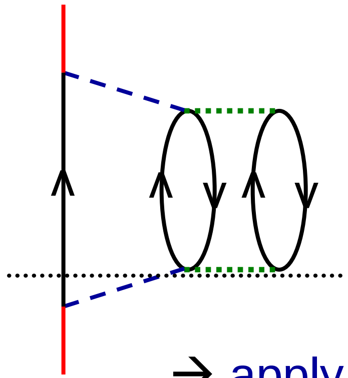


The primary nucleons produced in the weak decay continuously change energy, direction, charge and new secondary nucleons are emitted.

A. Ramos, M.J. Vicente-Vacas and E. Oset, PRC55 (1997) 735-743; Erratum: ibid. C66 (2002) 039903

1. Models for 2-nucleon induced decay Γ_2: ΛNN → NNN

Caculate in nuclear matter .

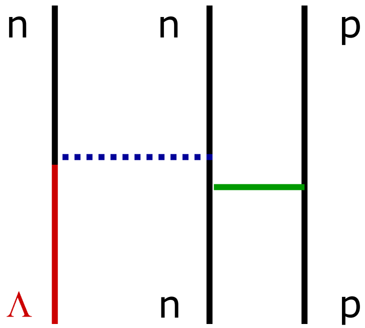


$$\Gamma_2 = -2\,\mathrm{Im}\,\Sigma_\Lambda$$

→ apply Local Density Approximation for finite nucleus result.

A. Phenomenological model

(the contribution is adjusted to two-nucleon pion absorption data)



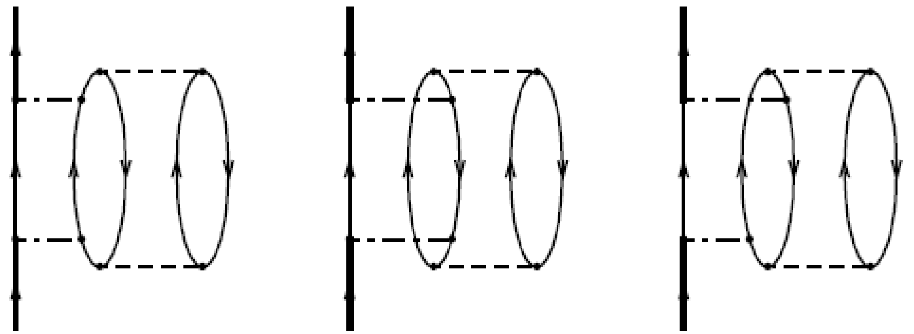
$$\Gamma_2 \sim \Gamma_{np}$$

$$\frac{\Gamma_2}{\Gamma_1} = 0.25 \quad \text{en} \quad {}^{12}_{\Lambda}\mathrm{C}$$

W.M. Alberico, A. De Pace, M. Ericson and M. Molinari, Phys. Lett. B 256 (1991) 13

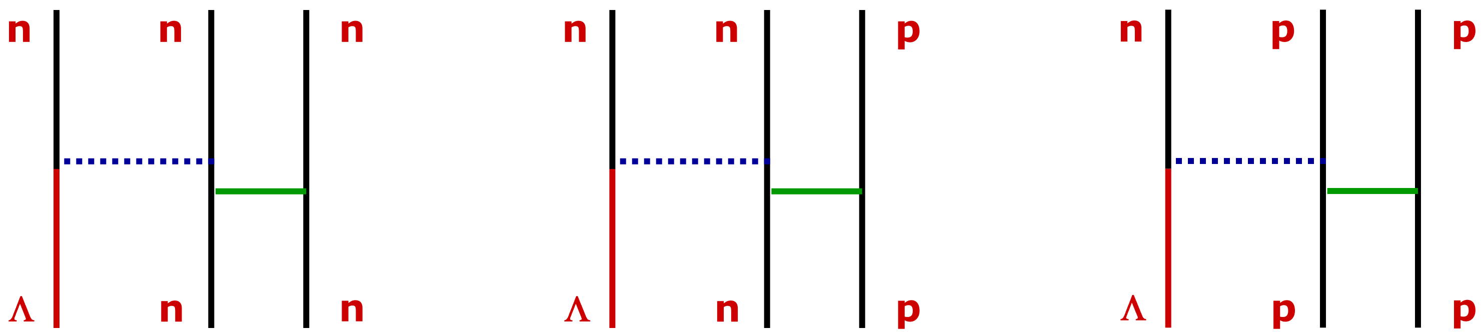
A. Ramos, E. Oset and L.L. Salcedo, Phys. Rev. C 50 (1994) 2314

B. Microscopic model



E. Bauer and F. Krmpotic, Nucl. Phys. A739 (2004) 109

E. Bauer, G. Garbarino, A. Parreño and A. Ramos, nucl-th/0602066



$$\frac{\Gamma_{nn}}{\Gamma_1} = 0.01 \qquad \frac{\Gamma_{np}}{\Gamma_1} = 0.2 \qquad \frac{\Gamma_{pp}}{\Gamma_1} = 0.05$$

$$\frac{\Gamma_2}{\Gamma_1} = 0.26 \quad \text{en} \quad {}^{12}_{\Lambda}\mathrm{C}$$

2. The final state interaction (FSI) of the primary nucleons

Monte Carlo simulation:

✓ A random number generator determines:

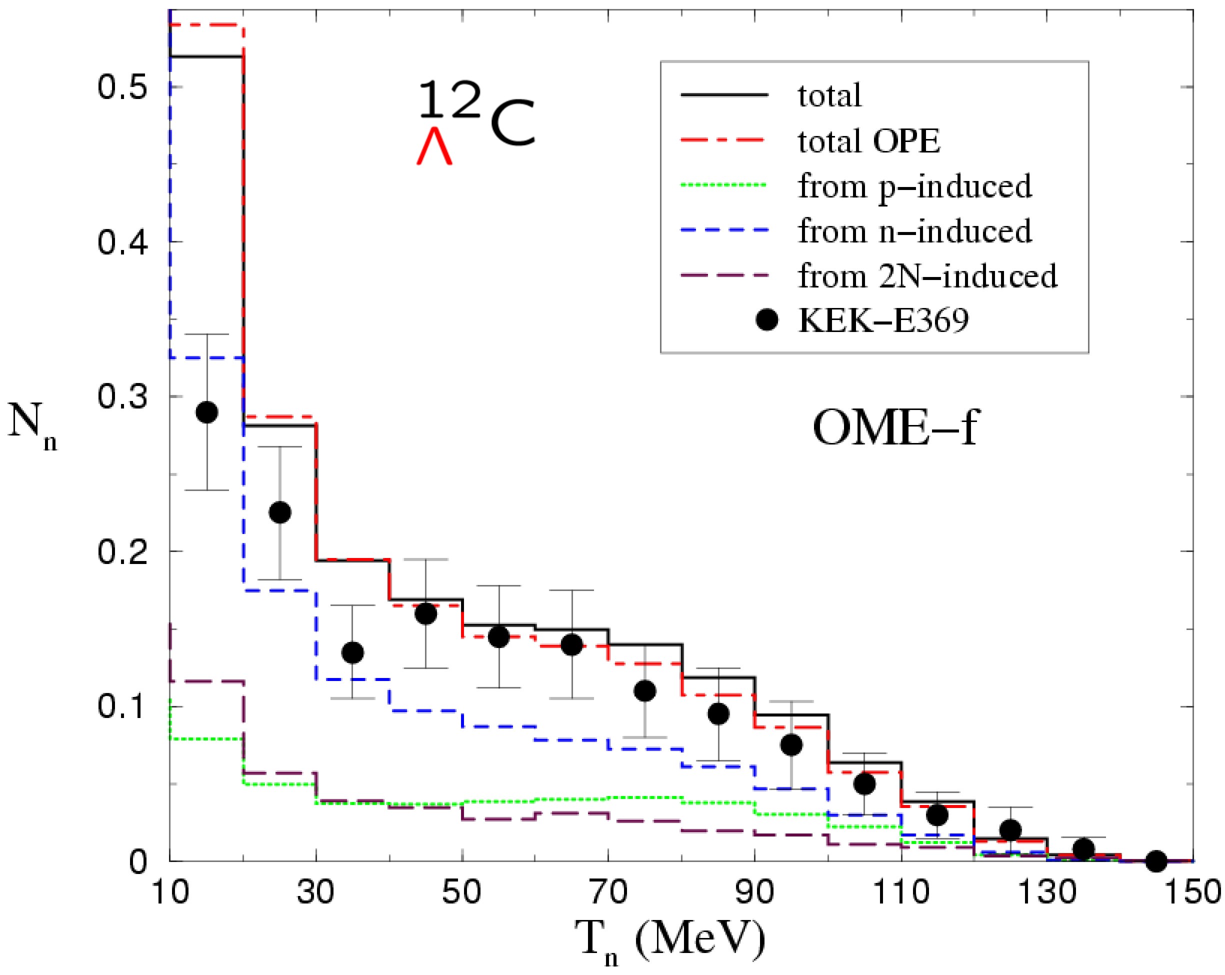
- The decay channel ($\Lambda n \rightarrow n n$, $\Lambda p \rightarrow n p$, $\Lambda N N \rightarrow N N N$) according to the values Γ_n, Γ_p, Γ_{nn}, Γ_{np} , Γ_{pp} of the theoretical model.

- Positions, momenta and charges of the primary nucleons according to the distributions generated by the theoretical model.

✓ "Intranuclear cascade": the nucleons are allowed to propagate through the nucleus and they collide with other nucleons (according to NN collision cross sections) →

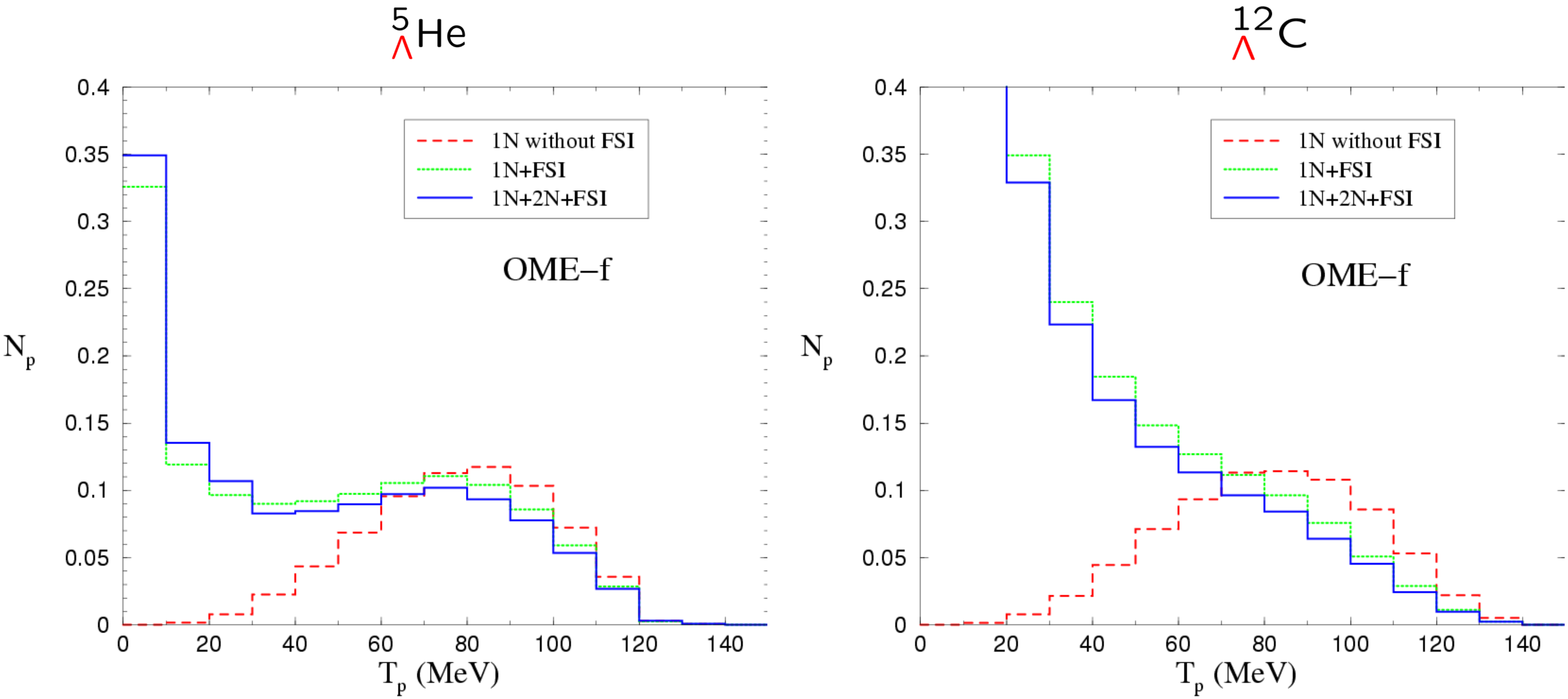
The nucleons generated in the decay (primary) change their energy, direction, charge and new less energetic nucleons (secondary) are emitted.

Neutron spectrum



J.H. Kim et al., Phys. Rev. C68 (2003) 065201

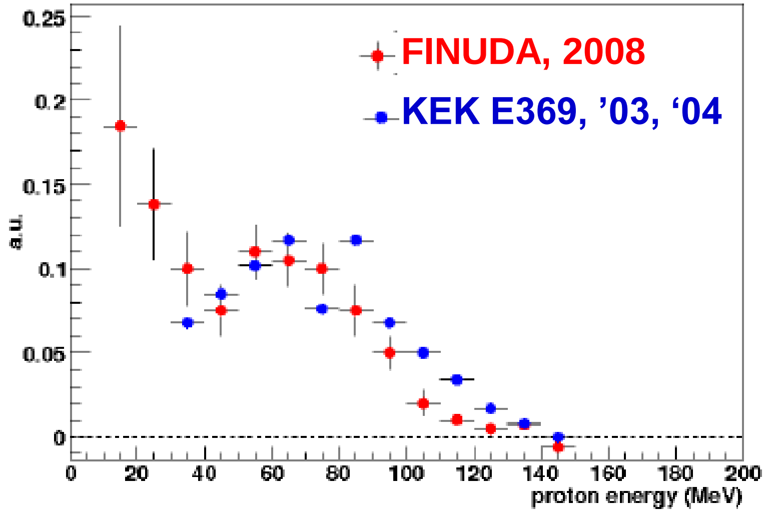
Single proton spectra

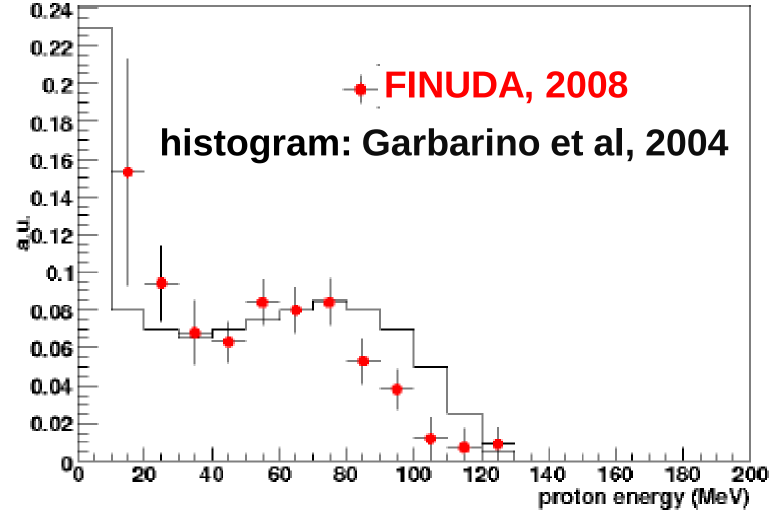


G. Garbarino, A. Parreño and A. Ramos, Phys. Rev. Lett. 91, 112501 (2003)

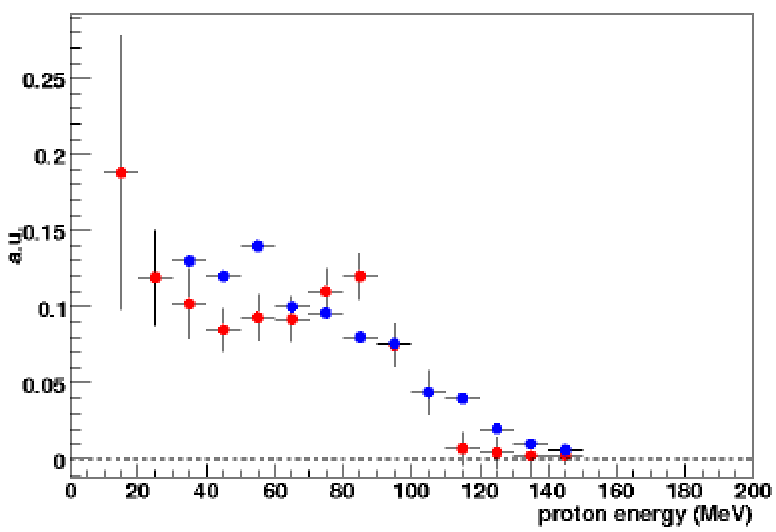
G. Garbarino, A. Parreño and A. Ramos, Phys. Rev. C 69, 054603 (2004)

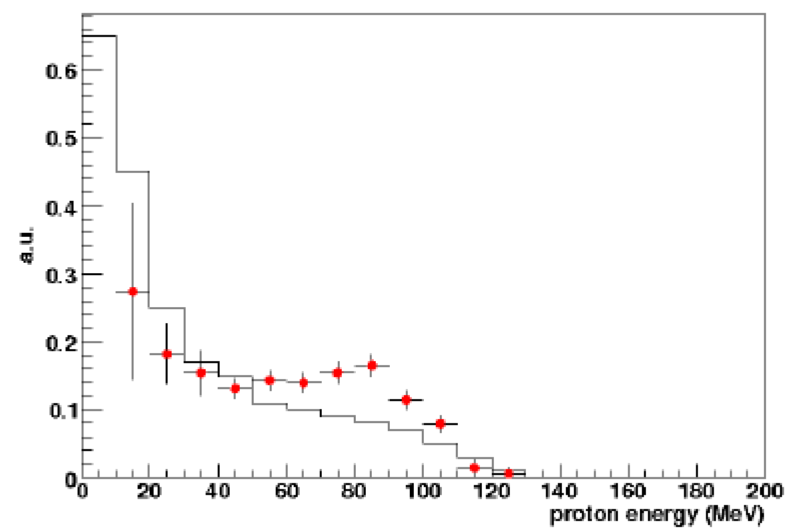
$^{5}_{\Lambda}$He





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





The solution to the Γ_n/Γ_p puzzle

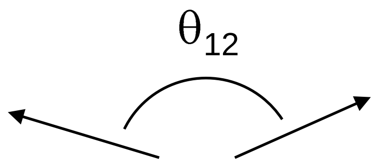
✓ A key issue in obtaining a better determination of Γ_n/Γ_p was the feasibility of measuring the distribution of total energy and angular correlation of nucleon pairs in coincidence.

IDEA: the *contaminating effects* might be concentrated in a reduced energy or angular window which could be eliminated by applying appropriate cuts.

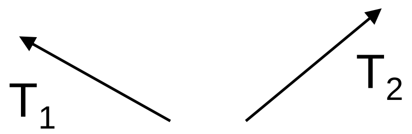
✓ Theoretical simulations have also contributed notably in the task of determining Γ_n/Γ_p , since they provide information on the energy/angular distribution of nucleons from each of the decay processes..

NN coincidences

Angular correlations



Energy correlations: T_1+T_2



Measuring distributions of NN pairs in coincidence permits a better determination of the ratio Γ_n/Γ_p :

- ✓ Reduces contamination from the process Γ_2: $\Lambda NN \rightarrow NNN$
- ✓ More exclusive measurement → eliminates FSI events

EXP

B.H. Kang et al., Phys. Rev. lett. 96 (2006) 062301

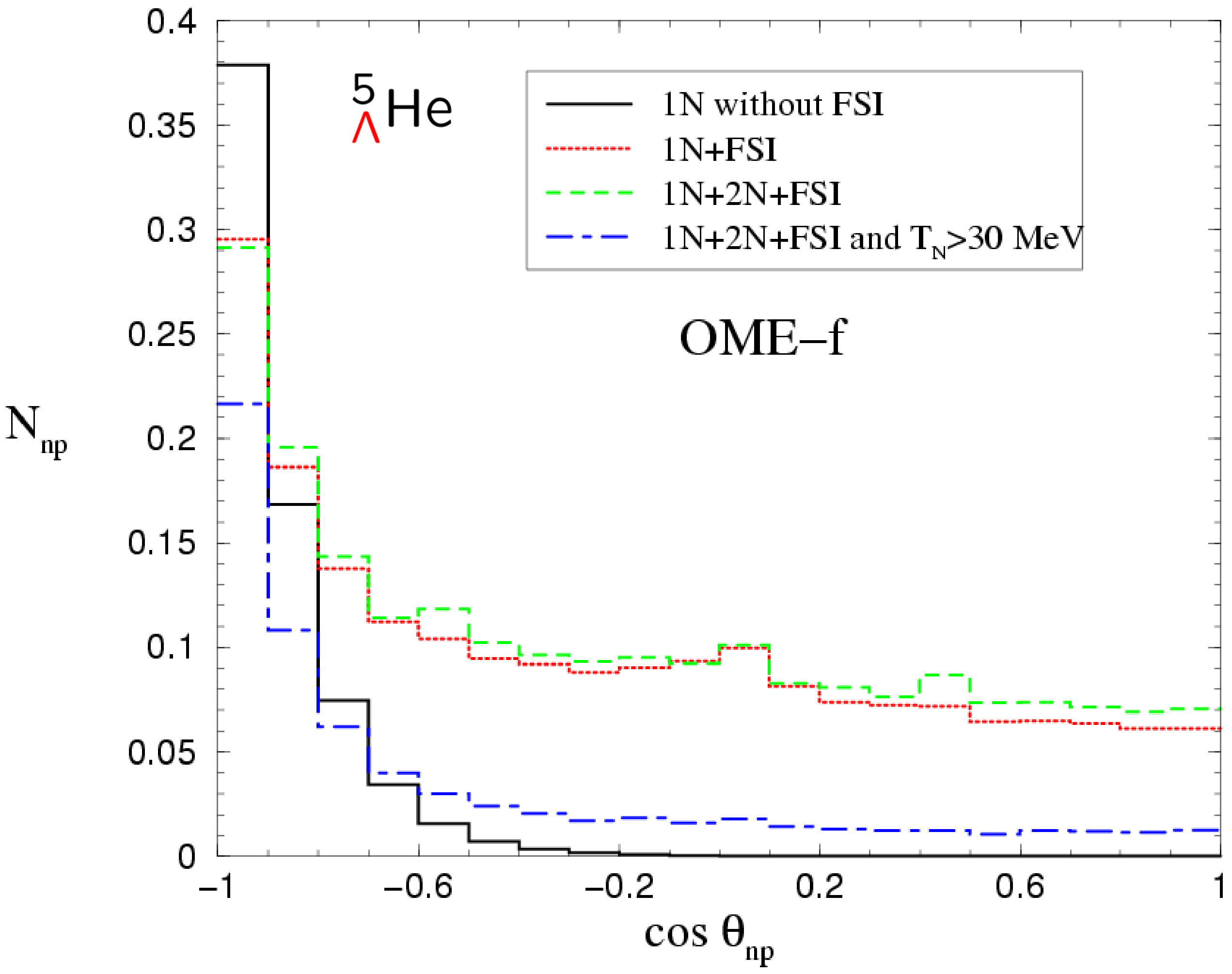
M.J. Kim et al., Phys. lett. B641 (2006) 28

TEO

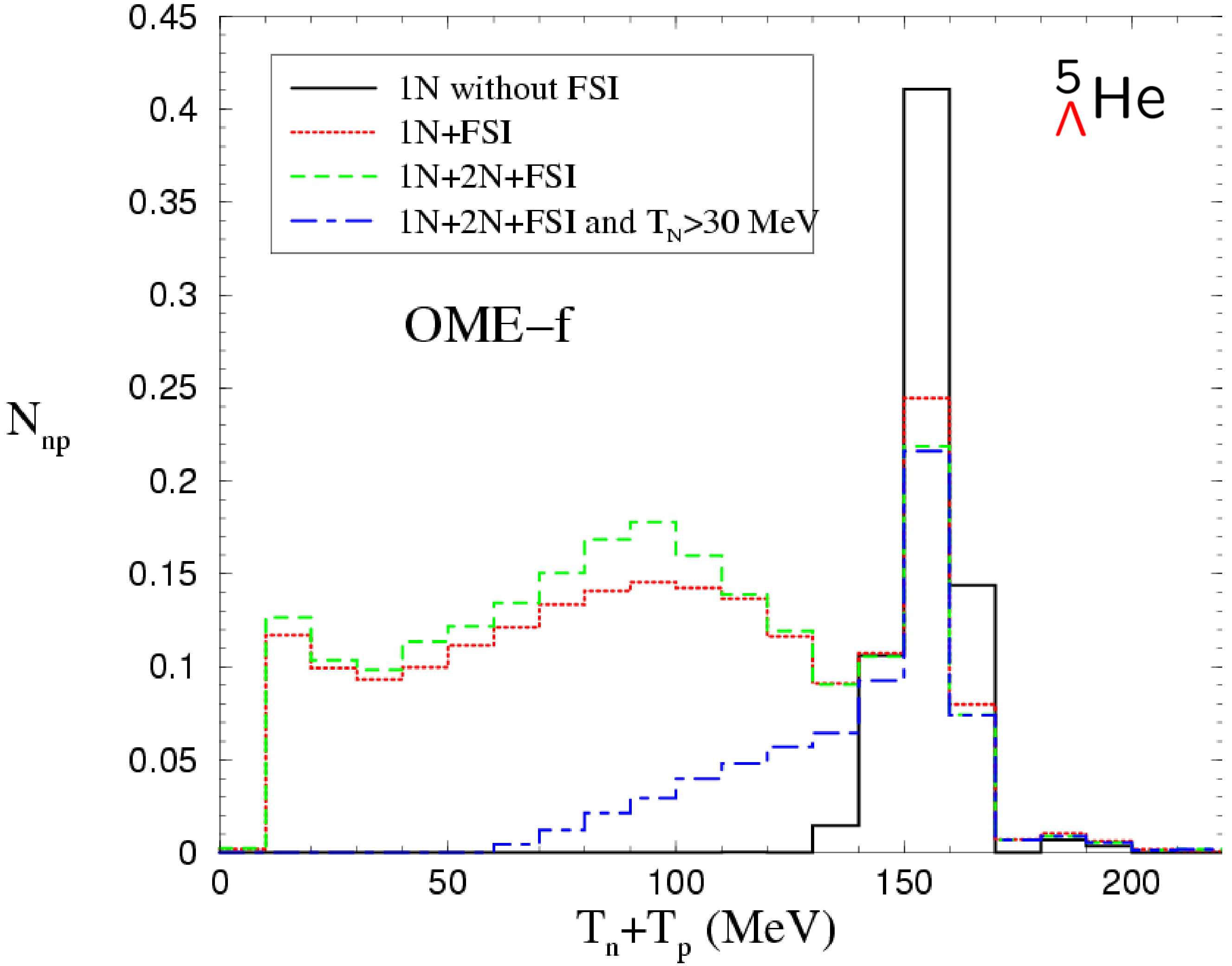
G. Garbarino, A. Parreño and A. Ramos, Phys. Rev. Lett. 91, 112501 (2003)

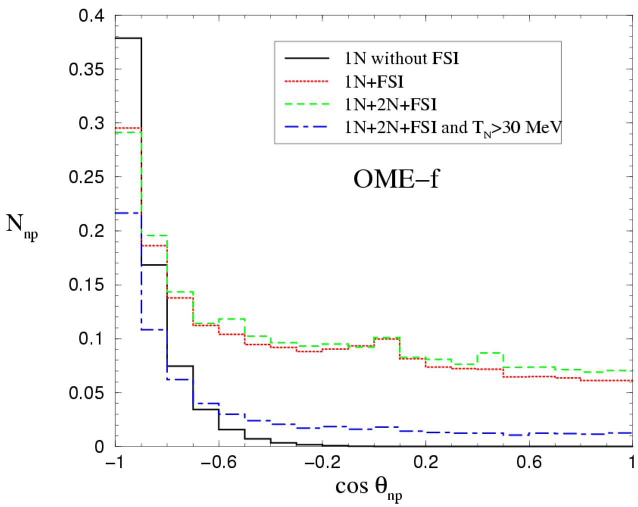
G. Garbarino, A. Parreño and A. Ramos, Phys. Rev. C 69, 054603 (2004)

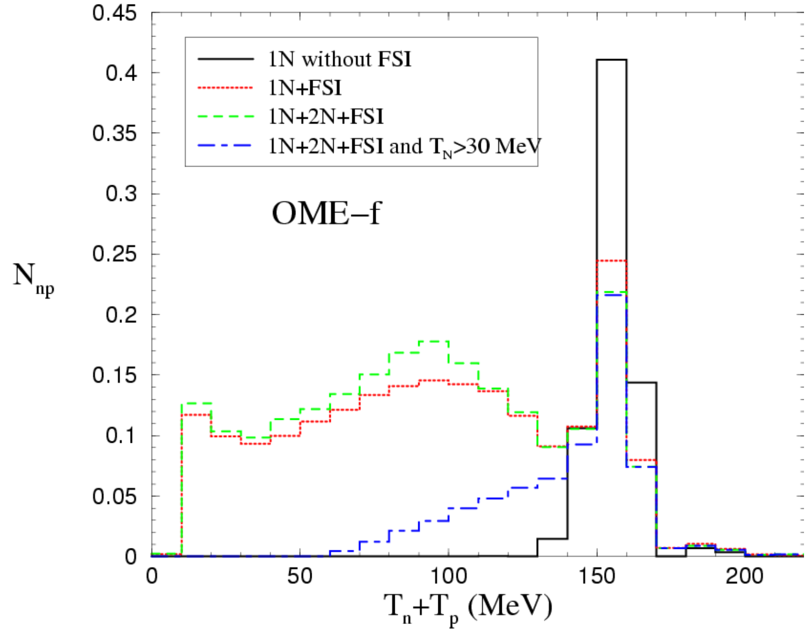
Angular correlation between n and p pairs

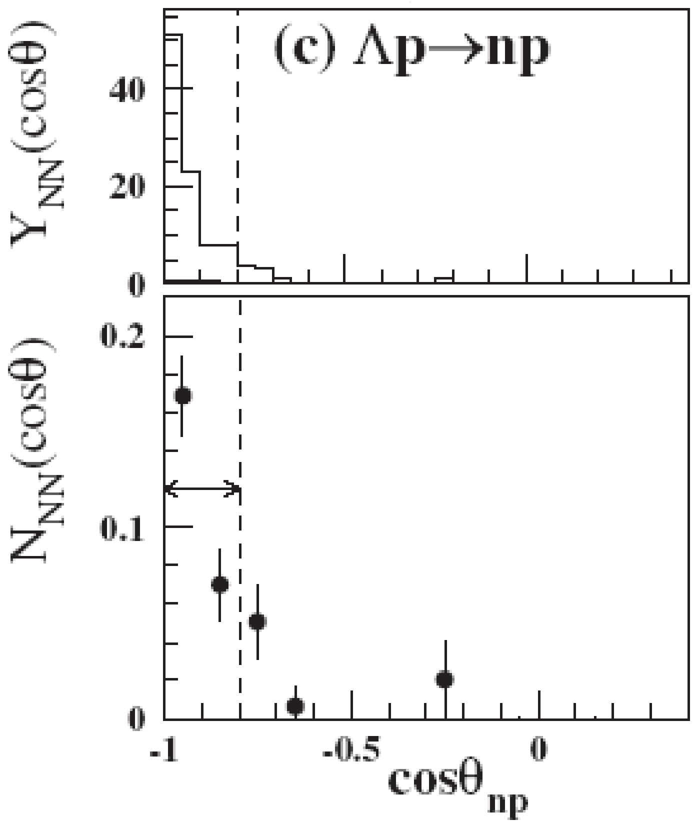


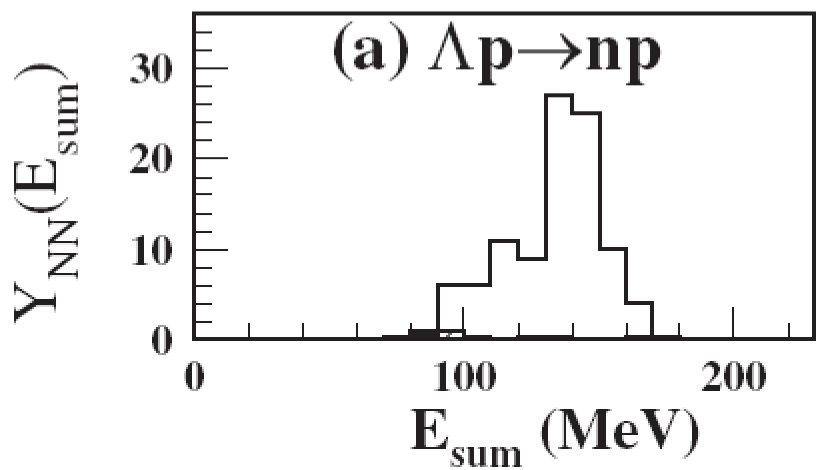
Kinetic energy correlations between np pairs





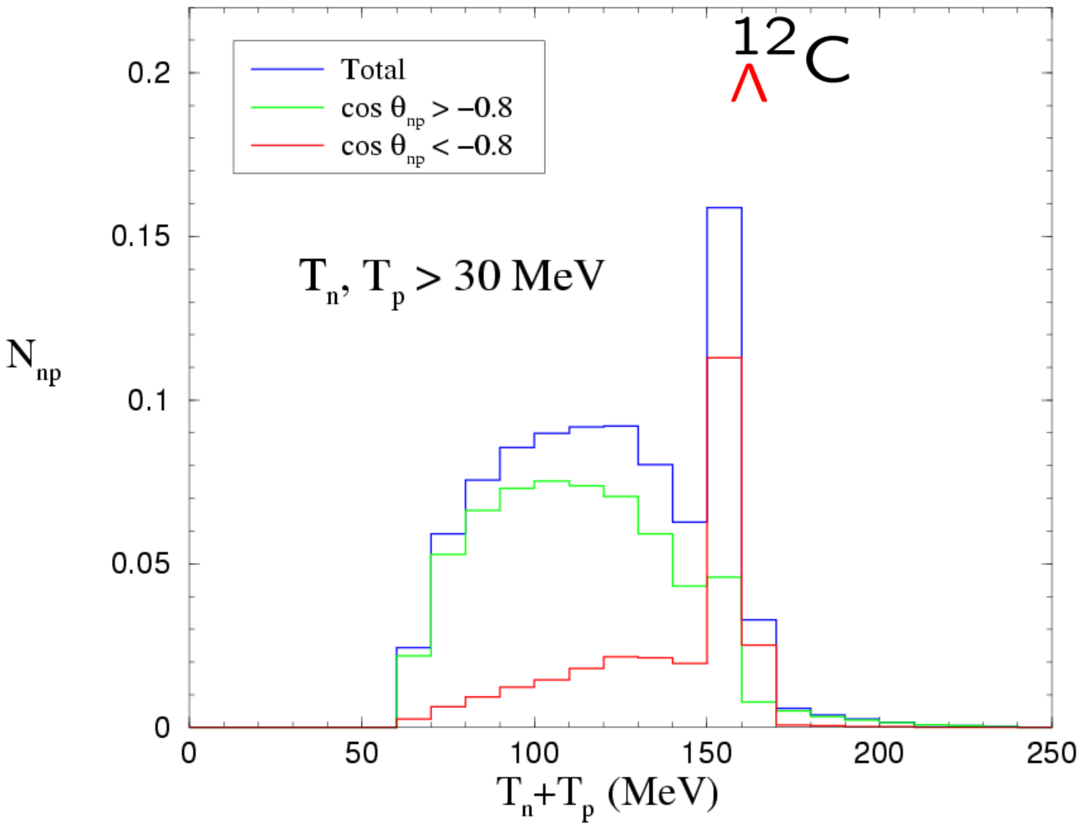


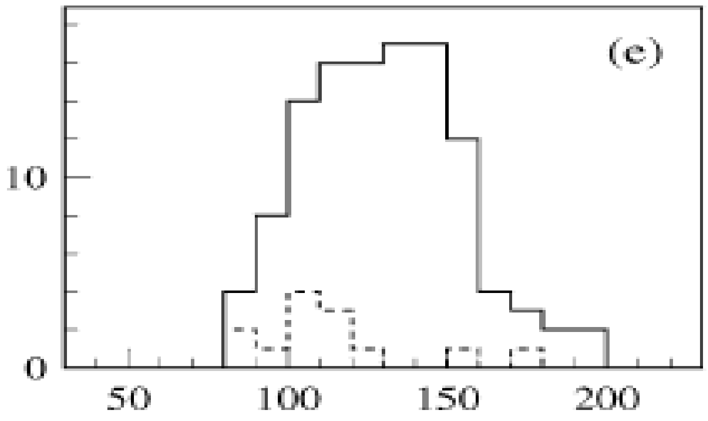




B.H. Kang et al., Phys. Rev. lett. 96 (2006) 062301

n-p total energy correlation





M.J. Kim et al., Phys. lett. B641 (2006) 28

Without FSI and ignoing Γ_2: $\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N_{nn}^{wd}}{N_{np}^{wd}}$

With FSI: → $\frac{\Gamma_n}{\Gamma_p} \neq \frac{N_{nn}}{N_{np}}$ ← This is what is measured!

N_{nn}, N_{np}: number of nucleon-nucleon per weak decay (after FSI)

	${}^{5}_{\Lambda}$He		${}^{12}_{\Lambda}$C	
	$\frac{N_{nn}}{N_{np}}$	$\frac{\Gamma_n}{\Gamma_p}$	$\frac{N_{nn}}{N_{np}}$	$\frac{\Gamma_n}{\Gamma_p}$
OPE	0.25	0.09	0.24	0.08
OME-a	0.51	0.34	0.39	0.29
OME-f	0.61	0.46	0.43	0.34
EXP-E462	0.45 ± 0.14			
EXP-508			0.51 ± 0.18	

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

Theory and experiment are compatible !!

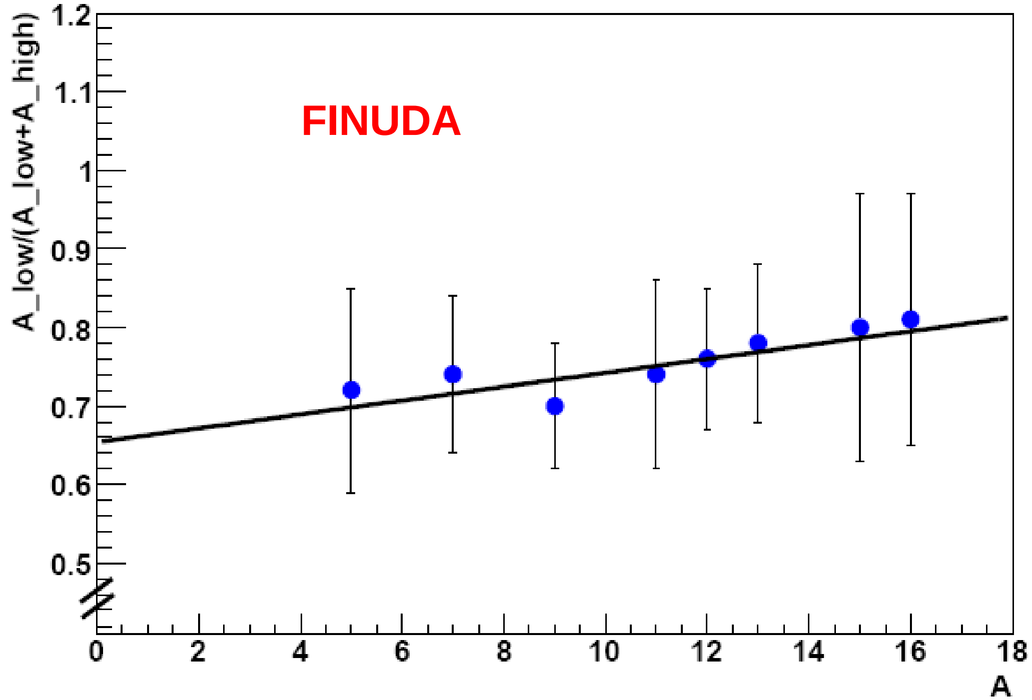
New! Two independent experimental determinations of Γ_2

1. A clever extraction of FSI effects from the low and high energy tails of single proton spectra gives:

$$R(A) = \frac{0.5 + \frac{\Gamma_2}{\Gamma_p}}{1 + \frac{\Gamma_2}{\Gamma_p}} + bA$$

$$\frac{\Gamma_2}{\Gamma_p} = 0.43 \pm 0.25$$

$$\frac{\Gamma_2}{\Gamma_{\mathrm{NMWD}}} = \frac{\Gamma_2/\Gamma_p}{(\Gamma_n/\Gamma_p) + 1 + (\Gamma_2/\Gamma_p)} = 0.24 \pm 0.10$$



M. Agnello et al., Phys.Lett.B685 (2010) 247.
e-Print: arXiv:0910.4939 [nucl-ex]

M. Kim et al., Phys.Rev.Lett.103 (2009) 182502

2. Single and double-nucleon spectra were consistently analyzed incorporating FSI effects that were fitted to inelastic (p,p') data.

KEK

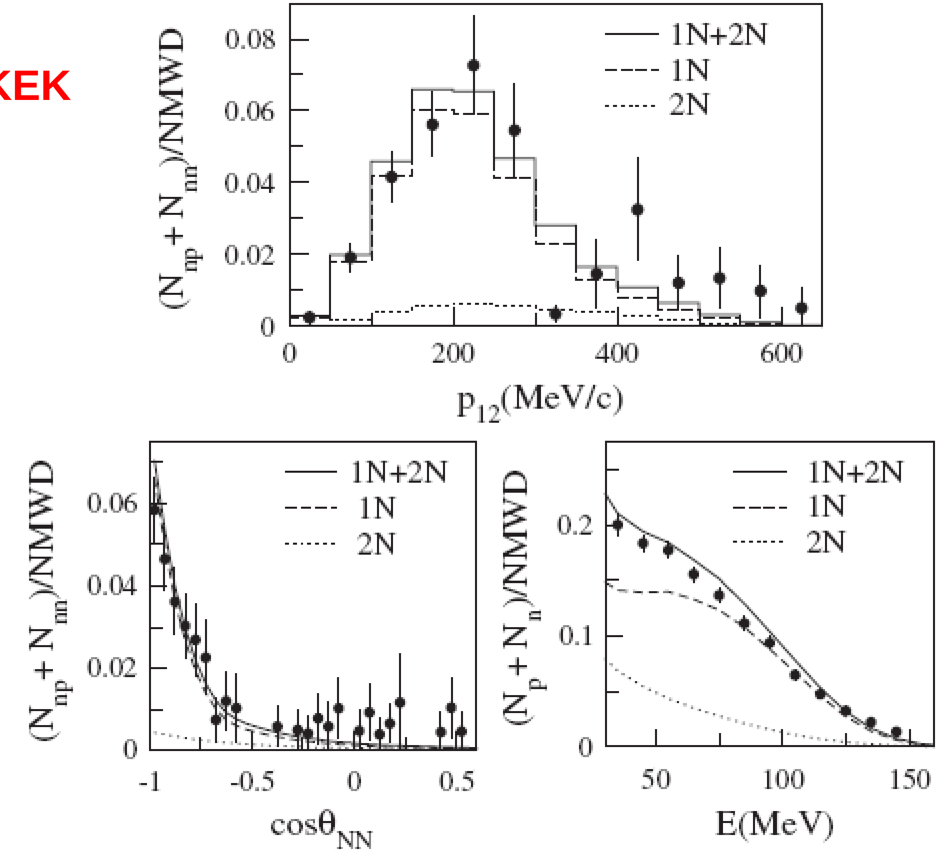


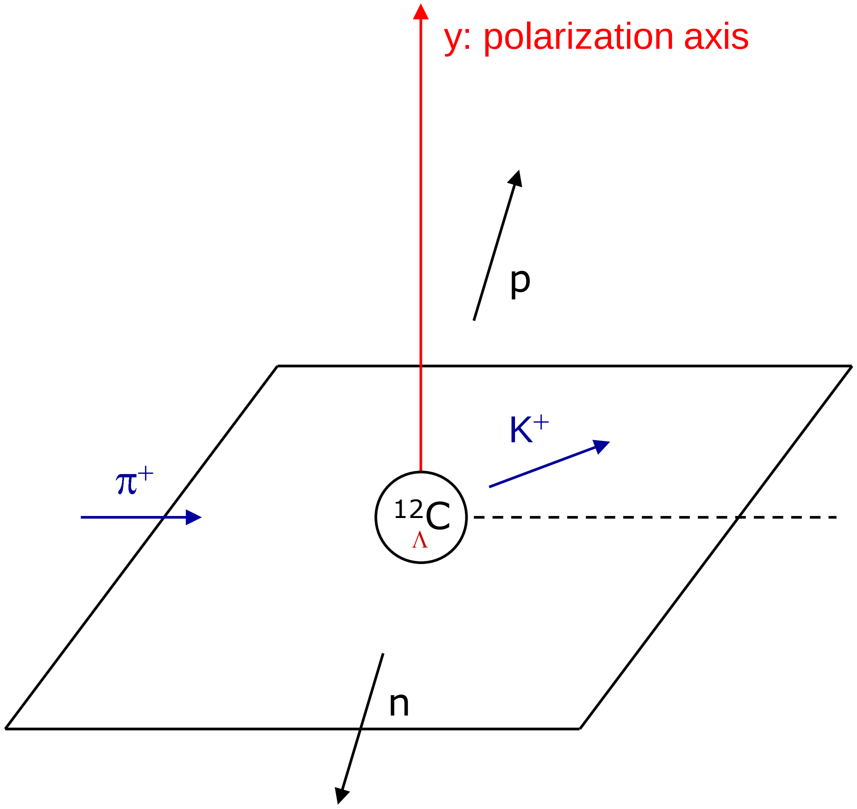
FIG. 4. The momentum sum (upper) and the angular (lower left) correlation of the pair sum $N_{np} + N_{nn}$ and the normalized nucleon yields $N_N(E)$ are compared with those of INC($1N + 2N$) (solid lines) with $b_{2N} = 0.29$. The decomposed $1N$- (dashed lines) and $2N$-NMWD (dotted lines) contribution also are shown.

TABLE I. Branching ratios and decay widt with the current theoretical values. The bold l Γ_{2N} in this work. The unit of the widths is I

	Present experiment
Γ_n/Γ_p	0.51 ± 0.13 ± 0.05 [4]
Γ_{nm}	0.95 ± 0.04 [16–18]
b_{2N}	**0.29 ± 0.13**
Γ_{2N}	**0.27 ± 0.13**
Γ_{1N}	**0.68 ± 0.13**
Γ_n	**0.23 ± 0.08**
Γ_p	**0.45 ± 0.10**

THEORY: $\Gamma_2/\Gamma_{NMWD} \sim 0.25$

New challenge in hypernuclear decay: Asymmetry



$$I_p(\theta) = I_0\left[1 + \mathcal{A}(\theta)\right]$$

$$\mathcal{A}(\theta) = \mathcal{A}\cos\theta$$

EXP: $$\mathcal{A} = \frac{N_p^{\uparrow} - N_p^{\downarrow}}{N_p^{\uparrow} + N_p^{\downarrow}}$$

$$\mathcal{A} = P_H A_H$$

characteristic of the production reaction (π^+,K^+)

characteristic of the weak decay process (and affected by FSI)

Weak coupling scheme of the Λ to the nuclear core → $\mathcal{A} \equiv p_\Lambda a_\Lambda$

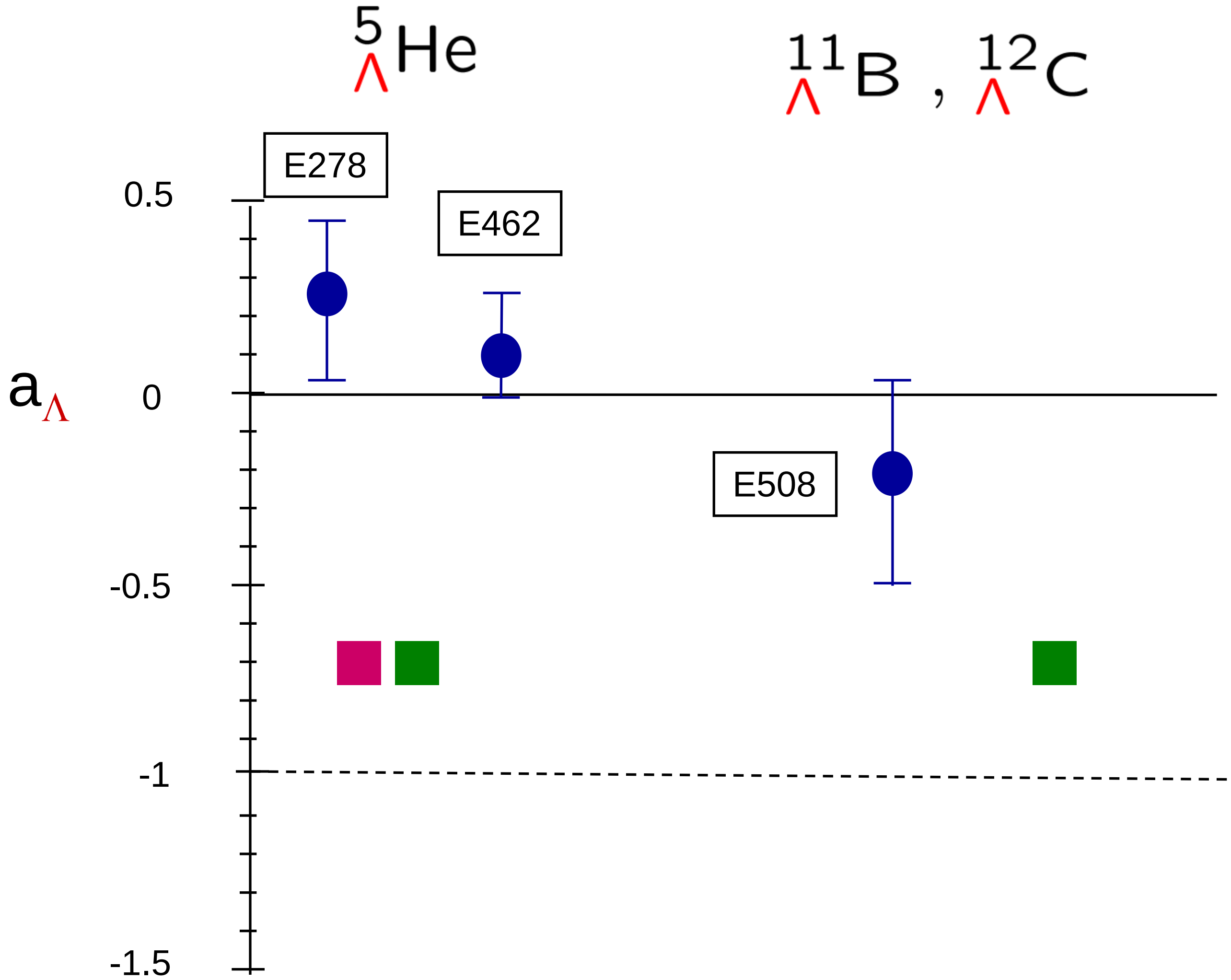
a_Λ : intrinsic asymmetry parameter (characteristic of $\pi^+ N \to K^+ \vec{\Lambda}$)

For a s-shell hypernucleus, the asymmetry can be approximately given in terms of a few transition amplitudes that characterize completely the four-fermion weak interaction

$$a_\Lambda = \frac{2\sqrt{3}\,\mathrm{Re}[ae^* - b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3[|c|^2 + |d|^2 + |e|^2 + |f|^2]}$$

→ Interference between PC and PV !

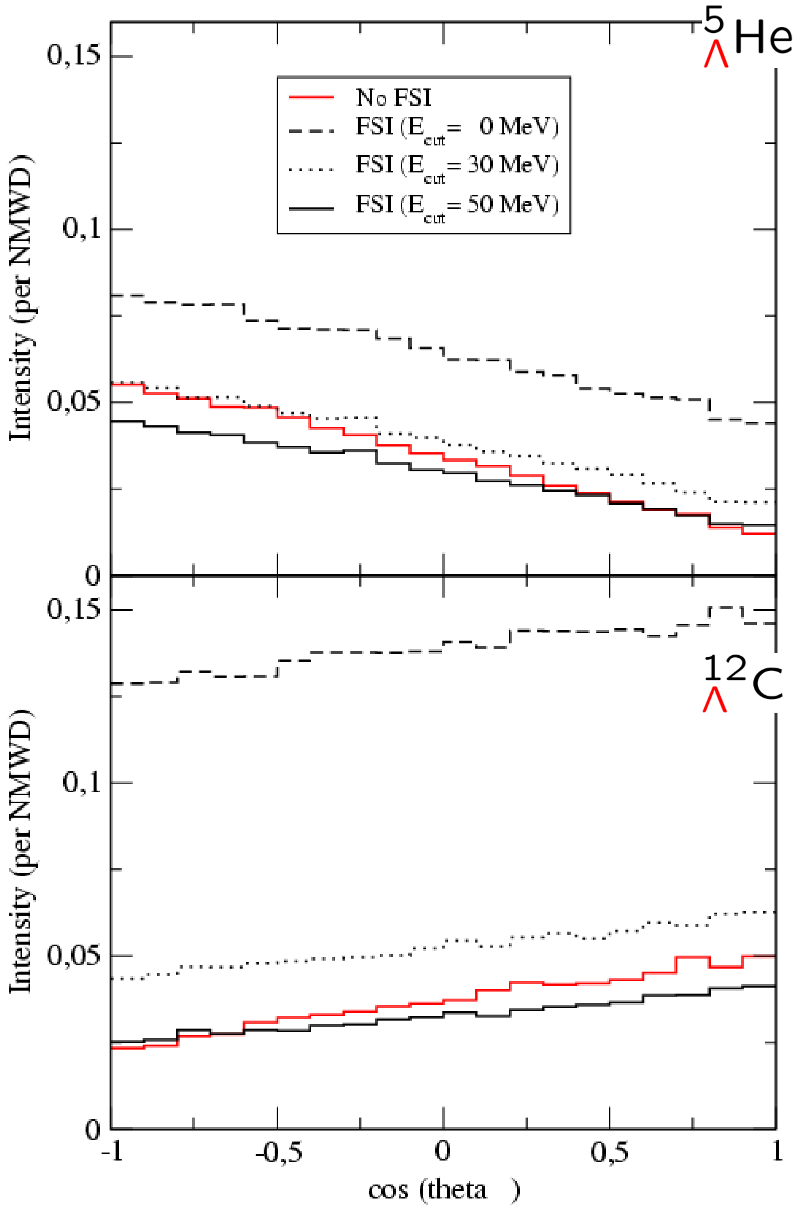
ΛN $^{(2S+1)}L_J$	NN $^{(2S'+1)}L'_J$	amplitude	NN isospin	PC/PV
$^1S_0$	$^1S_0$	a	1	PC
	$^3P_0$	b	1	PV
$^3S_1$	$^3S_1$	c	0	PC
	$^3D_1$	d	0	PC
	$^1P_1$	e	0	PV
	$^3P_1$	f	1	PV



K. Sasaki, T. Inoue, M.Oka, Nucl. Phys. A707 (2002) 477

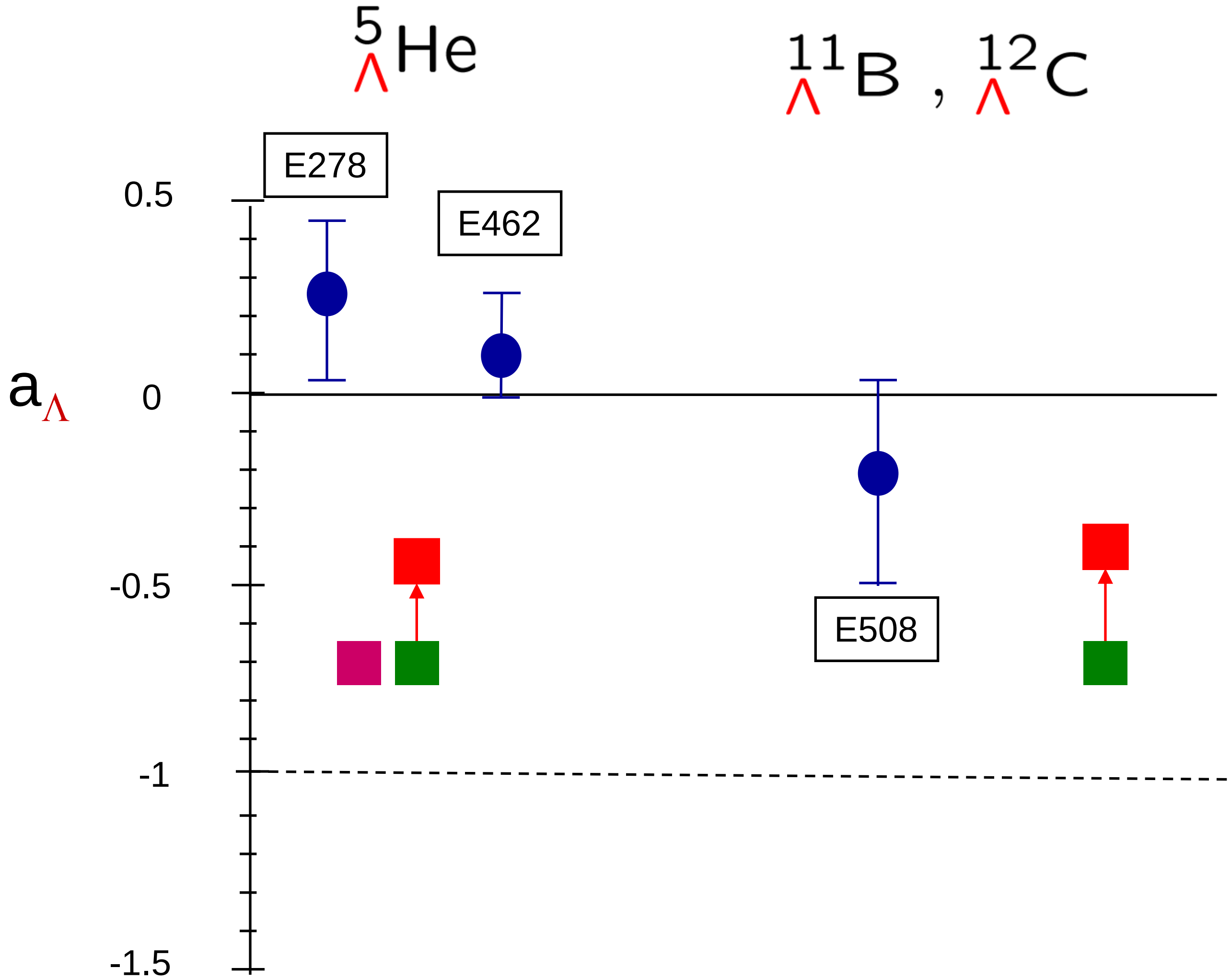
A. Parreño and A. Ramos, Phys. Rev. C65 (2002) 015204

Incorporation of FSI in the evaluation of the asymmetry



W. Alberico, G. Garbarino, A. Parreño, A. Ramos, Phys. Rev. Lett 94 (2005) 082501

The model generates the primary nucleons according to the meson exchange model for the weay decay process and it also incorporates final state interactions of the nucleon in its way out of the nucleus.



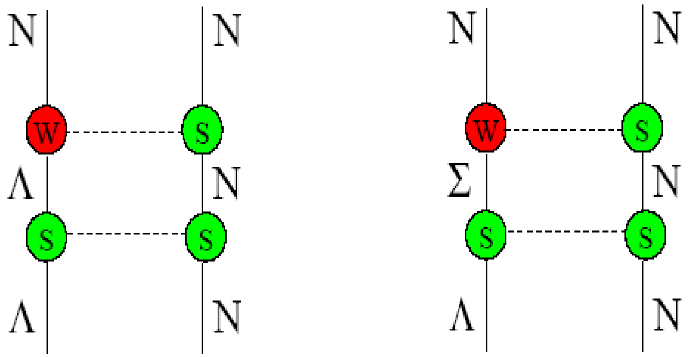
K. Sasaki, T. Inoue, M.Oka, Nucl. Phys. A707 (2002) 477

A. Parreño and A. Ramos, Phys. Rev. C65 (2002) 015204

W. Alberico, G. Garbarino, A. Parreño and A. Ramos, Phys. Rev. Lett. 94 (2005) 082501

Hypernuclear decay model needs to be improved!

1. Possible improve ment in the strong-sector part of the model. (ΛN- ΣN mixing)



H. Bando, Y. Shono and H. Takaki, Int. J. Mod. Phys. A3 (1988) 1581.

N.J. Robertson and W.H. Dickhoff,Phys.Rev.C72 (2005) 024320

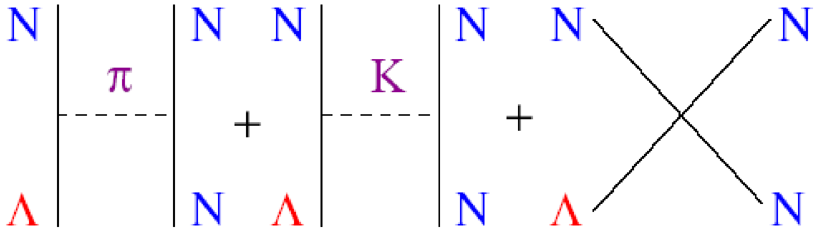
Tesis de C. Chumillas (UB)

Work in progress…

2. Improving the weak sector (decay mechanism)

Recent studies of the four-fermion interaction in the context of an Effective Field Theory indicated the dominance of a scalar-isoscalar contact term that was crucial to reproduce the asymmetry.

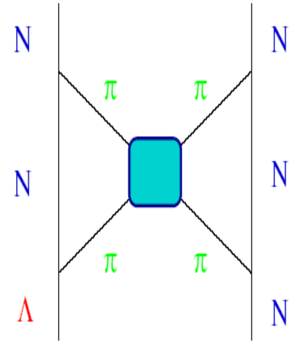
A. Parreño, C. Bennhold and B.R. Holstein, Phys. Rev. C70 (2004) 051601(R)



→ see A. Pérez-Obiol talk :

- ***extension to NLO,***
- ***matching EFT coeff's to OME model***

Dynamically, this term can be interpreted as coming from the exchange of the scalar-isoscalar meson σ (J=0,I=0) . From a more fundamentl poiint of view, this term is obtianed from the exchange of two-pions, including both correlated and uncorrelated exchange.



D. Jido, E. Oset, J.E. Palomar, Nucl. Pys. A694 (2001) 525

More phenomenologically:

K.Itonaga, T.Ueda, T.Motoba, 1994,2002

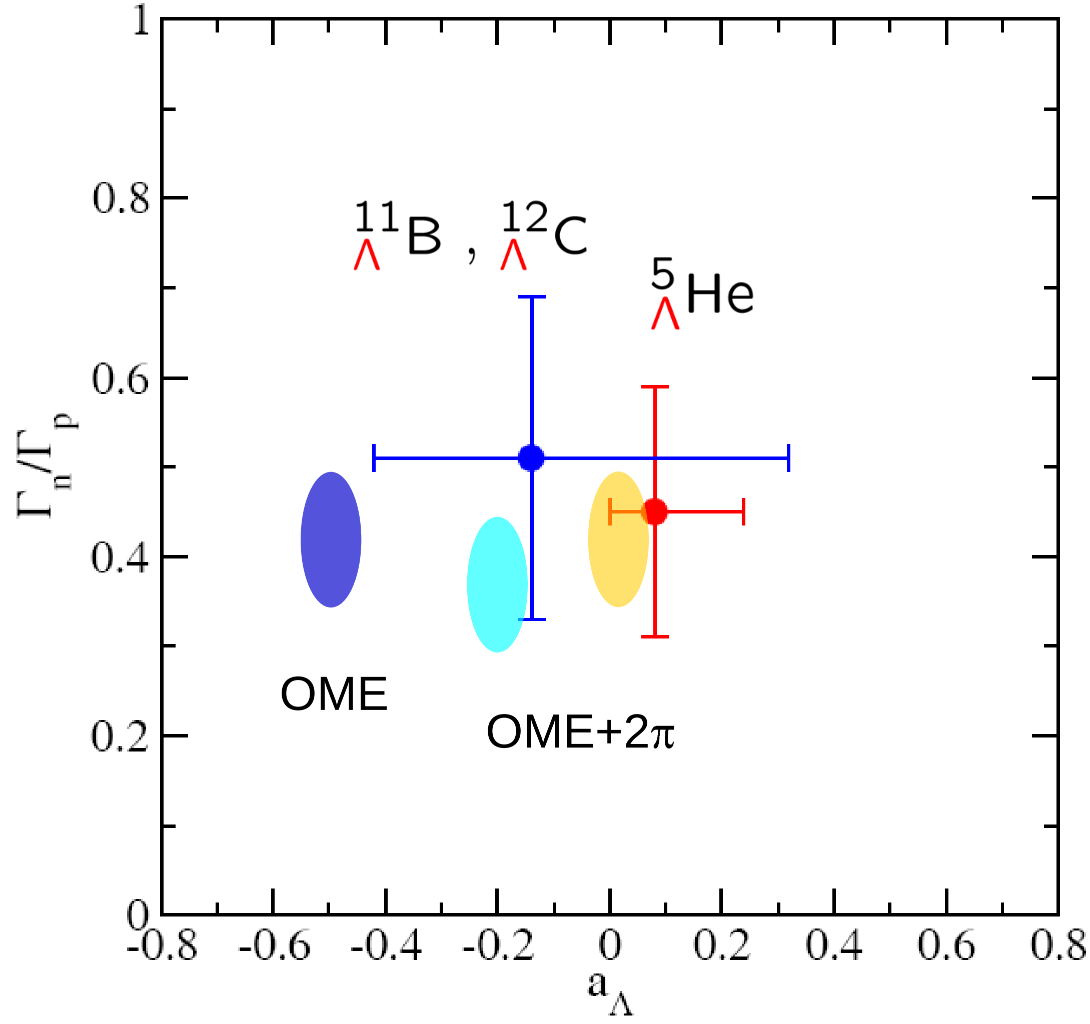
Results: OME+2π

$^{5}_{\Lambda}$He			
	Γ_{NM}	Γ_n/Γ_p	a_Λ
OME	0.379	0.474	-0.590
OME$+2\pi$	0.388	0.415	$+0.041$
KEK–E462	0.424 ± 0.024	$0.45 \pm 0.11 \pm 0.03$	$0.11 \pm 0.08 \pm 0.04$
KEK–E462			$0.08 \pm 0.08^{+0.08}_{-0.00}$

$^{12}_{\Lambda}$C			
	Γ_{NM}	Γ_n/Γ_p	a_Λ
OME	0.667	0.357	-0.698
OME$+2\pi$	0.722	0.366	-0.207
KEK–E508	0.940 ± 0.035	$0.51 \pm 0.13 \pm 0.05$	$-0.20 \pm 0.26 \pm 0.04$
KEK–E508			$-0.16 \pm 0.28^{+0.18}_{-0.00}$
KEK–E307	$0.828 \pm 0.056 \pm 0.066$		

C. Chumillas, G. Garbarino, A. Parreño y A. Ramos, Phys. Lett. B657 (2007) 180.

a_Λ (is an interference of amplitudes) → a change in the value and/or sign of an amplitud can give a very different asymmetry value without changing apreciably the values of Γ, Γ_n, Γ_p (sum of amplitudes squared)



$^{11}_{\Lambda}B$, $^{12}_{\Lambda}C$
$^{5}_{\Lambda}He$
OME
OME+2π
Γ_n/Γ_p
a_Λ
1
0.8
0.6
0.4
0.2
0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8

STRANGENESS NUCLEAR PHYSICS is a fascinating field that adds a new dimension (strangeness) into conventional nuclear physics and opens the door to investigate new phenomena associated to the enlarged flavour SU(3) world

Interdisciplinary field !

hypernuclear structure:

→ properties of the YN, YY interactions → ASTROPHYSICS (neutron star interior)

→ the Λ penetrates inside the nucleus → NUCLEAR PHYSICS

hypernuclear decay:

mesonic mode → NUCLEAR PHYSICS

non-mesonic mode → weak non-leptonic baryon-baryon interaction → ASTROPHYSICS, PARTICLE PHYSICS