Hyperon-nucleon interaction, hypernuclei & hyperonic matter

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"Interaction forte dans la matière nucléaire: nouvelles tendaces"

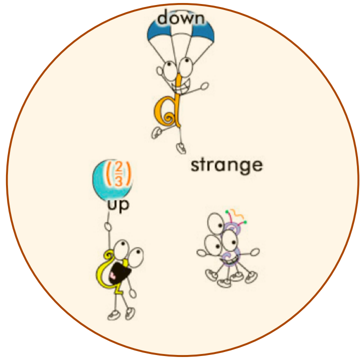
Ecole Internationale Joliot-Curie, 27 Sept.- 3 Oct. 2009, Lacanau (France)

Plan of the Lecture

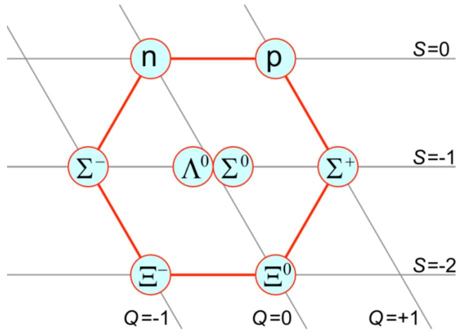
- Introduction & Historical Overview
- Birth, Life & Death of Hypernuclei
- Hyperon-Nucleon Interaction
- Hypernuclear Matter & Neutron Star Properties

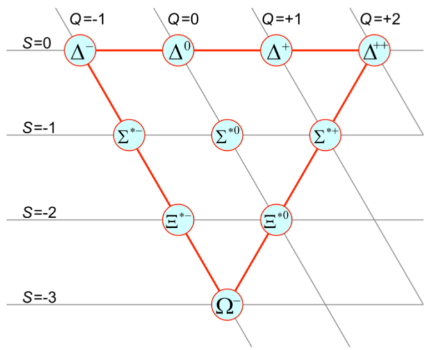
What is a hyperon ?

- A hyperon is a baryon made of one , two or three strange quarks



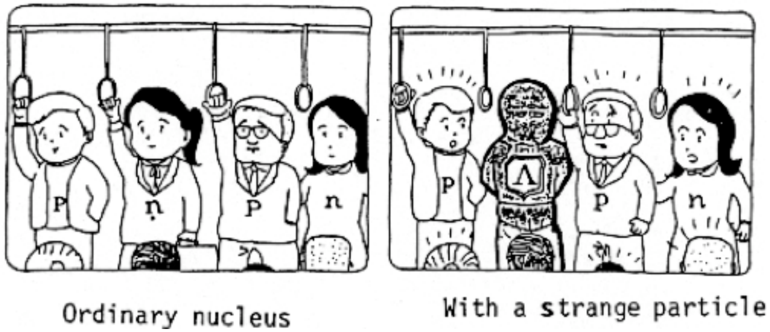
Hyperon	Quarks	I(J^P)	Mass (MeV)
Λ	uds	0(1/2$^+$)	1115
Σ^+	uus	1(1/2$^+$)	1189
Σ^0	uds	1(1/2$^+$)	1193
Σ^-	dds	1(1/2$^+$)	1197
Ξ^0	uss	1/2(1/2$^+$)	1315
Ξ^-	dss	1/2(1/2$^+$)	1321
Ω^-	sss	0(3/2$^+$)	1672



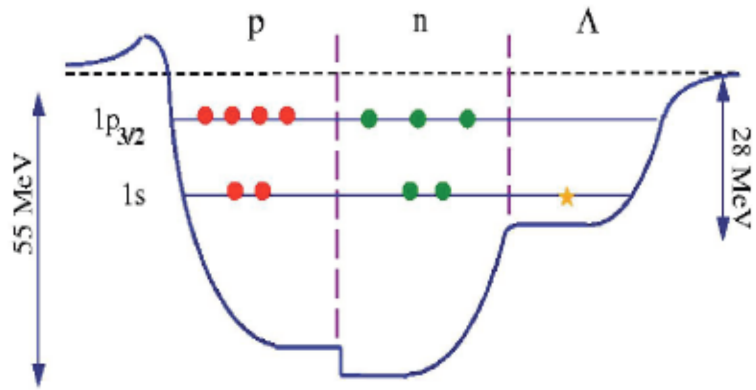


What is a hypernucleus ?

- A hypernucleus is a bound system of nucleons with one or more strange baryons (Λ,Σ,Ξ,Ω^- hyperons).



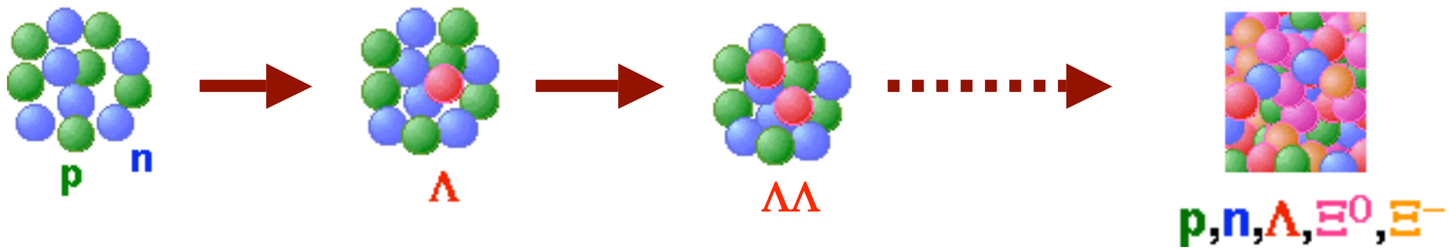
H. Bando, PARITY 1, 54 (1986)



Simple s.p. model of ${}^{12}_{\Lambda}C$

- In a simple single-particle model: protons, neutrons and hyperons are considered distinguishable particles placed in independent effective potential wells in which Pauli exclusion principle is applied.

- Since hyperons are distinguishable from nucleons, they are privileged probes to explore states deep inside the nucleus, extending our knowledge of conventional to flavored nuclear physics.



- Hyperons can change the nuclear nuclear structure. For instance the glue-like role of the Λ hyperon can facilitate the existance of neutron-rich hypernuclei, being a more suitable framework to study matter with extreme n/p ratios as compared to ordinary nuclei.

- A hypernucleus is a “laboratory” to study hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions.

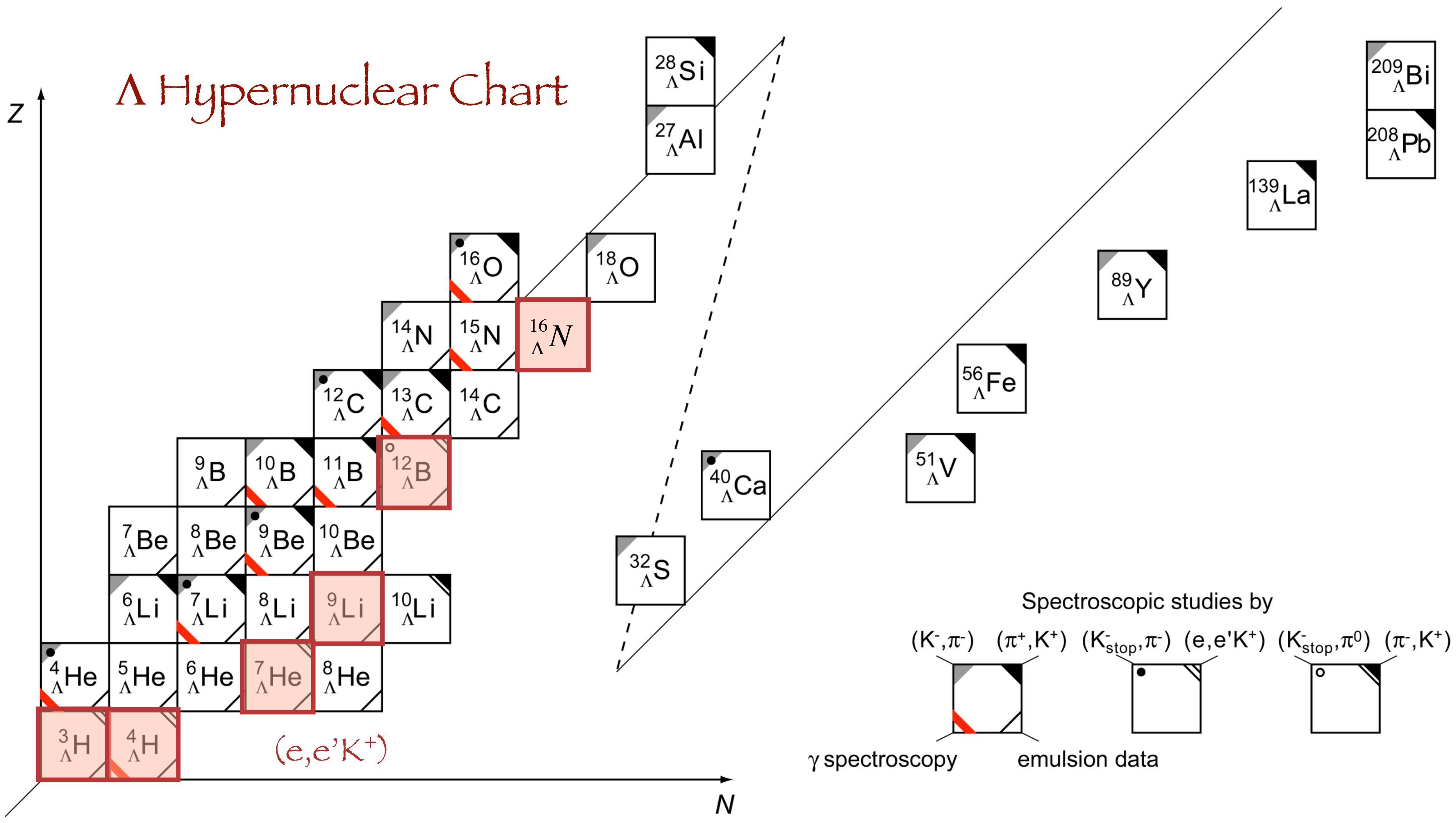
A simple model of hypernuclei: Hyperon-Nucleus effective potential

Hypernucleus ≈ Ordinary Nuclear Core + Hyperon
in a hyperon-nucleus effective potential

$$V_{\Lambda N}^{eff}(r) = V_0(r) + V_S(r)\left(\vec{S}_N \cdot \vec{S}_\Lambda\right) + V_T(r)S_{12} + V_{ls}(r)\left(\vec{L} \times \vec{S}^+\right) + V_{als}(r)\left(\vec{L} \times \vec{S}^-\right)$$

- $V_0(r)$: central
- $V_S(r)\left(\vec{S}_N \cdot \vec{S}_\Lambda\right)$: spin-spin
- $V_T(r)S_{12}$: tensor
- $V_{ls}(r)\left(\vec{L} \times \vec{S}^+\right)$: symmetric spin-orbit
- $V_{als}(r)\left(\vec{L} \times \vec{S}^-\right)$: antisymmetric spin-orbit (zero in NN due to Pauli principle)

Present status of Λ Hypernuclear Spectroscopy

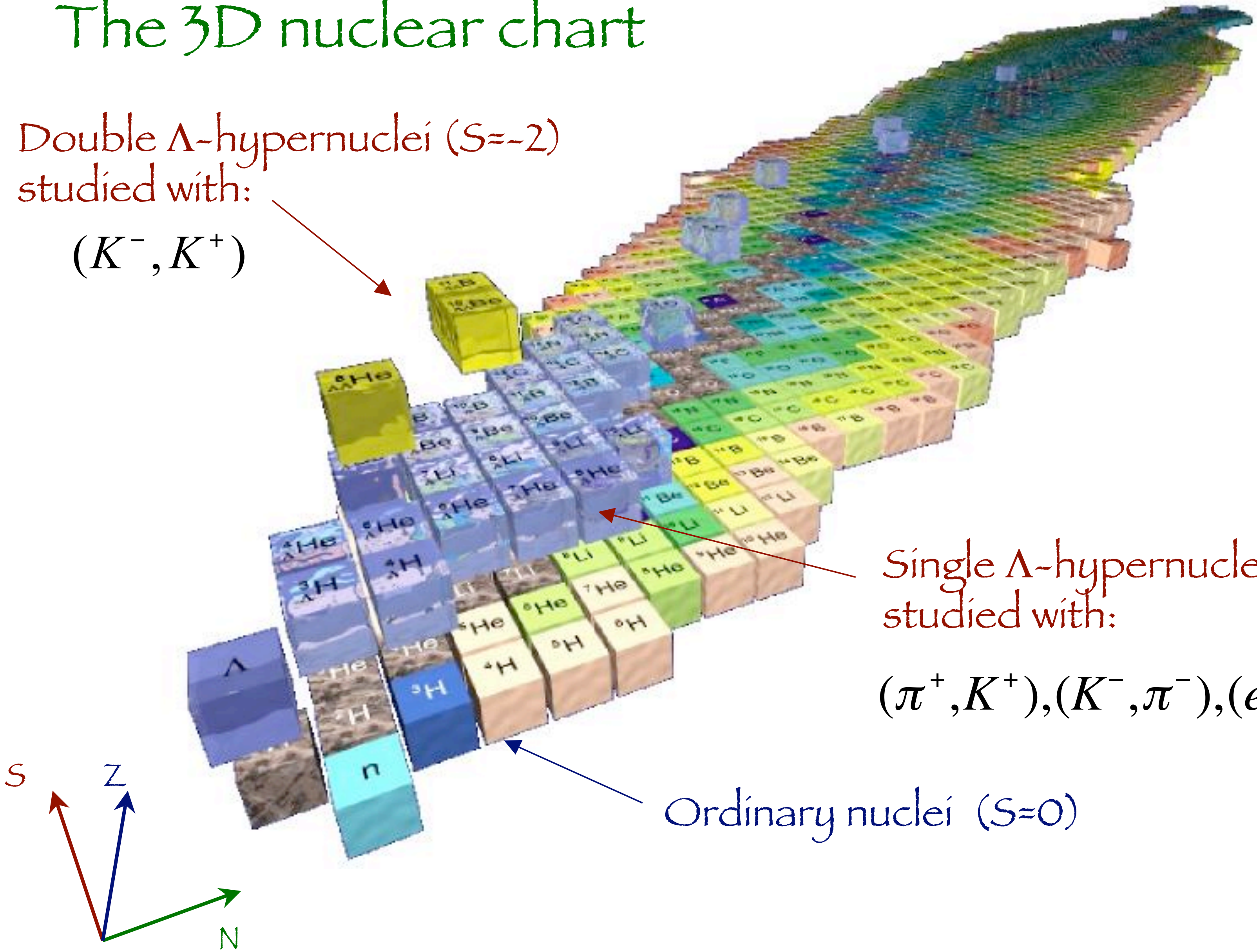


O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006)

The 3D nuclear chart

Double Λ-hypernuclei (S=-2) studied with:

(K^-, K^+)

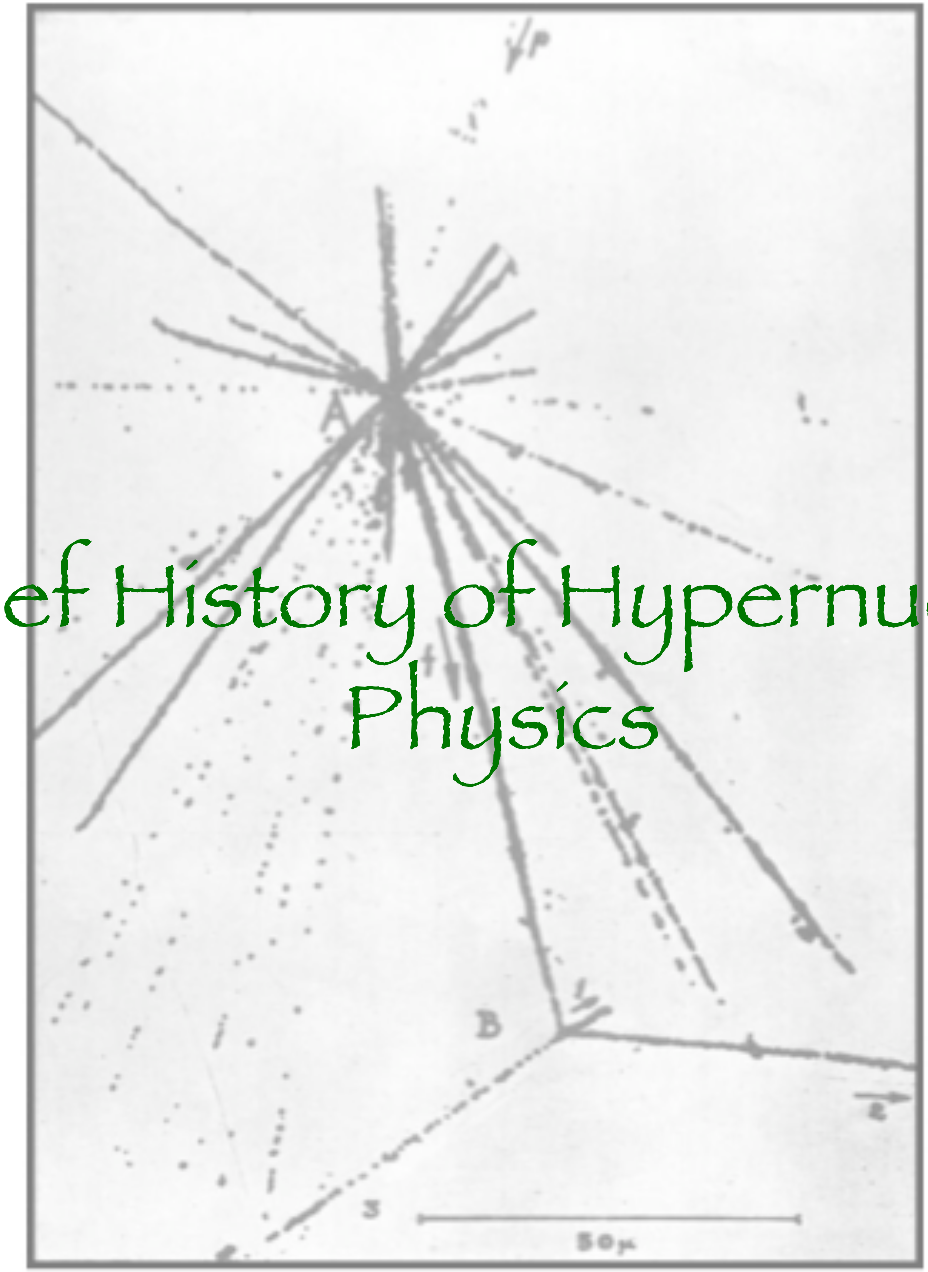


Single Λ-hypernuclei (S=-1) studied with:

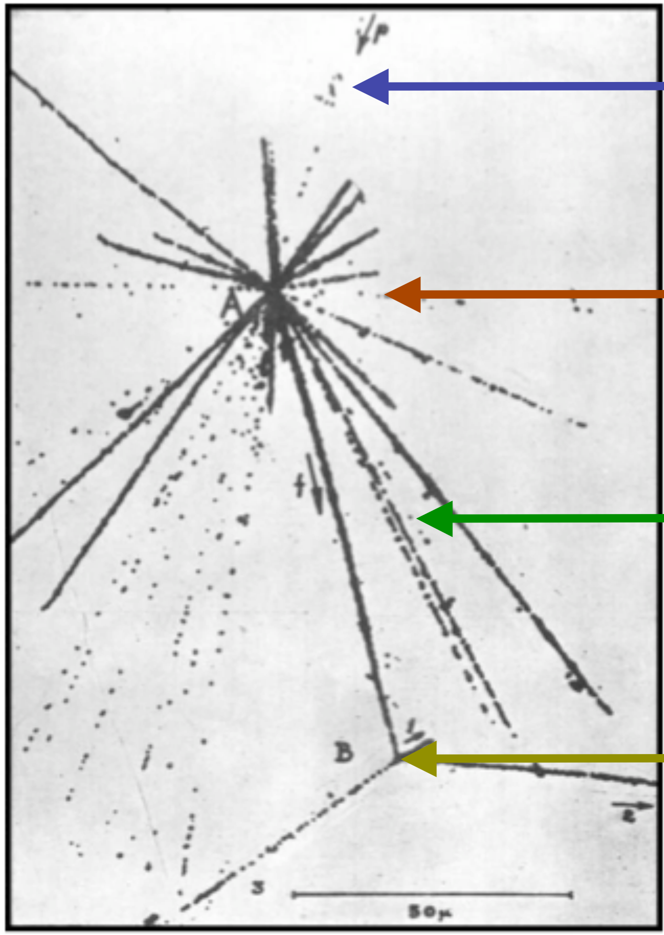
$(\pi^+, K^+), (K^-, \pi^-), (e, e' K^+)$

Ordinary nuclei (S=0)

Brief History of Hypernuclear Physics



First hypernuclear event observed in a nuclear emulsion by Marian Danysz and Jerzy Pniewski in 1952



Incoming high energy cosmic ray

Collision with the nucleus

Nuclear fragments that eventually stop in the emulssion

One fragment containing a hyperon disintegrates weakly

To commemorate the discovery of Danysz and Pniewski a postcard was issued by the Polish Post in May 1993

(200.000 postcards, postcard price 2000 zl, stamp 1500 zl)

A few years earlier, in 1989, the postmask designed on the basis of the first hypernucleus observation was used for the 20th International Physics Olympiad at the Warsaw post office number 64

Historical Overview

1953 → 1970 : hypernuclear identification with visualizing techniques emulsions, bubble chambers

1962 : first double Λ hypernucleus discovered in a nuclear emulsion irradiated by a beam of K^- mesons at CERN

1970 → Now : Spectrometers at accelerators:

CERN (up to 1980)

BNL : (K^-, π^-) and (π^+, K^+) production methods

KEK : (K^-, π^-) and (π^+, K^+) production methods

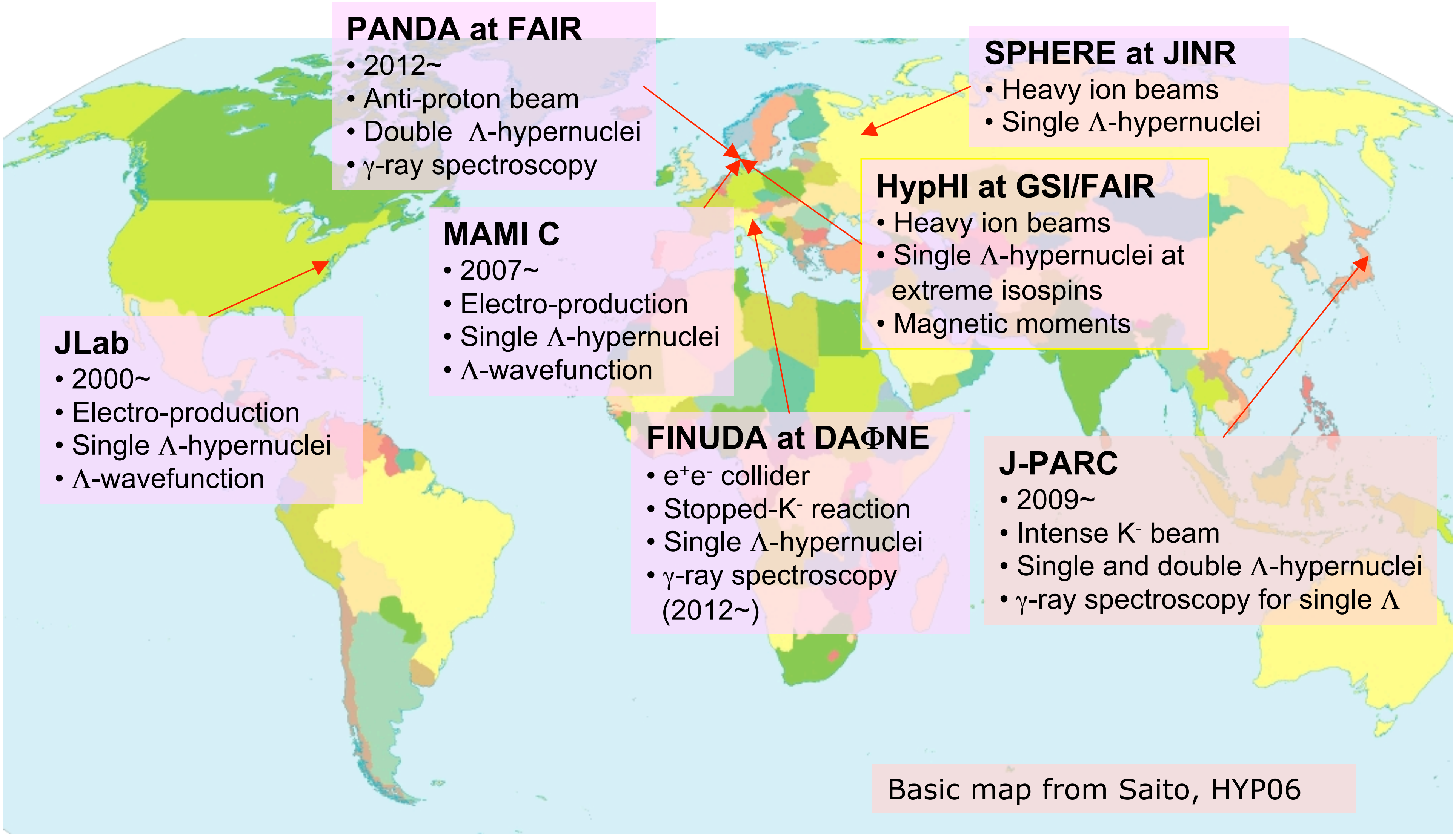
After 2000 : Stopped kaons at DAΦNE (FINUDA) : (K^-_{stop}, π^-)

The new electromagnetic way :

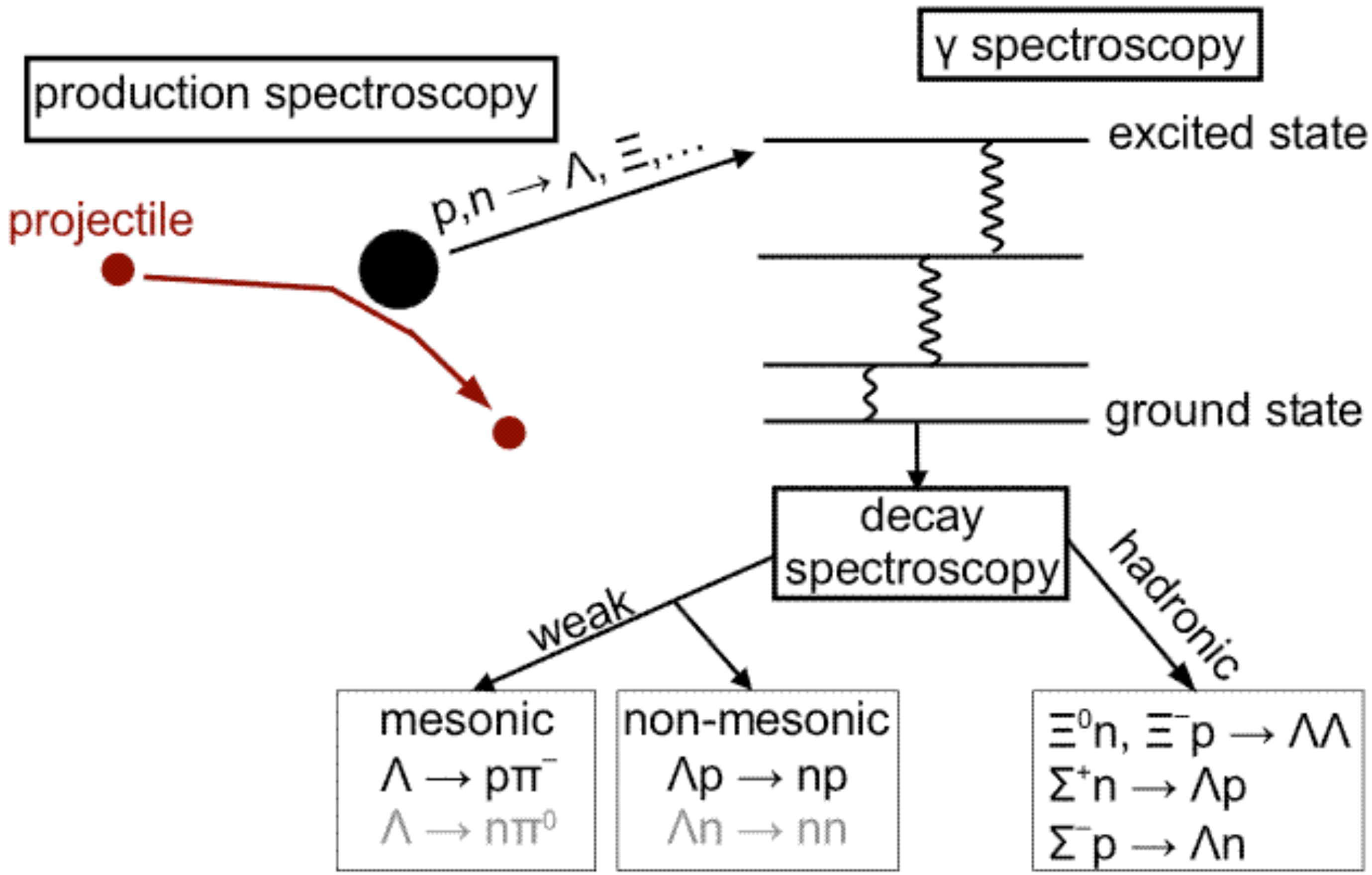
HYPERNUCLEAR production with

ELECTRON BEAM $(e,e'K^+)$ at JLAB &MAMI-C

International Hypernuclear Network



Hypernuclei: from the cradle to the grave

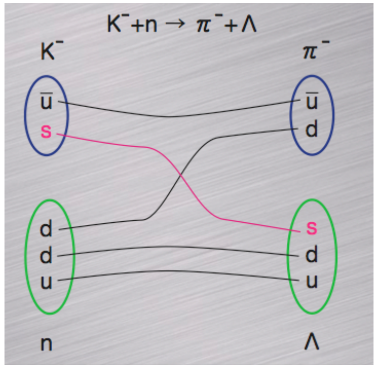


Production of Λ hypernuclei can occur by …

- Strangeness exchange: (BNL, KEK, JPARC)
  (replace a u or d quark with an s quark)

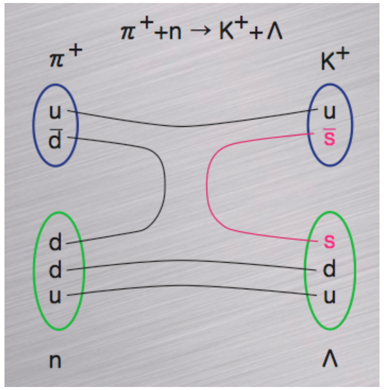
$$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$

Where the K^- in-flight or stopped



- Associated production: (BNL, KEK, GSI)
  (produces an $s\bar{s}$ pair)

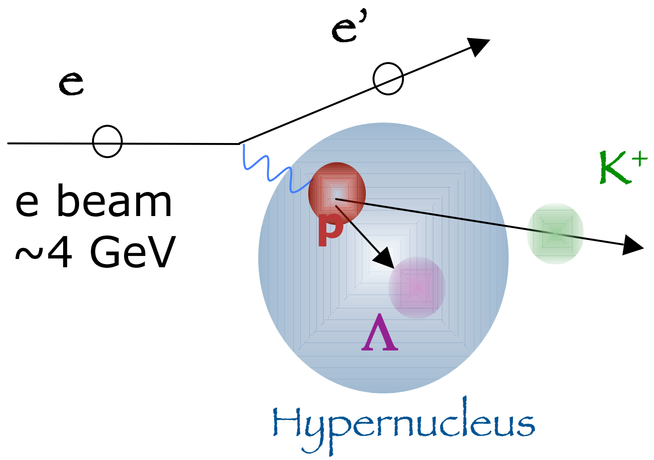
$$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$$



Electroproduction: (JLAB, MAMI-C)

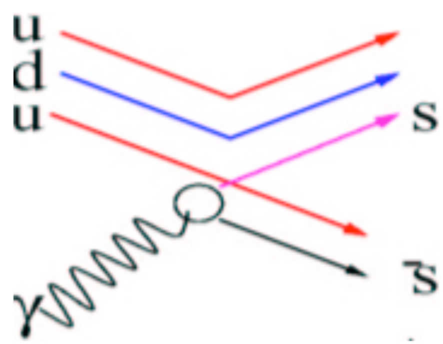
$$e^- + {}^{A}Z \rightarrow e^{-\prime} + K^+ + {}^{A}_{\Lambda}(Z-1)$$

${}^{A}Z(e,e'K)^{A}(Z\text{-}1)_{\Lambda}$

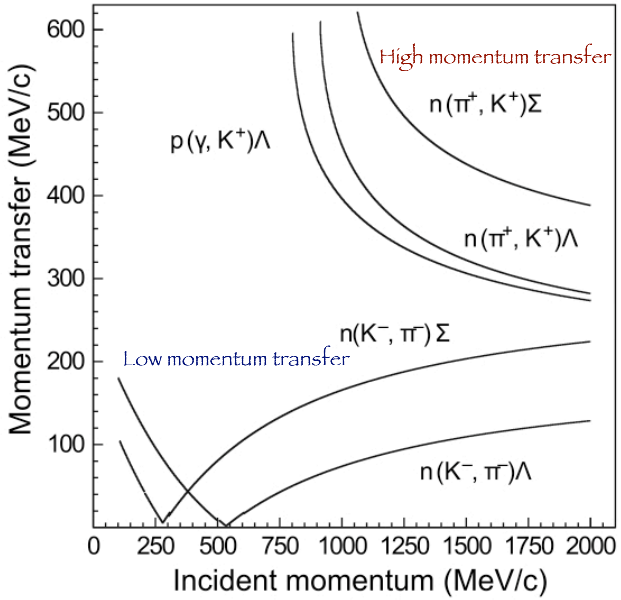


elementary process

$$\gamma + p \rightarrow \Lambda + K^+$$



Production kinematics



$n(\pi^+,K^+)\Lambda$, $p(\gamma,K^+)\Lambda$

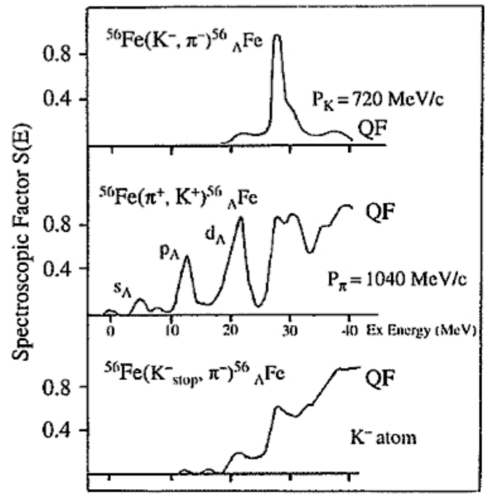
✓ High momentum transfer ➔ hyperon has large probability of escaping the nucleus.

✓ Longer π^+ and K^+ mean free path ➔ interaction with interior nucleons, significant angular momentum transfer.

$n(K^-,\pi^-)\Lambda$

✓ Low momentum transfer ➔ hyperon has large probability of being bound.

✓ Attenuation of (K^-,π^-) reaction in matter (resonance states). Interacion with outer shell neutrons replacing it with a Λ in the same shell.



Measurement of hypernuclear masses

$$M_{{}^{A}_{\Lambda}Z} - M_{{}^{A}Z} = B_{{}^{A}Z} - B_{{}^{A}_{\Lambda}Z} + M_{\Lambda} - M_{N}$$

- Stopped K⁻ reaction

$(K^{-}_{stopped}, \pi^{-})$

$$K^{-}_{stopped} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^{-}$$

$$M_{{}^{A}_{\Lambda}Z} = \sqrt{\left(E_{\pi} - M_{K} - M_{{}^{A}Z}\right)^{2} - p_{\pi}^{2}}$$

Need only π- outgoing momentum
➔ One Spectrometer

- In-flight reactions

$(K^{-}_{in-flight}, \pi^{-})$ (π^{+}, K^{+})

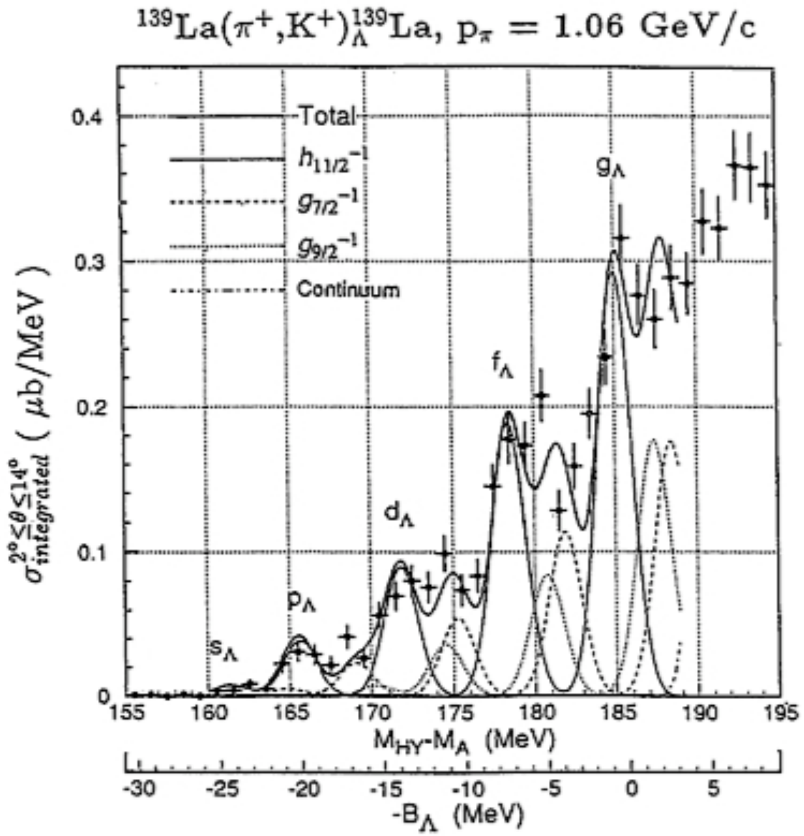
$$K^{-}_{in-flight} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^{-}$$

$$\pi^{+} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^{+}$$

$$M_{{}^{A}_{\Lambda}Z} = \sqrt{\left(E_{\pi} - E_{K} - M_{{}^{A}Z}\right)^{2} - \left(\vec{p}_{\pi} - \vec{p}_{K}\right)^{2}}$$

Need incident & outgoing momenta
➔ Two Spectrometers

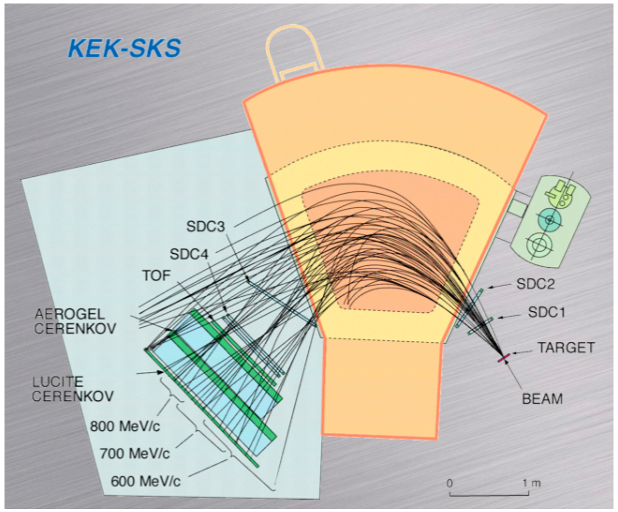
Example: spectrum for a (π^+,K^+) on a heavy target



T. Hasegawa et al., Phys. Rev. C 53, 1210 (1996)

$$\pi^+ + {}^{139}La \rightarrow {}^{139}_{\Lambda}La + K^+$$

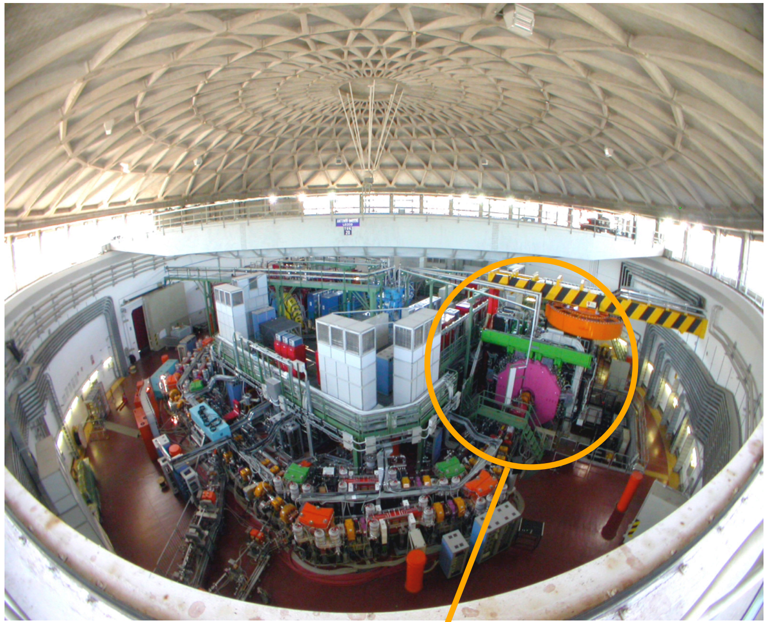
- ✓ Energy resolution: 2.5 MeV
- ✓ Clear shell structure
- ✓ Obtained with a typical magnetic spectrometer for the detection of K^+



The FINUDA experiment @ DAΦNE (Frascati)

DAΦNE: Double Annular e^+e^-
Φ-factory for Nice Experiments

e^+e^- collider dedicated to the production of Φ resonance

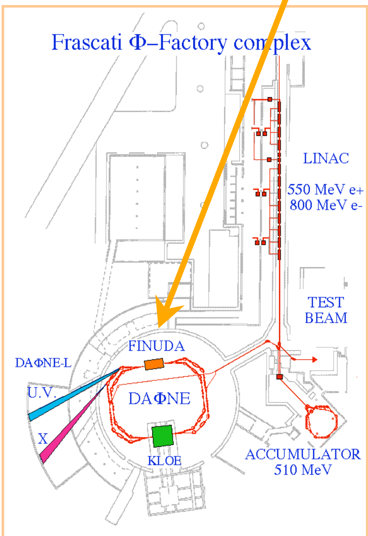


FINUDA: FIsica NUcleare at DAΦNE

produce hypernuclei by stopping negative kaon originating from Φ decay in nuclear target

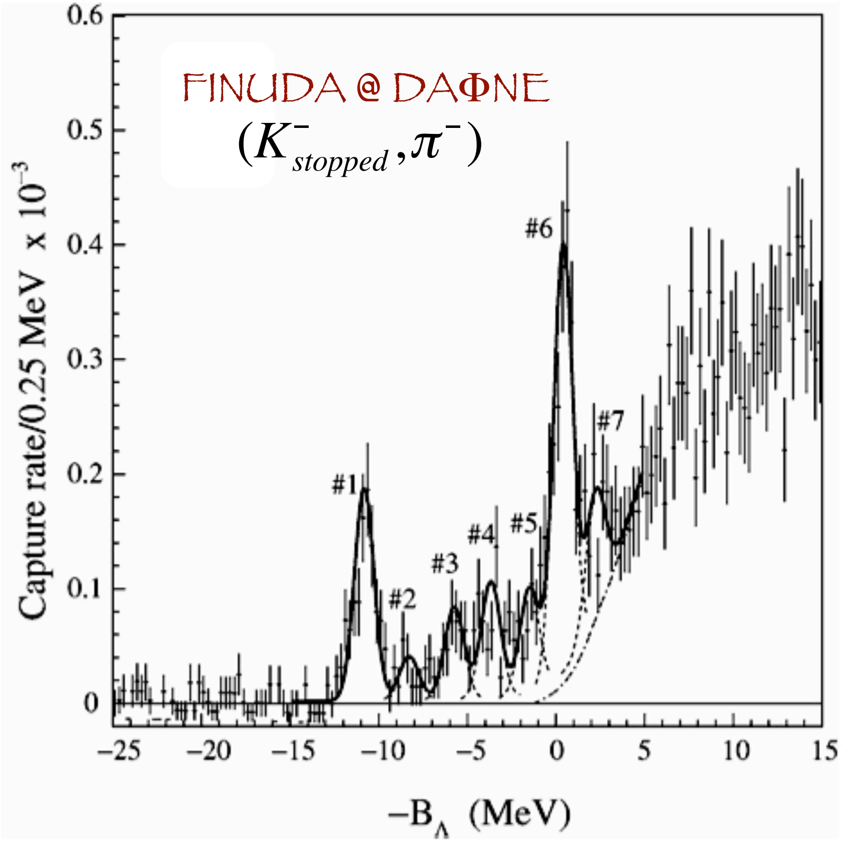
$$e^+ + e^- \to \Phi \to K^+ + K^-$$

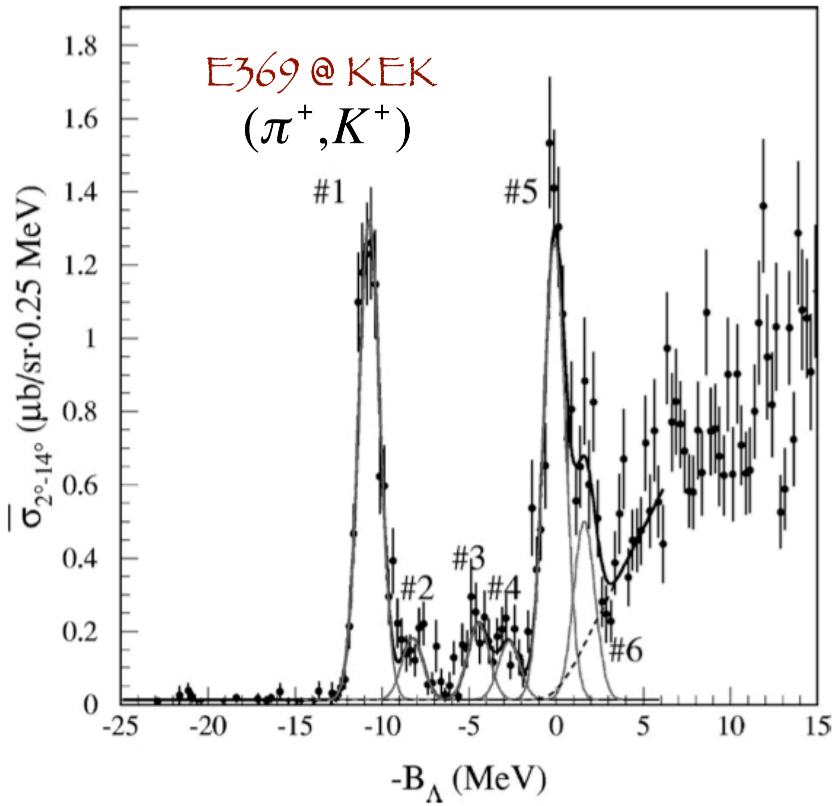
$$K^-_{stopped} + {}^{A}Z \to {}^{A}_{\Lambda}Z + \pi^-$$



FINUDA results on $^{12}{}_{\Lambda}C$

Very good agreement between FINUDA results & E368 @ KEK ones



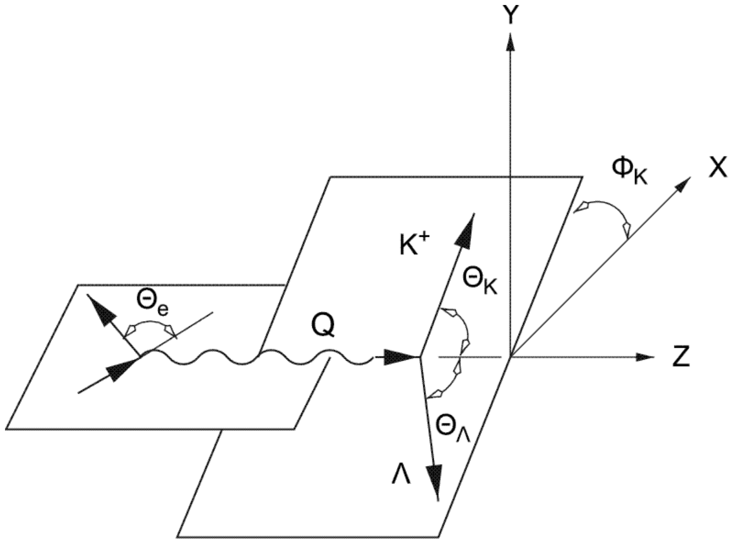


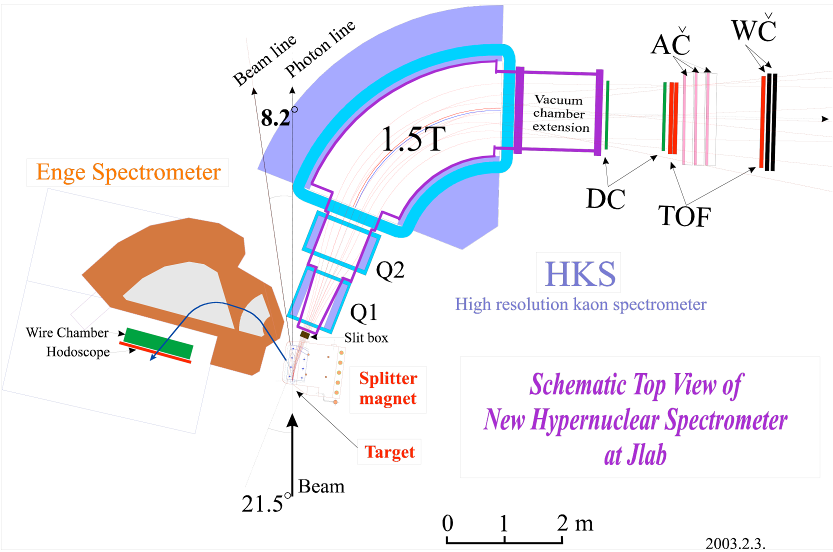
M. Agnello et al., Phys. Lett. B 622, 35 (2005)

H. Hotchi et al., Phys. Rev. C 64, 044302 (2001)

The (e,e'K$^+$) reaction

- Relatively new (JLAB, MAMI-C).
- Excellent energy resolution of energy spectrum.
- Although the cross section is 10^{-2} smaller than that of (π^+,K$^+$) this is compensated by larger beam intensity.





The experimental geometry requires two spectrometers to detect:

✓ the scattered electrons which defines the virtual photons

✓ the kaons

Hypernuclear spectrum from the (e,e'K$^+$) reaction

Energy left inside the nucleus
(related to the excitation energy)

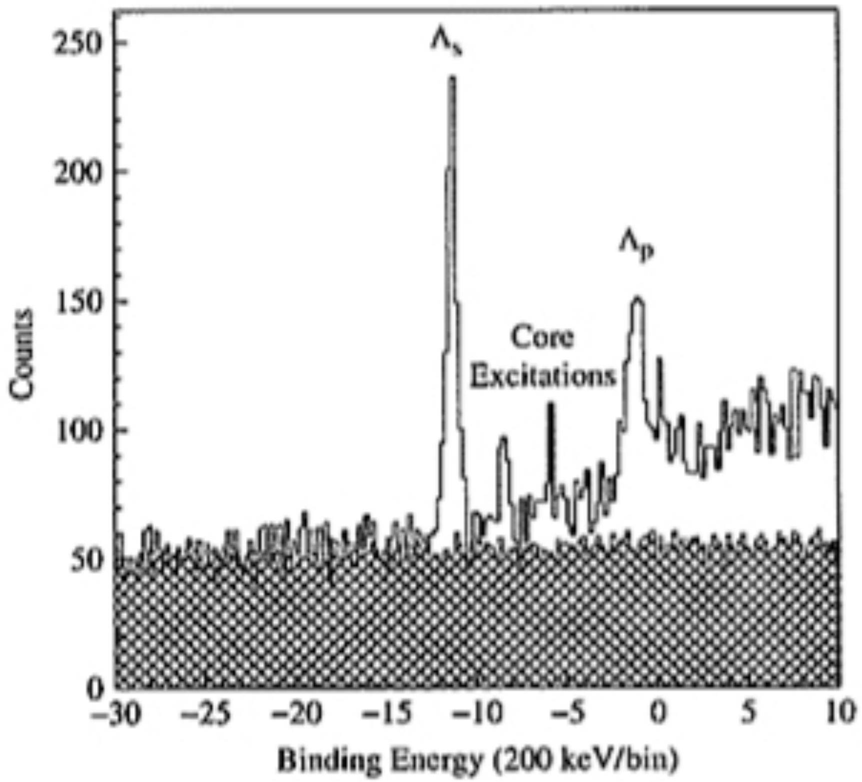
$$E_x = E_e - E_{e'} - E_{K^+}$$

Incoming electron (E_e)

Outgoing electron ($E_{e'}$)

Outgoing kaon (E_{K^+})

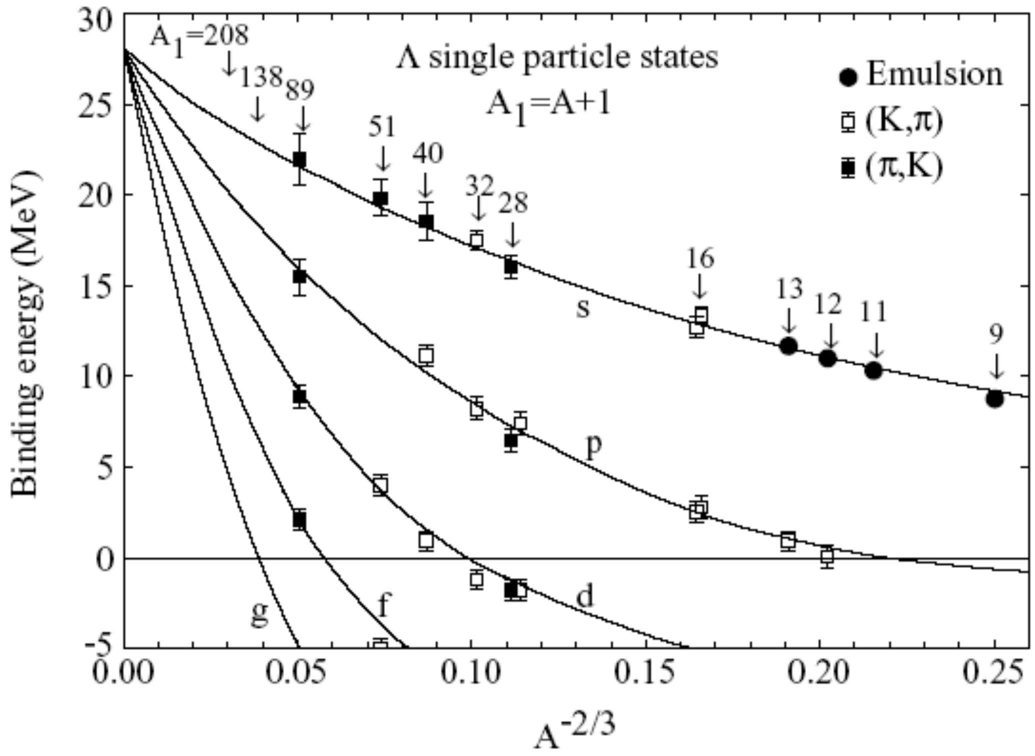
$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$ spectrum



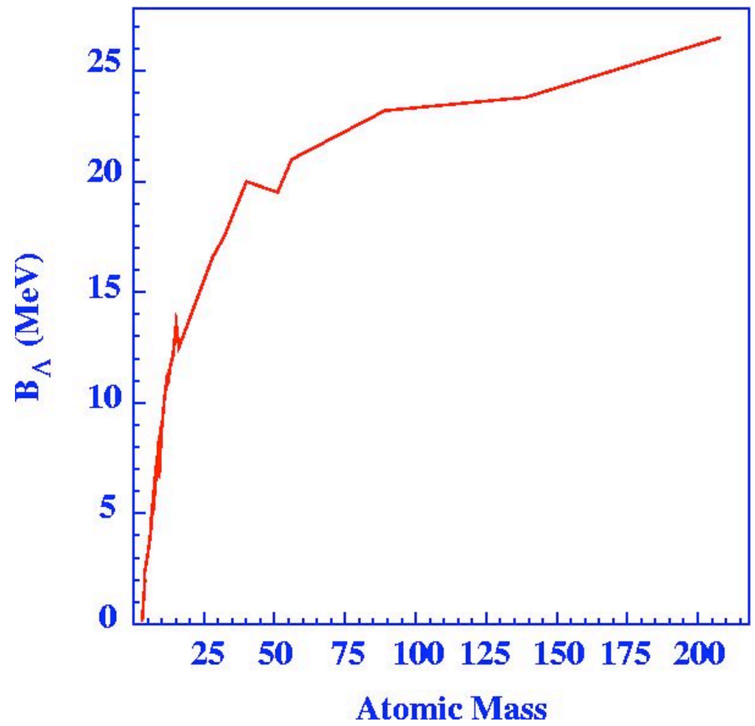
V. Rodrigues, PhD Thesis, University of Houston (2006)

In summary ...

The Λ single particle states



Hypernuclear binding energies

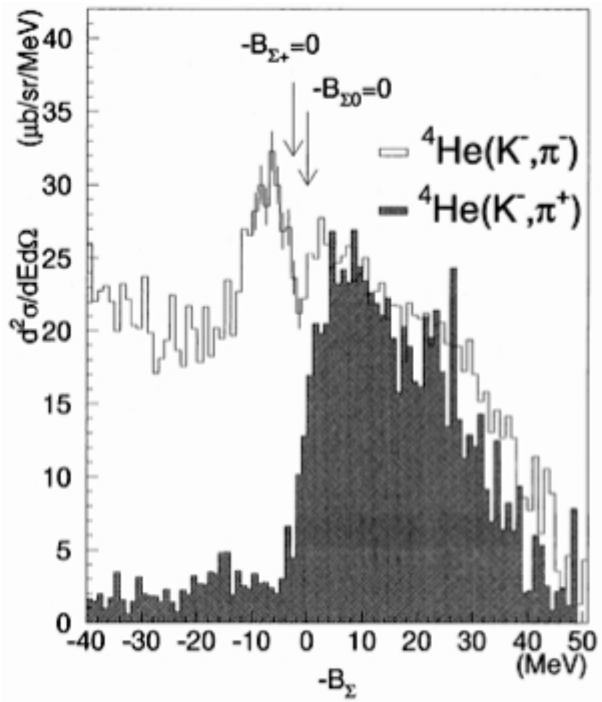


Hypernuclear binding energies show saturation as ordinary nuclei

Production of Σ hypernuclei

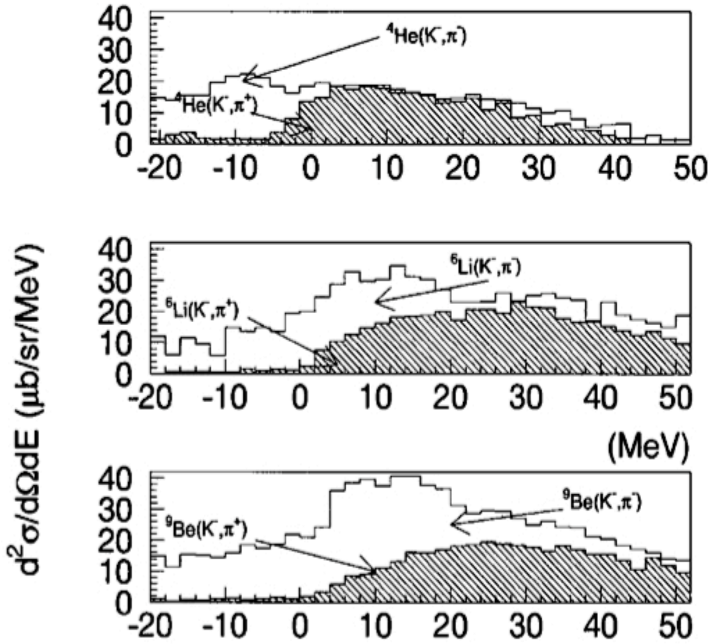
Production mechanisms similar to the ones considered for Λ hypernuclei like, e.g., strangeness exchange $(K^-,\pi^\pm)$

$^4_\Sigma$He bound state
E ~ 4 MeV, Γ ~ 7 MeV



T. Nagae et al., Phys. Rev. Lett. 80, 1605 (1998)

Σ hypernuclear states in p-shell hypernuclei



S. Bart et al., Phys. Rev. Lett. 83, 5238 (19989)

What do we know about double Λ hypernuclei ?

Not so much ....

	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)		
$^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6	Prowse	(1966)
$^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373	(2001)
$^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	Danysz	(1963)
$^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176	(1991)
$^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176	(1991)
$^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$		KEK-E373	(2001, unpublished)

Nagara event

same event

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

The production of double Λ hypernuclei

- Ξ^- conversion in two Λ's:

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\, MeV$$

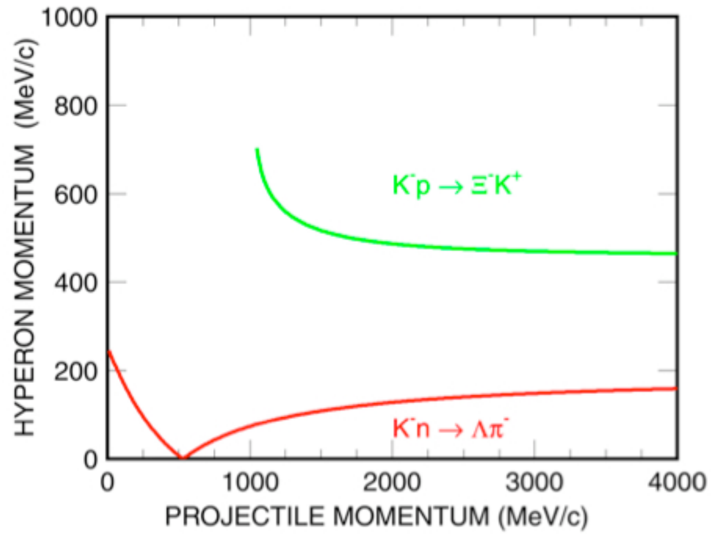
- Ξ^- production:

✓ (K^-,K^+) reaction (BNL, KEK)

$$K^- + p \rightarrow \Xi^- + K^+$$

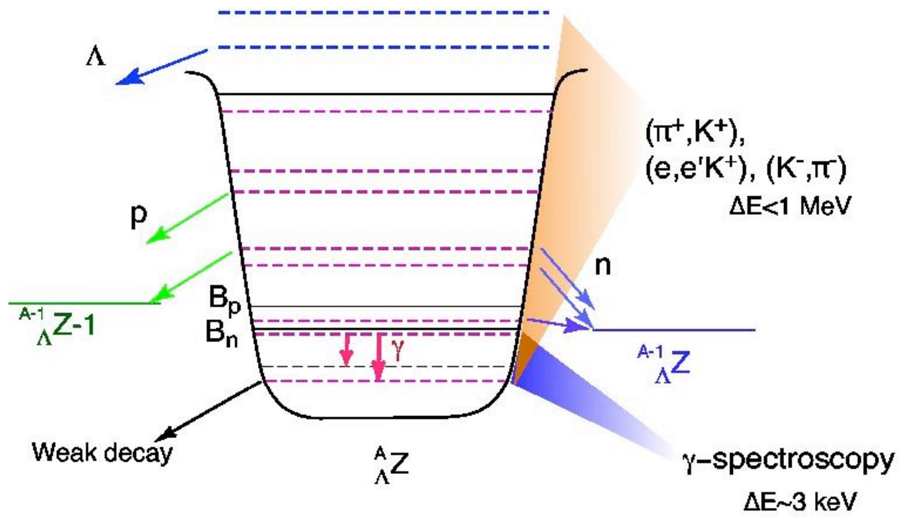
✓ Antiproton production (PANDA@FAIR)

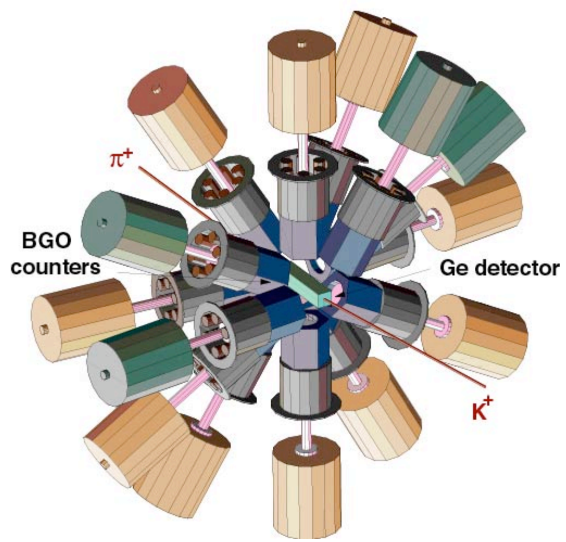
$$p + \bar{p} \rightarrow \Xi^- + \bar{\Xi}^+$$



Hypernuclear γ-ray spectroscopy

- Produced hypernuclei can be in an excited state.
- Energy released by emission of neutrons or protons or γ-rays when hyperon moves to lower states.

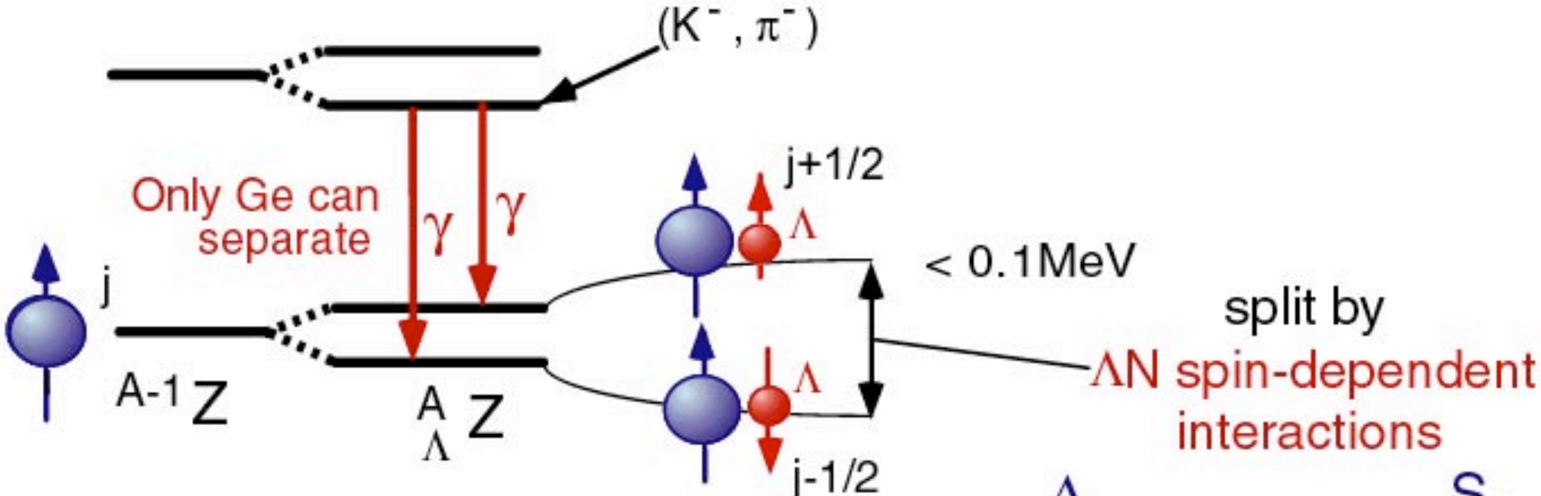




Hyperball

- Excellent resolution with Ge (NaI) detectors.
- Λ depth potential in nucleus ~ 30 MeV ➔ observation of γ-rays limited to low excitation region.
- γ-ray transition measures only energy difference between two states.

Hypernuclear fine structure and the spin-dependent ΛN interaction



$$V^{eff}_{\Lambda N} = V_0(r) + V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda + V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N + V_T(r)\, S_{12}$$

Δ S_Λ S_N T

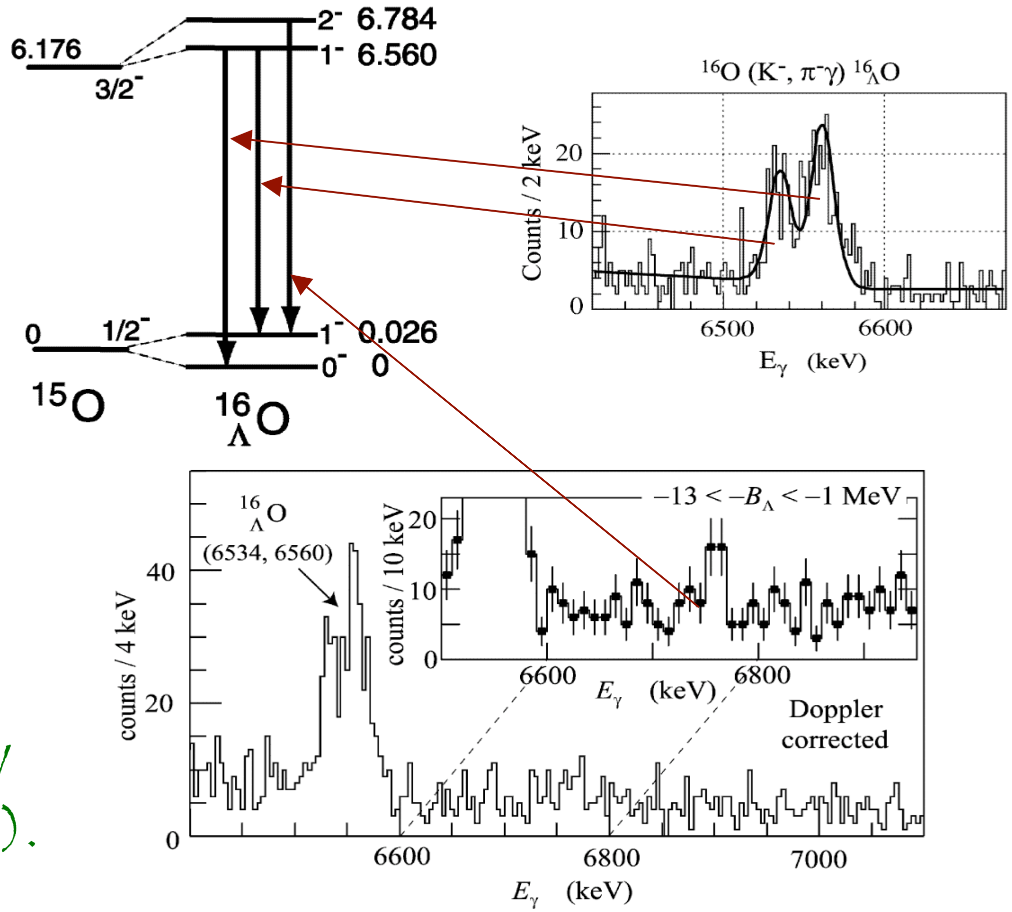
Integrated with shell-model w.f.
(Millener's parameterization)

γ-ray spectrum of $^{16}_{\Lambda}O$

- Observed twin peaks demonstrate hypernuclear fine structure for $^{16}_{\Lambda}O$ ($1^- \rightarrow 1^-, 0^-$) transitions.

- Small spacing in twin peaks caused by spin-dependent ΛN interaction.

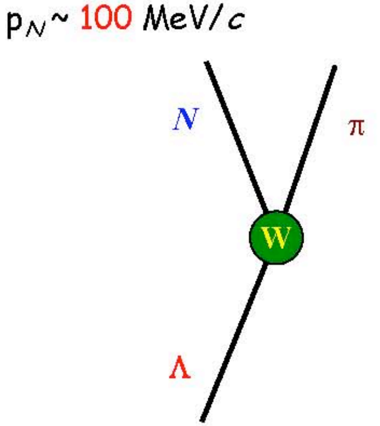
- Recent analysis revealed another transition at 6758 keV corresponding to $^{16}_{\Lambda}O$ ($2^- \rightarrow 0^-$).



M. Ukai et al., Phys. Rev. C 77, 05315 (2008)

The Weak Decay of Λ hypernuclei

free Λ decay

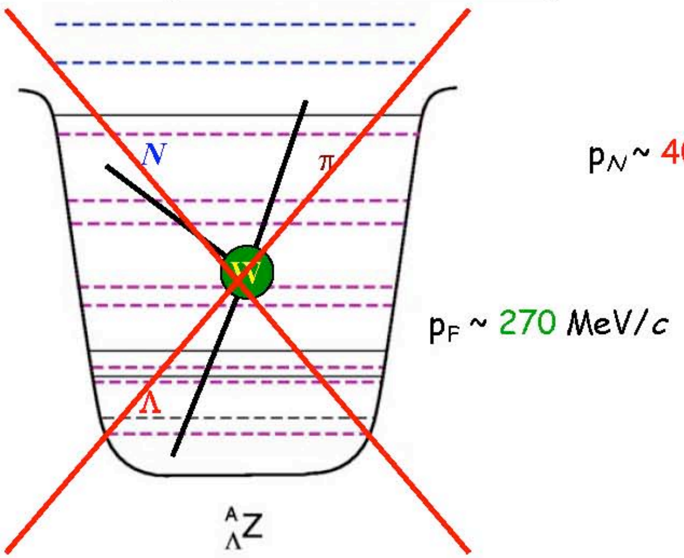


$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

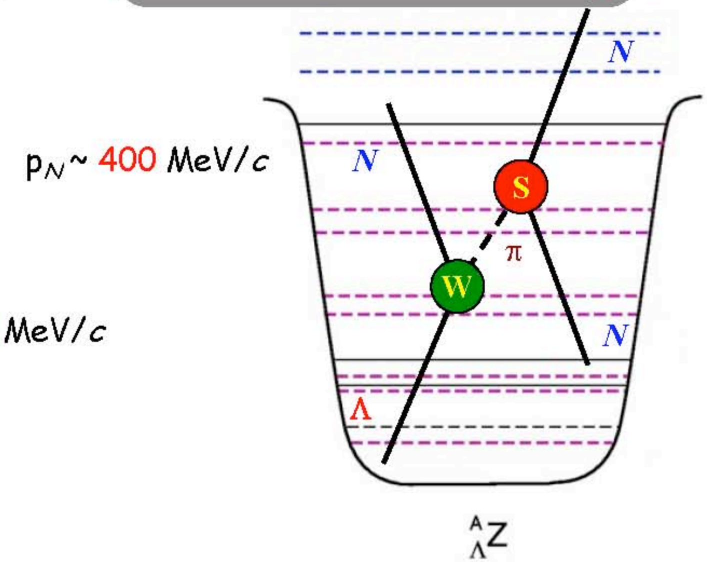
$\tau_\Lambda = 263$ ps

hypernucleus mesonic decay



suppressed by Pauli blocking

hypernucleus non-mesonic decay



$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

Decay observables

Hypernuclear lifetimes-Decay Rates

$$\Gamma = \Gamma_M + \Gamma_{NM} + \Gamma_{2N}$$

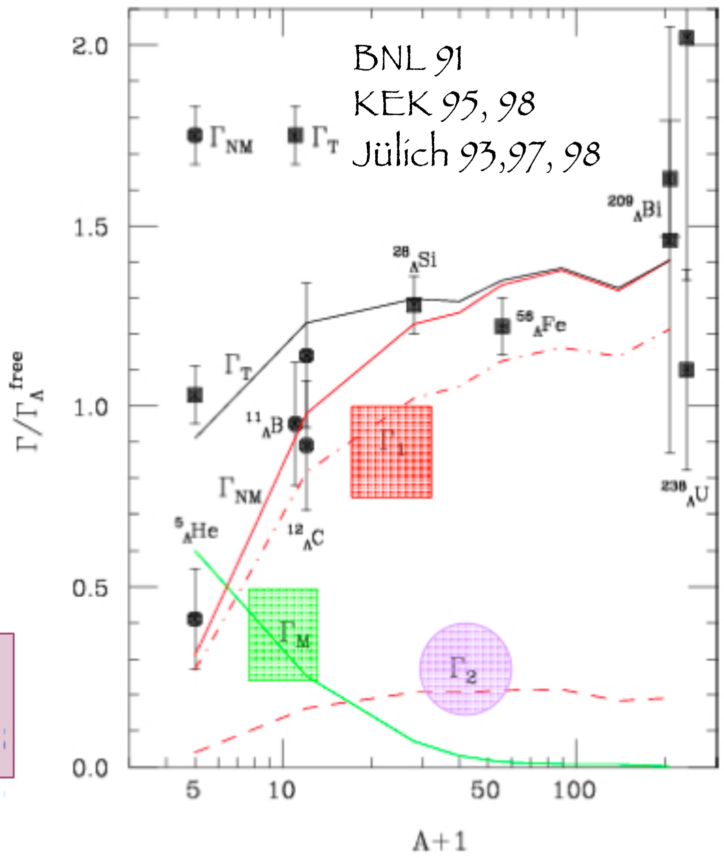
$$= \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_{np}$$

$\Lambda \to N\pi$
$p_N \sim 100\ MeV$

$\Lambda N \to NN$
$p_N \sim 420\ MeV$

$\Lambda N \to NNN$
$p_N \sim 340\ MeV$

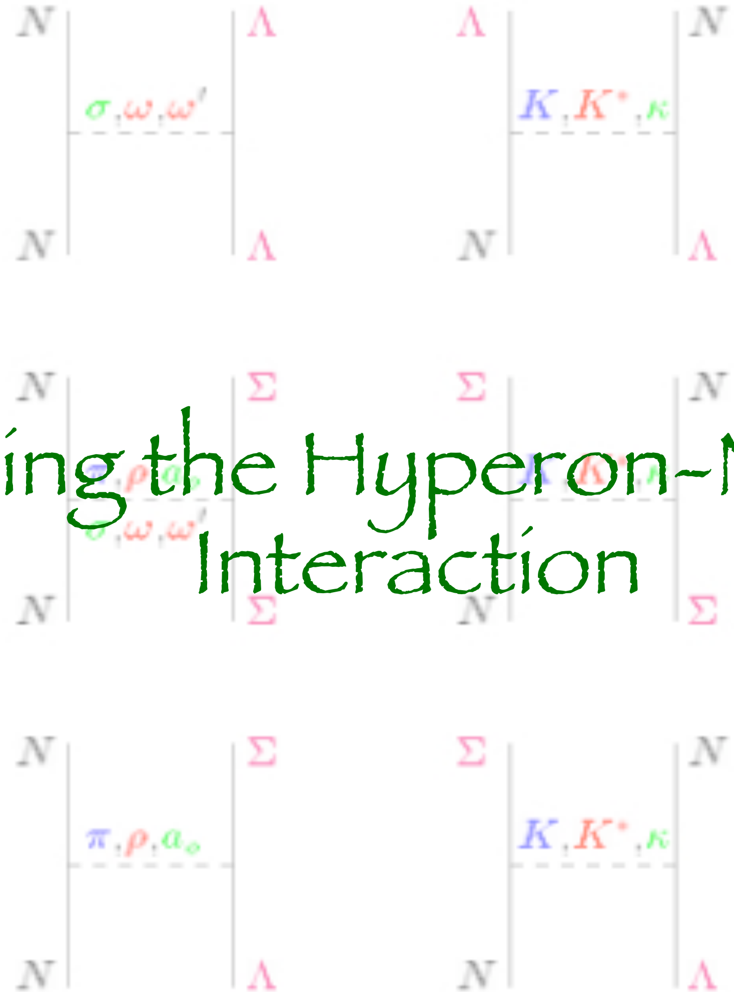
$$\Gamma \sim \Gamma_\Lambda^{free} = 3.8 \times 10^9\ s^{-1}$$



W. M. Alberico et al., Phys. Rev. C 61, 044314 (2000)

(well reproduced by theoretical models)

Building the Hyperon-Nucleon Interaction



The Hyperon-Nucleon interaction ...

- Study of the role of strangeness in low and medium energy nuclear physics.
- Test of $SU(3)_{flavor}$ symmetry.
- Input for Hypernuclear Physics & Astrophysics (Neutron Stars).

But due to:

✓ difficulties of preparation of hyperon beams.

✓ no hyperon targets available.

- Only about 35 data points, all from the 1960's
- 10 new data points, from KEK-PS E251 collaboration (2000)

(cf. > 4000 NN data for $E_{lab} < 350$ MeV)

YN meson-exchange models

Strategy: start from a NN model & impose $SU(3)_{flavor}$ constraints

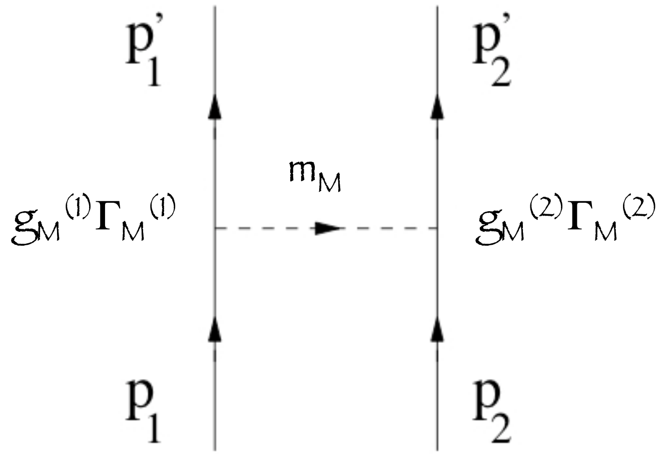
$$L = g_M \Gamma_M \left(\overline{\Psi}_B \Psi_B\right)\phi_M$$

- scalar: σ,δ $\Gamma_s = 1$
- pseudocalar: π,K,η $\Gamma_{ps} = i\gamma^5$
- vector: ρ,K,ω, ϕ $\Gamma_v = \gamma^\mu, \quad \Gamma_T = \sigma^{\mu\nu}$

$$\left\langle p_1' p_2' \middle| V_M \middle| p_1 p_2 \right\rangle = \bar{u}(p_1') g_M^{(1)} \Gamma_M^{(1)} u(p_1) \frac{P_M}{\left(p_1 - p_1'\right)^2 - m_M^2} \bar{u}(p_2') g_M^{(2)} \Gamma_M^{(2)} u(p_2)$$

$$\Downarrow$$

$$V(r) = V_0(r) + V_S(r)\left(\vec{\sigma}_1 \cdot \vec{\sigma}_2\right) + V_T(r) S_{12} + V_{ls}(r)\left(\vec{L} \times \vec{S}^+\right) + V_{als}(r)\left(\vec{L} \times \vec{S}^-\right)$$



The Nijmegen & Jülich models

Nijmegen

(Nagels, Rijken, de Swart, Maessen)

- Based on Nijmegen NN potential.
- Momemtum & Configuration Space.
- exchange of nonets of pseudo-scalar, vector and scalar.
- Strange vertices related by SU(3) symmetry with NN vertices.
- Gaussian Form Factors:

$$F_M(k^2) = e^{-\frac{k^2}{2\Lambda_M^2}}$$

Jülich

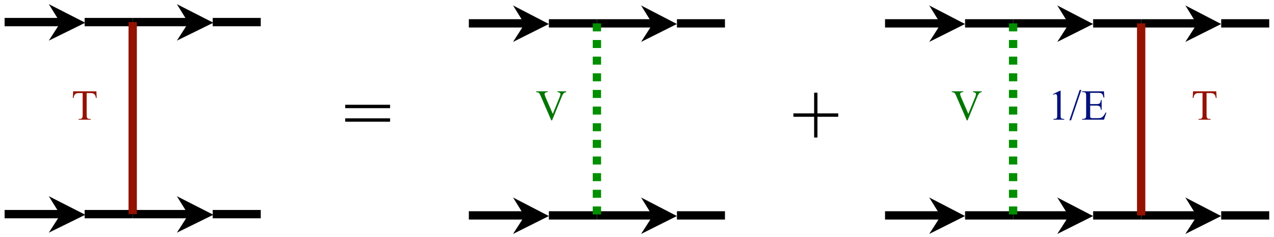
(Holzenkamp, Reube, Holinde, Speth, Haidenbauer, Meissner, Melnitchouck)

- Based on Bonn NN potential.
- Momemtum Space & Full energy-dependence & non-locality structure.
- higher-order processes involving π- and ρ-exchange (correlated 2π-exchange) besides single meson exchange.
- Strange vertices related by SU(6) symmetry with NN vertices.
- Dipolar Form Factors:

$$F_M(k^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k^2}\right)^2$$

Scattering amplitudes

Scattering amplitudes describing the hyperon-nucleon scattering are obtained by solving the Lipmann-Schwinger equation

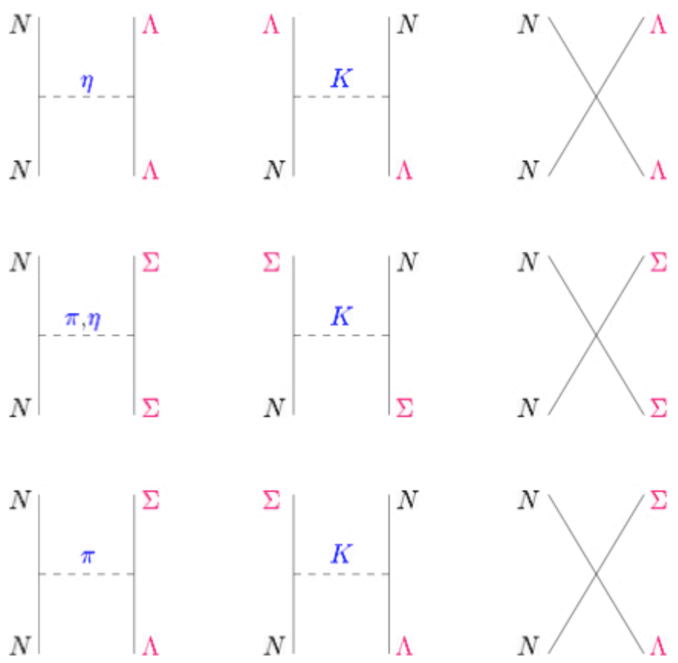


$$T = V + V \frac{1}{E} T$$

Chiral Effective Field Theory for YN

Strategy: start from a chiral effective lagrangian in a way similar to the NN case

Leading order (LO)



Polinder, Haidenbauer & Meissner, NPA 779, 244 (2006)

- Contact terms

$$L_1 = C_i^1 \langle \bar{B}_a \bar{B}_b (\Gamma_i B)_b (\Gamma_i B)_a \rangle$$

$$L_2 = C_i^2 \langle \bar{B}_a (\Gamma_i B)_a \bar{B}_b (\Gamma_i B)_b \rangle$$

$$L_3 = C_i^3 \langle \bar{B}_a (\Gamma_i B)_a \rangle \langle \bar{B}_b (\Gamma_i B)_b \rangle$$

$$\Downarrow$$

$$V^{B_1B_2 \to B_3B_4} = C_S^{B_1B_2 \to B_3B_4} + C_T^{B_1B_2 \to B_3B_4} \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

- One-pseudoscalar meson exchange

$$L = \left\langle i\bar{B}\gamma^\mu D_\mu B - M_0 \bar{B}B + \frac{D}{2}\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\} + \frac{F}{2}\bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right\rangle$$

$$\Downarrow$$

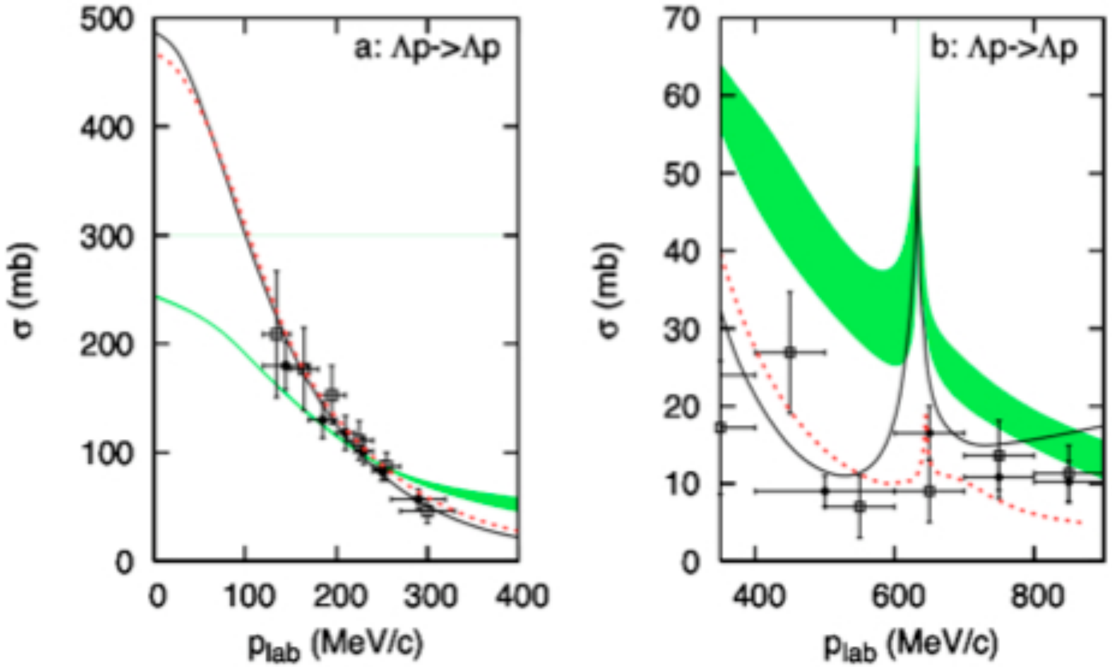
$$V^{B_1B_2 \to B_3B_4} = -f_{B_1B_2M} f_{B_3B_4M} \frac{(\vec{\sigma}_1 \cdot \vec{k})(\vec{\sigma}_2 \cdot \vec{k})}{k^2 + m_M^2}$$

- Lippmann-Schwinger equation cut-off with the regularized

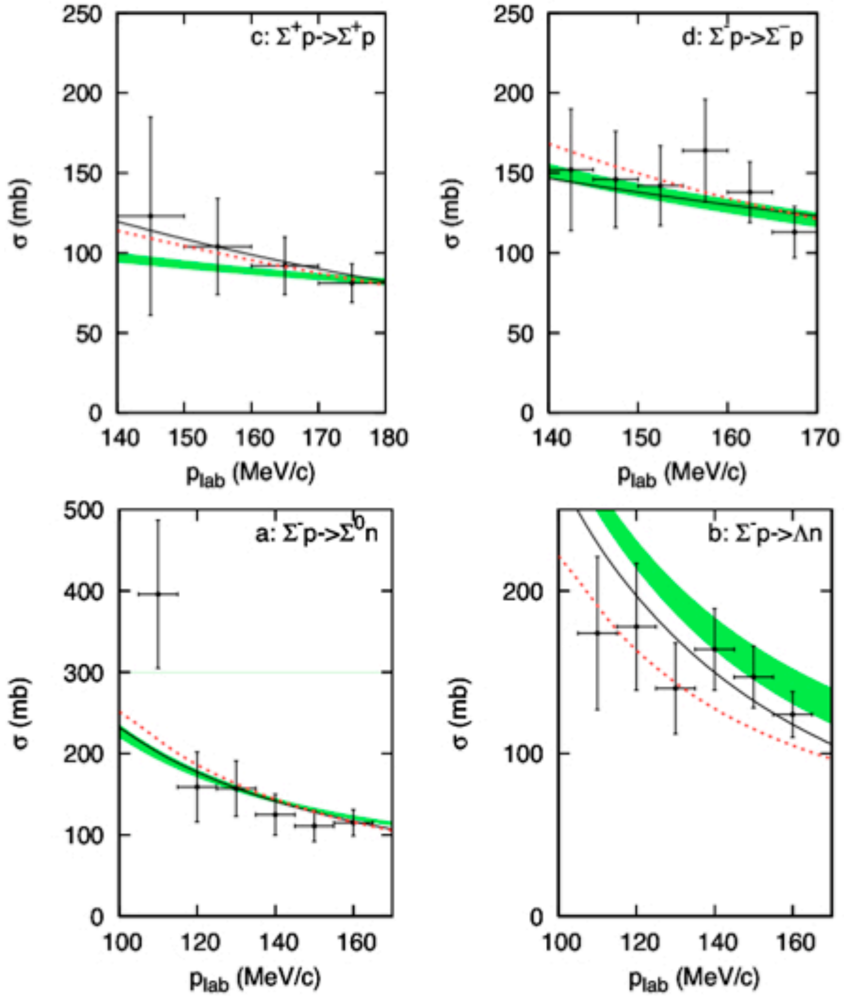
$$F(p,p',\Lambda) = e^{-\frac{\left(p^4 + p'^4\right)}{\Lambda^4}}$$

Cutoff dependence:
Λ=550-700 MeV

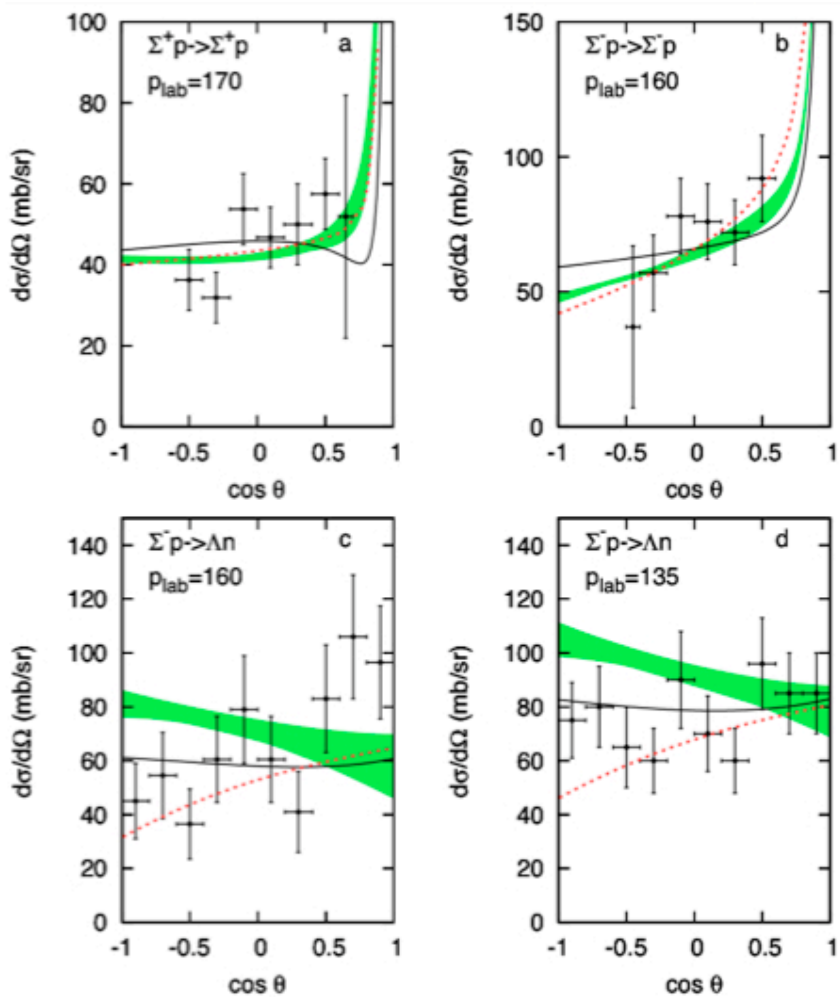
YN data rather
well described



Total cross YN sections



Differential YN cross sections



Solid: NSC97f

NPA 779, 224 (2006)

Green band: EFT

Dashed: Jülich04

Light hypernuclei properties

- Hypertriton ($^3H_\Lambda$) binding energy cutoff independent

Λ=550	Λ=600	Λ=650	Λ=700	Jülich04	NSC97f	Expt.
-2.35	-2.34	-2.34	-2.36	-2.27	-2.30	-2.354(50)

Deuteron B(^2H): -2.224 MeV

- A=4 doublet: $^4H_\Lambda$ - $^4He_\Lambda$

$^4H_\Lambda$	Λ=550	Λ=600	Λ=650	Λ=700	Jülich04	NSC97f	Expt.
$E_{sep}(0^+)$	2.63	2.46	2.36	2.38	1.87	1.60	2.04
$E_{sep}(1^+)$	1.85	1.51	1.23	1.04	2.34	0.54	1.00
ΔE_{sep}	0.78	0.95	1.13	1.34	-0.48	0.99	1.04

CSB-0^+	0.01	0.02	0.02	0.03	-0.01	0.10	0.35
CSB-1^+	-0.01	-0.01	-0.01	-0.01		-0.01	0.24

(All units are given in MeV)

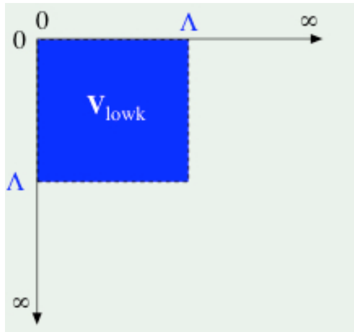
Low-momentum YN interaction

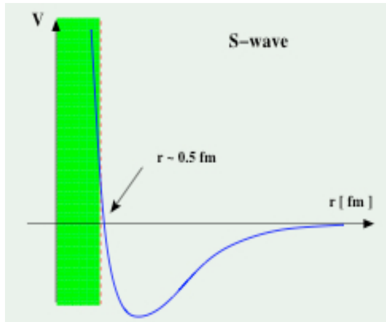
Idea: start from a realistic YN interaction & integrate out the high-momentum components in the same way as as been done for NN.

$V_{low\,k}$

- ✓ phase shift equivalent
- ✓ energy independent
- ✓ softer (no hard core)
- ✓ hermitian

B. -J. Schaefer et al., Phys. Rev. C 73, 011001 (2006)





Lippmann-Schwinger Equation

$$T(k',k;E_k) = V_{low\,k}(k',k) + \frac{2}{\pi} P \int_0^{\Lambda} dq\, q^2 V_{low\,k}(k',q) \frac{1}{E_k - H_0(q)} T(q,k;E_k)$$

Conditions

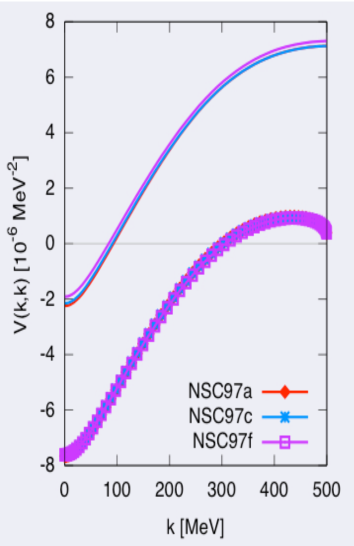
$$\frac{dT_\Lambda}{d\Lambda} = 0; \quad V_{low\,k} = \Lambda \qquad \Lambda \to \infty : V_{low\,k} = V_{bare}$$

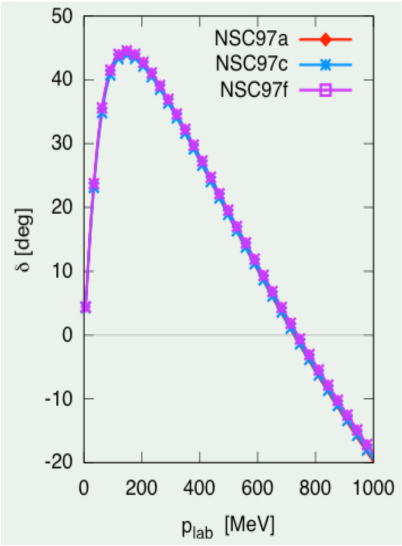
Renormalization Group Flow Equation

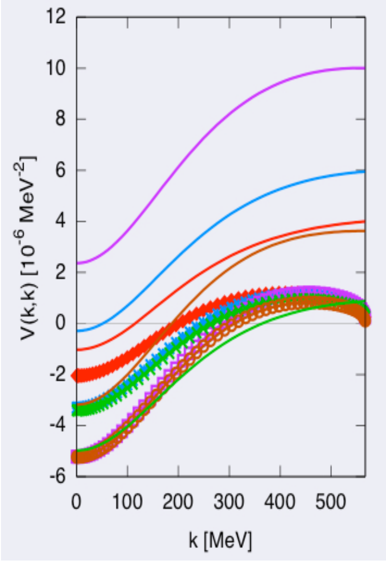
$$\frac{d}{d\Lambda} V_{low\,k}(k',k) = -\frac{2}{\pi} \frac{V_{low\,k}(k',\Lambda) T(\Lambda,k;\Lambda^2)}{E_k - H_0(\Lambda)}$$

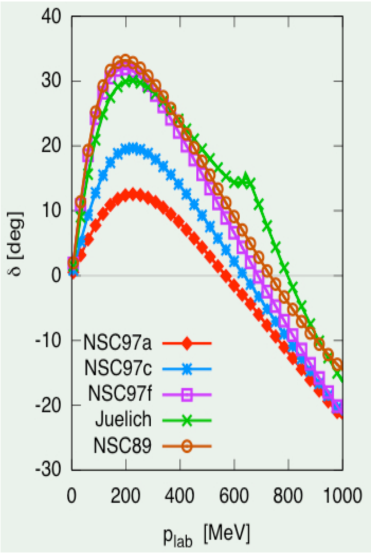
$^1S_0$ (I=3/2) matrix elements and phase-shift for ΣN➔ΣN

Λ=500 MeV







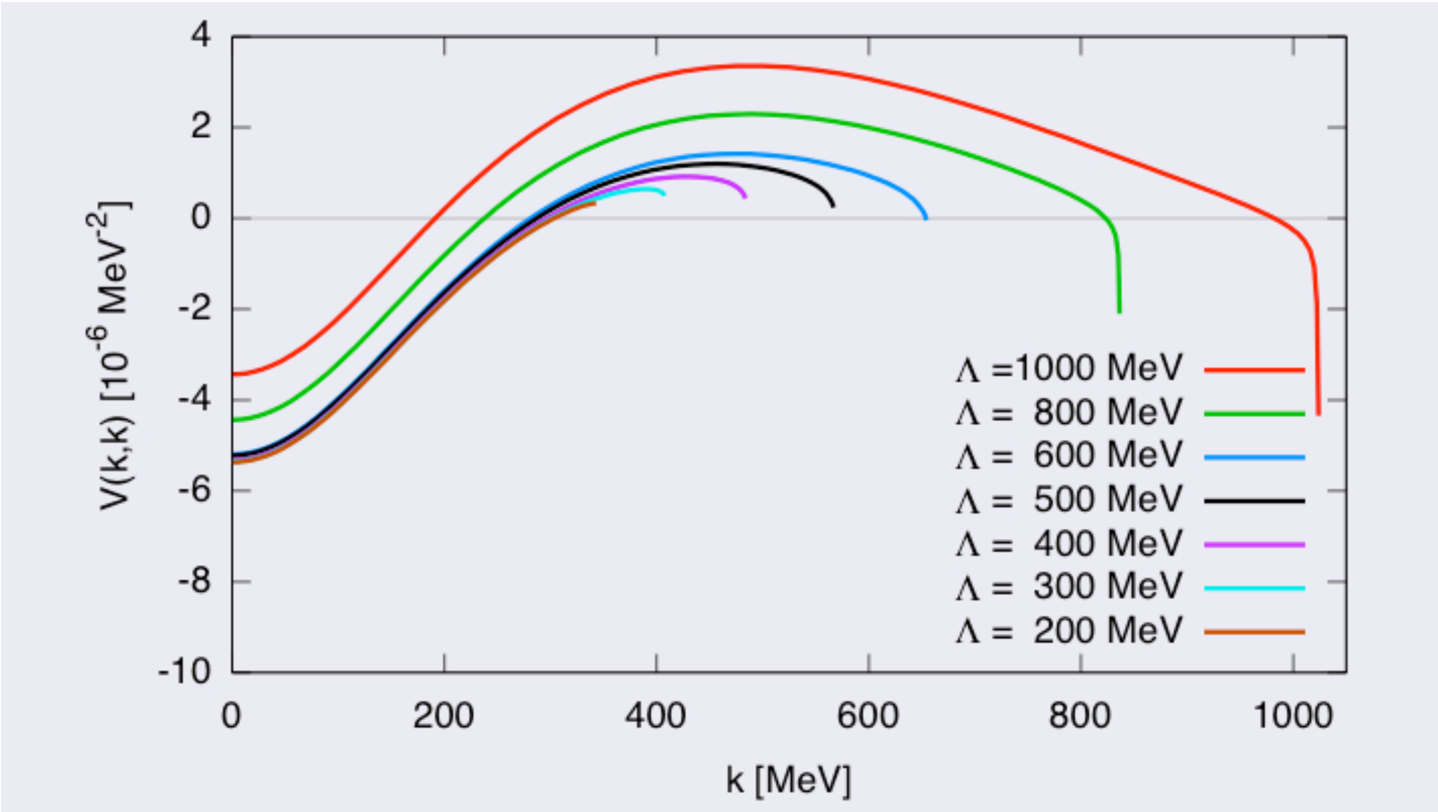


$^1S_0$ (I=1/2) matrix elements and phase-shift for ΛN➔ΛN

Λ=500 MeV

B. -J. Schaefer et al., Phys. Rev. C 73, 011001 (2006)

Cut-off dependence



$^1S_0$ (I=1/2) matrix elements for ΛN→ΛN (NSC97f)

B. -J. Schaefer et al., Phys. Rev. C 73, 011001 (2006)

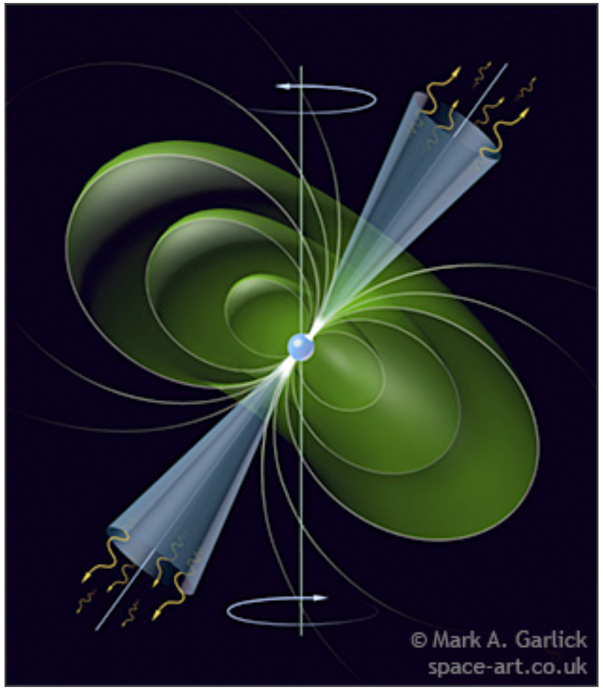
Hypernuclear Matter & Neutron Star Properties

Well known facts about Neutron Stars

- Formed from the collapse remnant of a massive star after a Type II, Ib or Ic supernova.
- Baryonic number: $N_b \sim 10^{57}$ ("giant nuclei")
- Mass: $M \sim 1\text{-}2\, M_\odot$
  $M_{PSR1913+16} = (1.4411 \pm 0.0035)\, M_\odot$
- Radius: $R \sim 10\text{-}12$ km
- Density: $\rho \sim 10^{15}$ g/cm^3

$\rho_{universe} \sim 10^{-30}$ g/cm^3
$\rho_{sun} \sim 1.4$ g/cm^3
$\rho_{earth} \sim 5.5$ g/cm^3

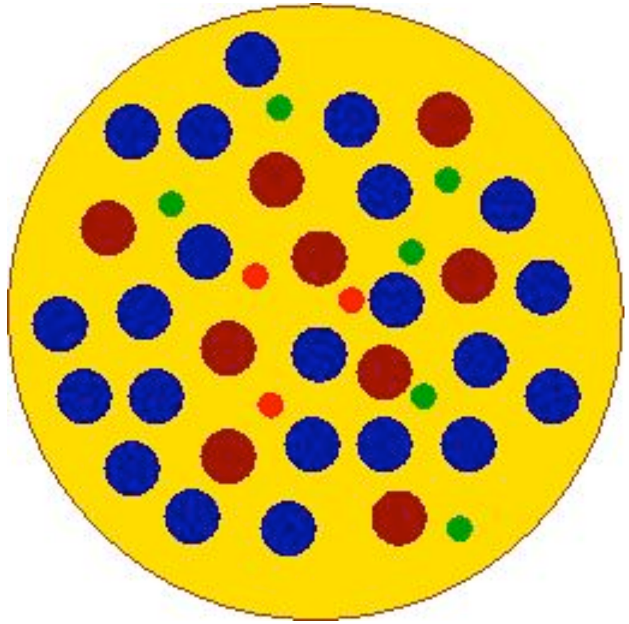
- Magnetic field: $B \sim 10^{8...16}$ G
- Electric field: $E \sim 10^{18}$ V/cm
- Temperature: $T \sim 10^{6...11}$ K



- Shortest rotational period: $P_{B1937+2} \approx 1.58$ ms
  Latest discovery: PSR in Terzan 5: $P_{J1748-244ad} \approx 1.39$ ms
- Accretion rates: 10^{-10} to 10^{-8} $M_\odot$/year

Let's have a look into the neutron star interior

In a traditional and conservative picture the internal composition of a neutron star has been modelled by a uniform fluid of neutron rich nuclear matter in equilibrium with respect to weak interactions



$$\left.\begin{array}{l} n \rightarrow p + e^{-} + \bar{\nu}_{e^{-}} \\ p + e^{-} \rightarrow n + \nu_{e^{-}} \end{array}\right\} \longrightarrow \mu_p = \mu_n - \mu_{e^-} + \mu_{\nu_{e^-}}$$

But because of ....

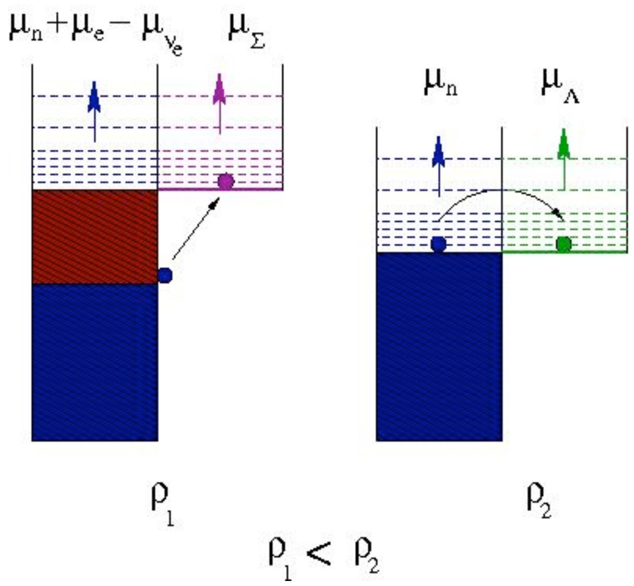
- The value of the central density is high: $\rho_c \sim (4\text{-}8)\,\rho_0$

  $(\rho_0 = 0.17\ \mathrm{fm}^{-3} = 2.8 \times 10^{14}\ \mathrm{g/cm}^3)$

- The rapid increase of the nucleon chemical potential with density

More exotic degrees of freedom are expected in the neutron star interior, in particular hyperons.

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

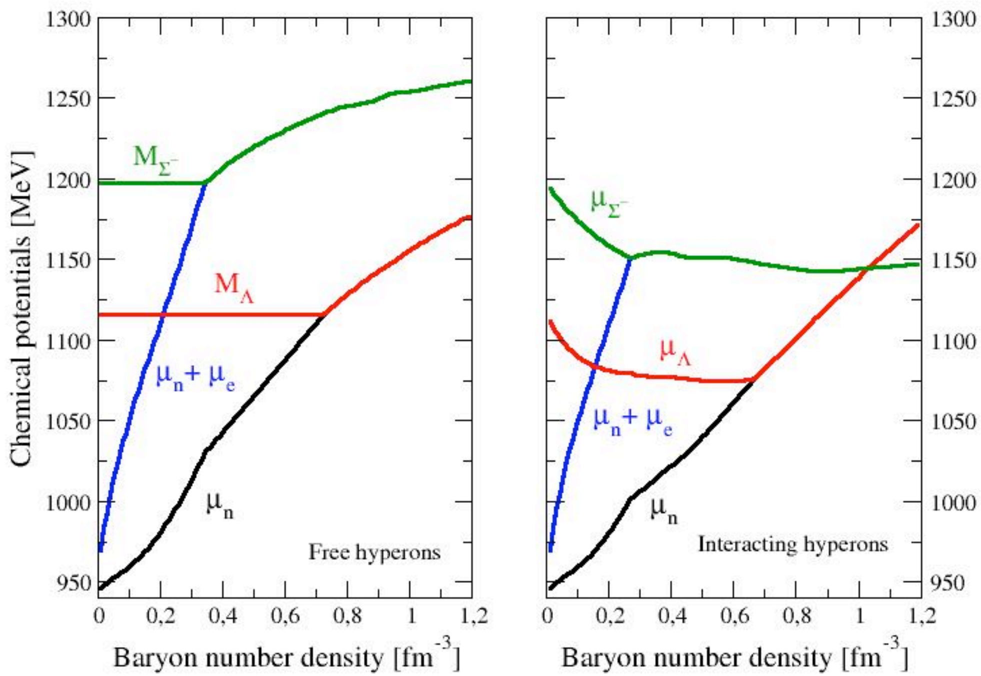
$$\mu_\Lambda = \mu_n$$

$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

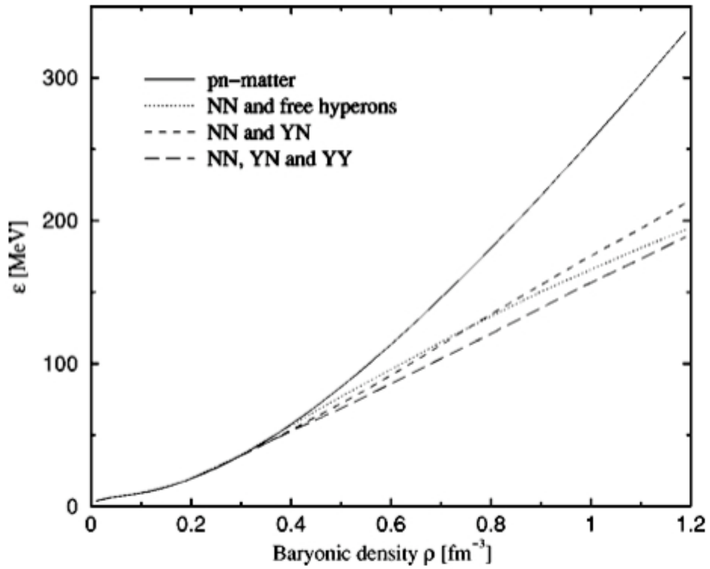


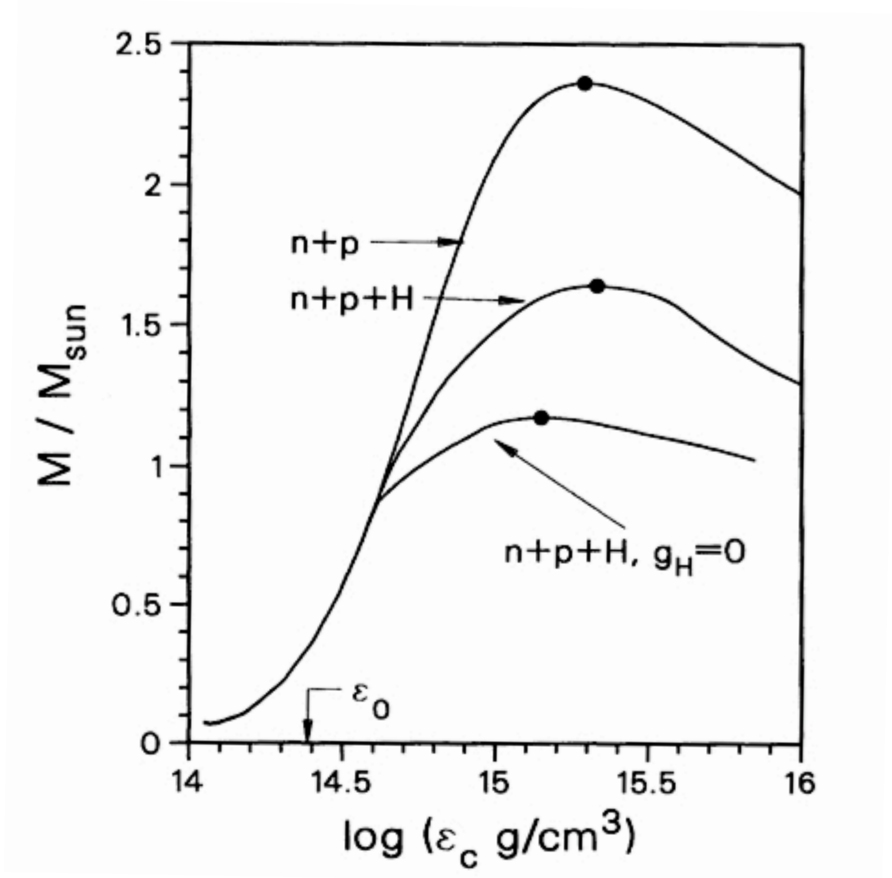
Hyperons in Neutron Stars

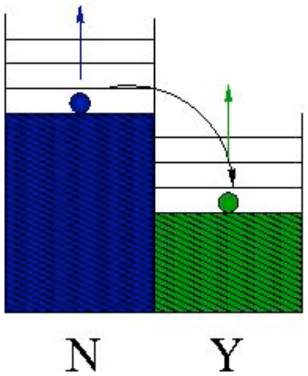
Since the pioneering work of Ambartsumyan & Saakyan (1960) …

- Relativistic Mean Field Models: Glendenning, 1985; Knorren, Prakash & Ellis, 1995; Shaffner-Bielich & Mishustin, 1996
- Non-realtivistic potential model: Balberg & Gal, 1997
- Quark-meson coupling model: Pal *et al.*, 1999
- Brueckner-Hartree-Fock theory: Baldo, Burgio & Schulze, 2000; Engvik, Hjorth-Jensen, Polls, Ramos & Vidaña, 2000
- Chiral Effective Lagrangians: Hanauske et al., 2000
- Density dependent hadron field models: Hofmann, Keil & Lenske, 2001

Effect of Hyperons in the EoS and Mass of Neutron Stars





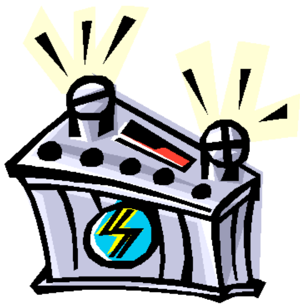


Hyperons make the EoS softer ➔ reduction of the mass

β-stable Neutron Star Matter

The equilibrium composition of the neutron star material is determined by the requirement of:

Charge neutrality



Equilibrium with respect to weak interacting processes

$$b_1 \rightarrow b_2 + l + \bar{\nu}_l \qquad b_2 + l \rightarrow b_1 + \nu_l$$

Relativistic Mean Field approach of hyperonic matter

Using the Lagrangian density ...

$$L = \sum_B \overline{\psi}_B \left(i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - \frac{1}{2} g_{\rho B}\gamma_\mu \vec{\tau} \cdot \vec{\rho}^\mu \right) \psi_B$$

$$+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$

$$- \frac{1}{4}\vec{\rho}_{\mu\nu} \cdot \vec{\rho}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{3} b m_N (g_{\sigma N}\sigma)^3 - \frac{1}{4} c (g_{\sigma N}\sigma)^4$$

$$+ \sum_\lambda \overline{\psi}_\lambda \left(i\gamma_\mu \partial^\mu - m_\lambda \right) \psi_\lambda$$

$$\omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu; \quad \vec{\rho}_{\mu\nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu$$

$$B = n, p, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0; \quad \lambda = e^-, \mu^-$$

one arrives at the hyperonic EoS in the mean field approximation

$$\varepsilon = \frac{1}{3}bm_N\left(g_{\sigma N}\sigma\right)^3 + \frac{1}{4}c\left(g_{\sigma N}\sigma\right)^4 + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 + \sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_{F_B}}\sqrt{k^2+\left(m_B+g_{\sigma B}\sigma\right)^2}\,k^2dk + \sum_\lambda \frac{1}{\pi^2}\int_0^{k_{F_\lambda}}\sqrt{k^2+m_\lambda^2}\,k^2dk$$

$$p = -\frac{1}{3}bm_N\left(g_{\sigma N}\sigma\right)^3 - \frac{1}{4}c\left(g_{\sigma N}\sigma\right)^4 - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 + \frac{1}{3}\sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_{F_B}}\frac{k^4dk}{\sqrt{k^2+\left(m_B+g_{\sigma B}\sigma\right)^2}} + \frac{1}{3}\sum_\lambda \frac{1}{\pi^2}\int_0^{k_{F_\lambda}}\frac{k^4dk}{\sqrt{k^2+m_\lambda^2}}$$

Coupling Constants

The nucleon coupling constants $g_{\sigma N}$, $g_{\omega N}$, $g_{\rho N}$, b and c are constrained by the empirical values of density ρ_0, energy per particle E/A, compression modulus K, symmetry energy a_{sym} and effective mass m* at nuclear saturation.

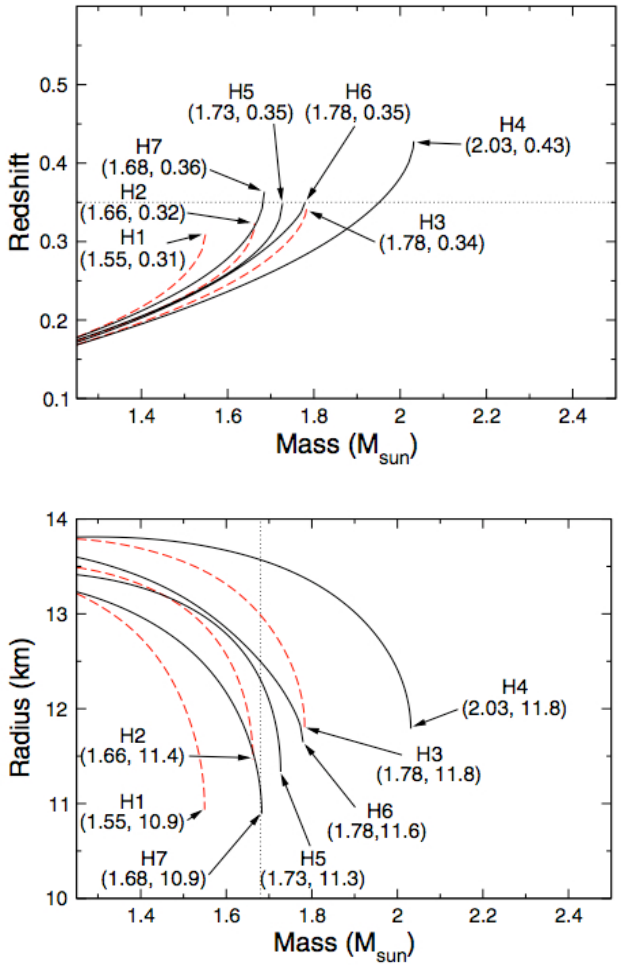
The hyperon coupling constants $g_{\sigma Y}$, $g_{\omega Y}$ and $g_{\rho Y}$ are constrained by: the binding of Λ hyperon in nuclear matter, hypernuclear levels and neutron star masses.

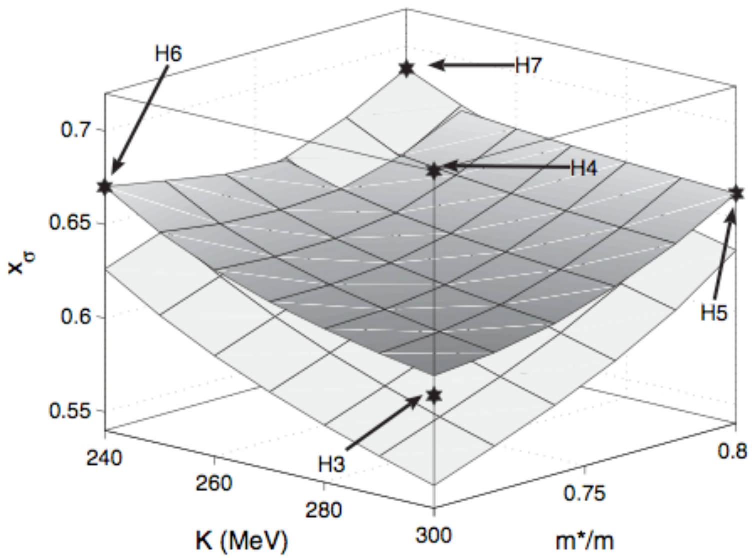
Assuming that all hyperons in the octet have the same coupling, the hyperon couplings are expressed as a ratio to the above mentioned nucleon couplings

$$x_\sigma = \frac{g_{\sigma Y}}{g_{\sigma N}}; \quad x_\omega = \frac{g_{\omega Y}}{g_{\omega N}}; \quad x_\rho = \frac{g_{\rho Y}}{g_{\rho N}};$$

Two astrophysical constraints to the hyperon couplings

- Red shift of EXO0748-676, z ~ 0.35
- Mass of Ter 5 I M ~ 1.68 $M_\odot$





Below dark: EoS compatible with red shift

Above light: EoS compatible with mass

B. D. Lackey, M. Nayyar & B. J. Owen, PRC 73, 024021 (2006)

Brueckner-Hartree-Fock approach of hyperonic matter

Bethe-Goldstone Equation

$$G(\omega)_{B_1B_2;B_3B_4} = V_{B_1B_2;B_3B_4} + \sum_{B_5B_6} V_{B_1B_2;B_5B_6} \frac{Q_{B_5B_6}}{\omega - E_{B_5} - E_{B_6} + i\eta} G(\omega)_{B_5B_6;B_3B_4}$$

Single particle energy & single particle potential

$$E_{B_i}(k) = M_{B_i}c^2 + \frac{\hbar^2 k^2}{2M_{B_i}^2} + \mathrm{Re}\left[U_{B_i}(k)\right]$$

$$U_{B_i}(k) = \sum_{B_j} \sum_{k \le k_{F_{B_j}}} \left\langle \vec{k}_i \vec{k}_j \left| G\left(\omega = E_{B_i} + E_{B_j}\right) \right| \vec{k}_i \vec{k}_j \right\rangle$$

Note that the Bethe-Goldstone equation

$$G = V + V \frac{Q}{\omega - H_0 + i\eta} G$$

is formally identical to the Lippman-Schwinger equation for the scattering of two particles in the vaccum.

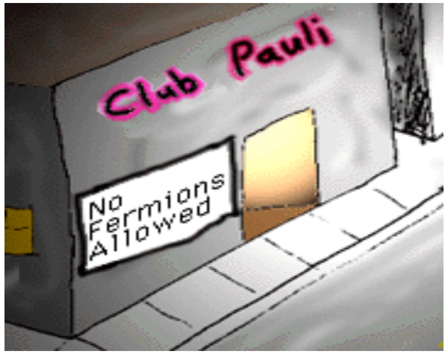
$$T = V + V \frac{1}{\omega - K + i\eta} T$$

In fact the G-matrix can be considered as a generalization of the T-matrix to the medium, when one takes into account the presences of other particles.

Medium effects are taken into account through …

- Pauli blocking of the intermediate states

  The Pauli operator Q prevents the scattering to any occupied state, limiting the phase space of the intermediate states.



- Dressing of the intermediate particles

  The modification of the single-particle spectrum due to the inclusion of the averaged potential U "felt" by a particle due to its interaction with the others must be taken into account in the propagator.

Enery density & Pressure of β-stable Hyperonic Matter

$$\varepsilon = 2\sum_{B_i}\int_0^{k_{F_{B_i}}} \frac{d^3k}{(2\pi)^3}\left[M_{B_i}c^2 + \frac{\hbar^2k^2}{2M_{B_i}} + \frac{1}{2}\mathrm{Re}[U^N_{B_i}] + \frac{1}{2}\mathrm{Re}[U^Y_{B_i}]\right]$$

$$+\sum_{\lambda}\frac{1}{\pi^2}\int_0^{k_{F_\lambda}}\sqrt{k^2+m_\lambda^2}\,k^2dk$$

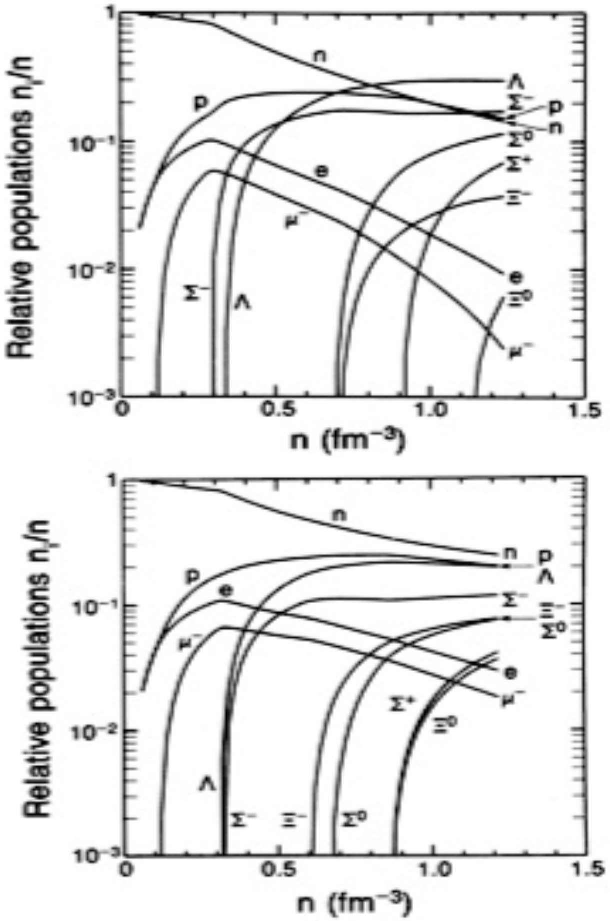
$$p = \rho\frac{\partial\varepsilon}{\partial\rho} - \varepsilon$$

Isospin and Strangeness channels

	S = 0	S = -1	S = -2	S = -3	S = -4
I = 0	$(NN \to NN)$		$\begin{pmatrix} \Lambda\Lambda \to \Lambda\Lambda & \Lambda\Lambda \to \Xi N & \Lambda\Lambda \to \Sigma\Sigma \\ \Xi N \to \Lambda\Lambda & \Xi N \to \Xi N & \Xi N \to \Sigma\Sigma \\ \Sigma\Sigma \to \Lambda\Lambda & \Sigma\Sigma \to \Xi N & \Sigma\Sigma \to \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \to \Xi\Xi)$
I = 1/2		$\begin{pmatrix} \Lambda N \to \Lambda N & \Lambda N \to \Sigma N \\ \Sigma N \to \Lambda N & \Sigma N \to \Sigma N \end{pmatrix}$		$\begin{pmatrix} \Lambda\Xi \to \Lambda\Xi & \Lambda\Xi \to \Sigma\Xi \\ \Sigma\Xi \to \Lambda\Xi & \Sigma\Xi \to \Sigma\Xi \end{pmatrix}$	
I = 1	$(NN \to NN)$		$\begin{pmatrix} \Xi N \to \Xi N & \Xi N \to \Lambda\Sigma & \Xi N \to \Sigma\Sigma \\ \Lambda\Sigma \to \Xi N & \Lambda\Sigma \to \Lambda\Sigma & \Lambda\Sigma \to \Sigma\Sigma \\ \Sigma\Sigma \to \Xi N & \Sigma\Sigma \to \Lambda\Sigma & \Sigma\Sigma \to \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \to \Xi\Xi)$
I = 3/2		$(\Sigma N \to \Sigma N)$		$(\Sigma\Xi \to \Sigma\Xi)$	
I = 2			$(\Sigma\Sigma \to \Sigma\Sigma)$		

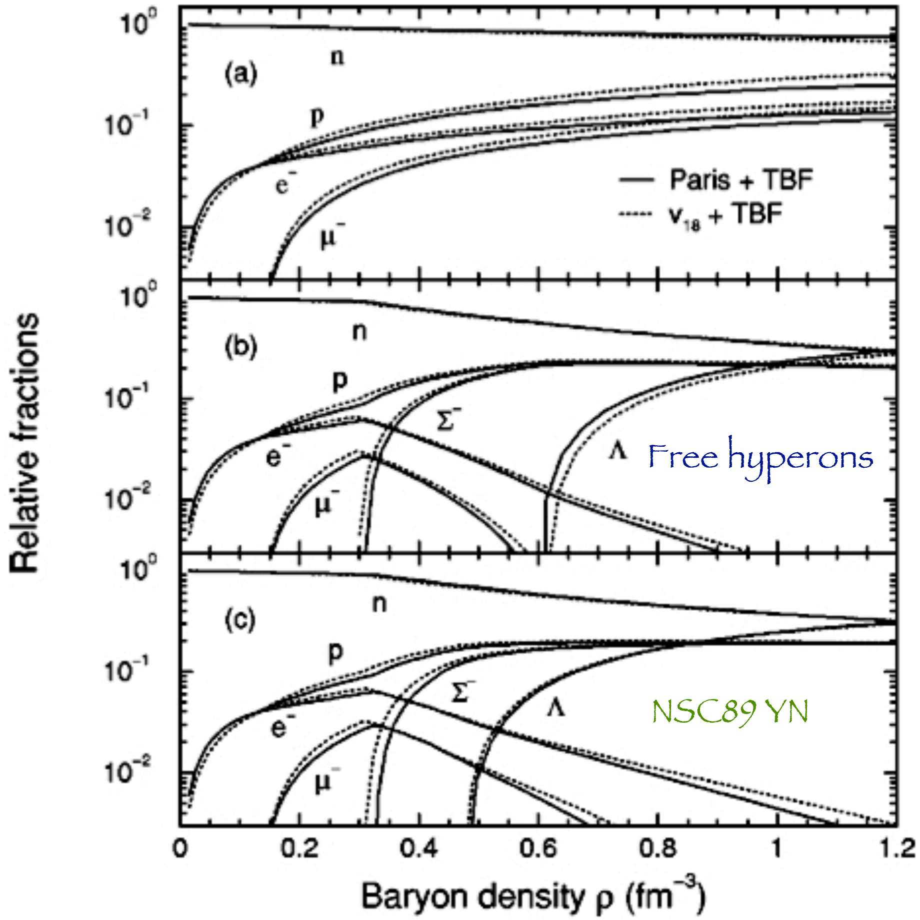
Neutron Star Matter Composition

RMFT



N.K. Glendenning, ApJ 293, 470 (1985)

BHF

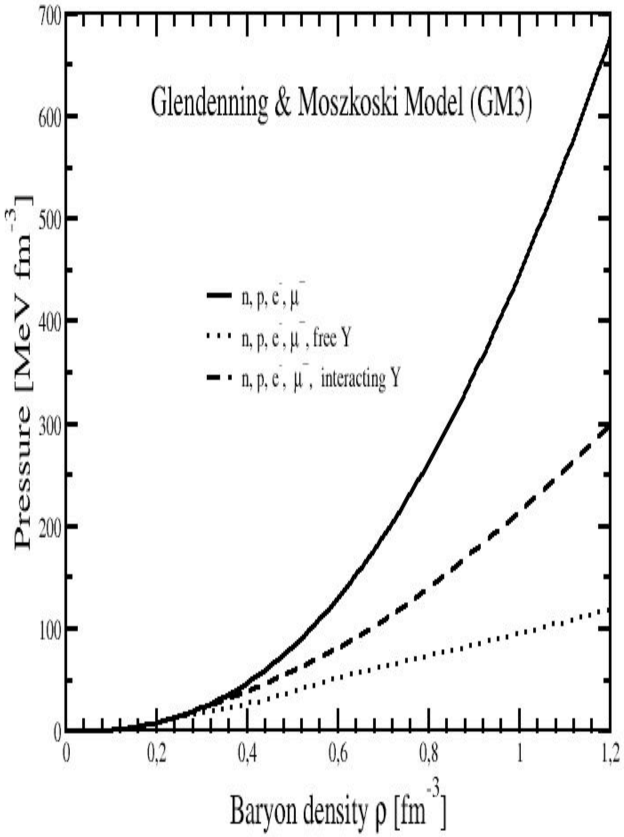


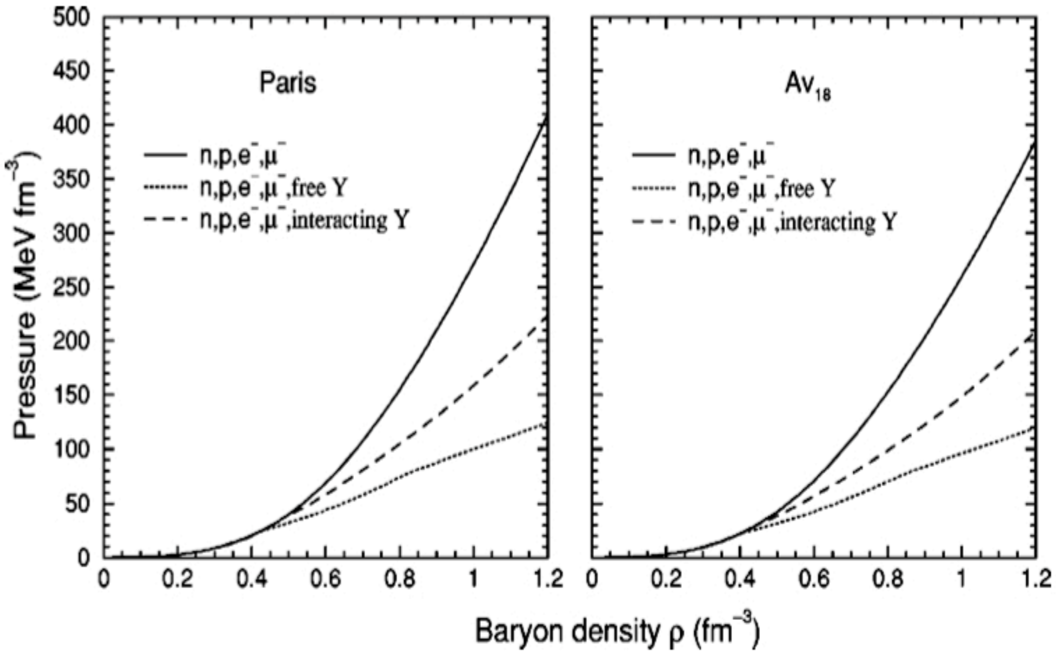
M. Baldo *et.al.*, Phys. Rev. C 61, 055801 (2000)

Neutron Star Matter EoS (I)

RMFT

BHF

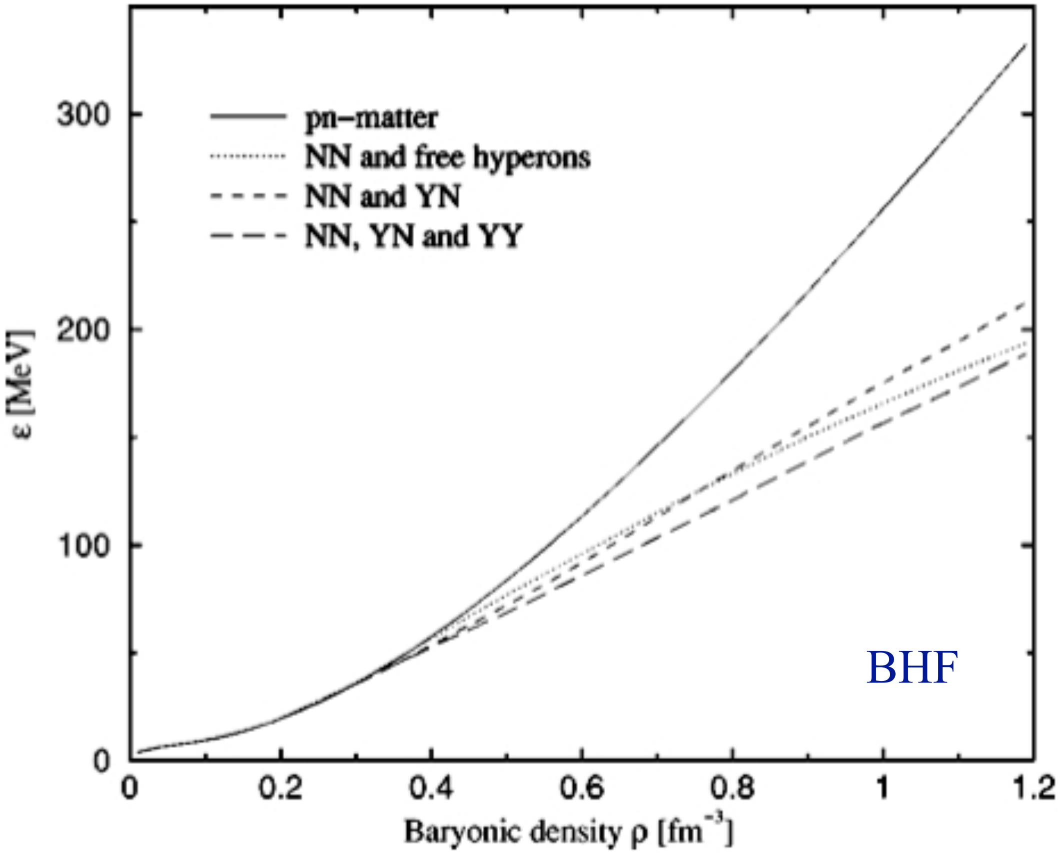




M. Baldo *et.al.*, Phys. Rev. C 61, 055801 (2000)

No YY interaction !

Neutron Star Matter EoS (II)



Additional softening from YY interaction

I. V. *et.al.*, Phys. Rev. C 62, 035801 (2000)

Structure equations for Neutron Stars: TOV Equations

Since neutron stars have masses $M \sim 1\text{-}2\ M_{\odot}$, and radii $R \sim 10\text{-}20$ km, the value of the gravitational potential on the neutron star surface is of the order 1

$$\frac{GM}{c^2 R} \sim 1$$

with escape velocities of the order of c/2. Therefore, general relativistic effects become very important and thus the structure equations read

$$\frac{dp}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{p(r)}{c^2\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 p(r)m(r)}{c^2}\right)\left(1-\frac{Gm(r)}{c^2 r}\right)^{-1}$$

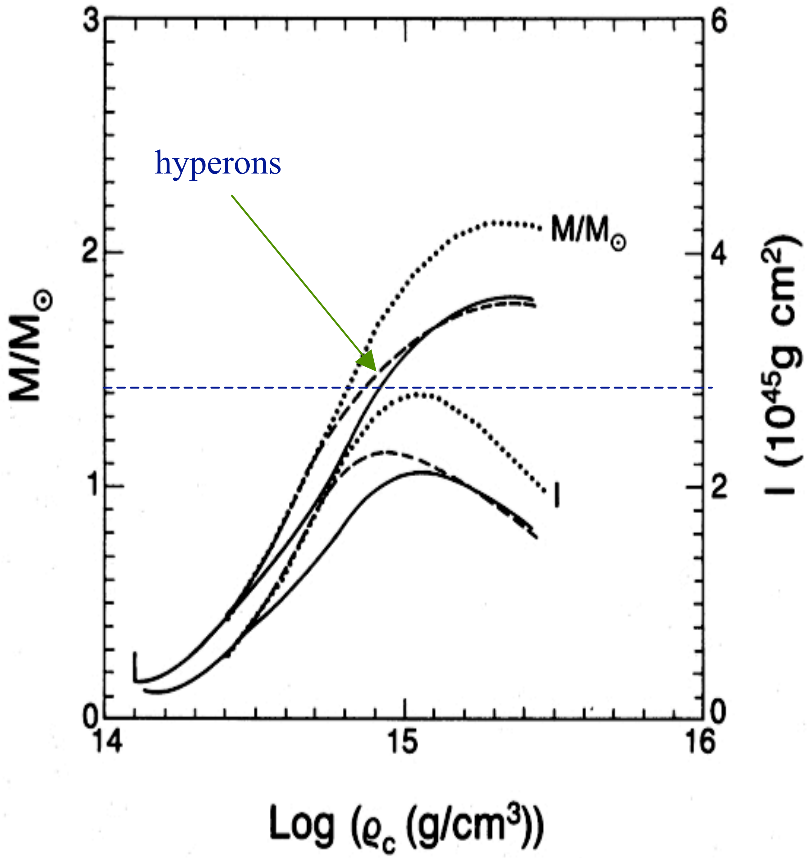
$$\frac{dm}{dr} = 4\pi r^2\varepsilon(r)$$

with the boundary conditions

$$m(r=0)=0$$
$$p(r=R)=p_{surf}$$

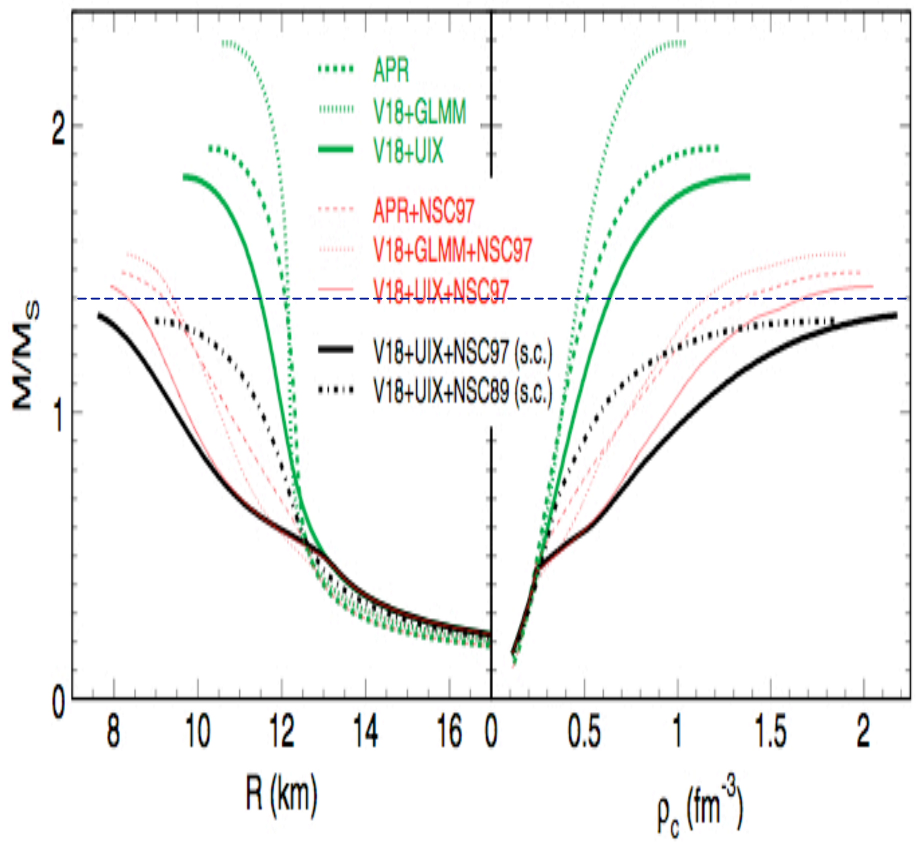
Neutron Star Structure

RMFT



N.K. Glendenning, ApJ 293, 470 (1985)

BHF



H.-J- Schulze, I.V., A. Polls & A. Ramos Phys. Rev. C 73, 08801 (2006)

Implications for Neutron Star Structure

- The presence of hyperons reduces the maximum mass of Neutron Stars by an amount $\Delta M_{max} \sim (0.5\text{-}0.8) M_{\odot}$

- Microscopic EoS "very soft EoS" not compatible with measured masses of NS

✓Need for extra pressure at high densities

✓Two-body forces: Improved YN and YY

✓Three-body forces: NNY, NYY and YYY

Obrigado

DS