Nuclei with strangeness.

(From hypernuclei to kaonic nuclei)

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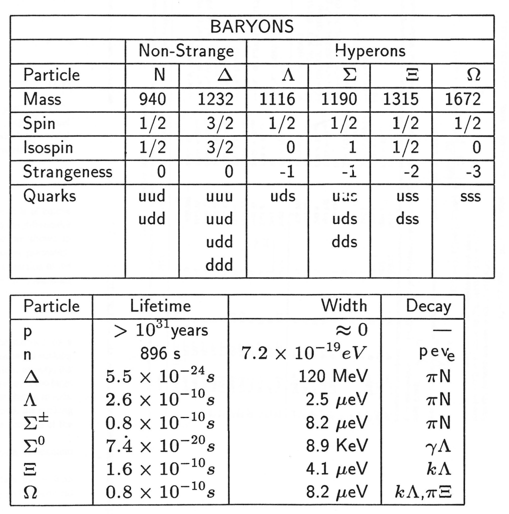
Hypernuclei

- Hypernuclei = nuclear systems containing nucleons + 1 or more hyperons. (M.Danysz, J. Pniewski, Bull. Pol. Acad.Sci. 1 (1953) 42.)



BARYONS						
	Non-Strange		Hyperons			
Particle	N	Δ	Λ	Σ	Ξ	Ω
Mass	940	1232	1116	1190	1315	1672
Spin	1/2	3/2	1/2	1/2	1/2	1/2
Isospin	1/2	3/2	0	1	1/2	0
Strangeness	0	0	-1	-1	-2	-3
Quarks	uud udd	uuu uud udd ddd	uds	uus uds dds	uss dss	sss

Particle	Lifetime	Width	Decay
p	$> 10^{31}$years	≈ 0	—
n	896 s	$7.2 \times 10^{-19} eV$	p e ν_e
Δ	$5.5 \times 10^{-24} s$	120 MeV	πN
Λ	$2.6 \times 10^{-10} s$	2.5 μeV	πN
$\Sigma^{\pm}$	$0.8 \times 10^{-10} s$	8.2 μeV	πN
Σ^0	$7.4 \times 10^{-20} s$	8.9 KeV	$\gamma\Lambda$
Ξ	$1.6 \times 10^{-10} s$	4.1 μeV	$k\Lambda$
Ω	$0.8 \times 10^{-10} s$	8.2 μeV	$k\Lambda$,$\pi\Xi$

Hypernuclei

Why to study hypernuclei?

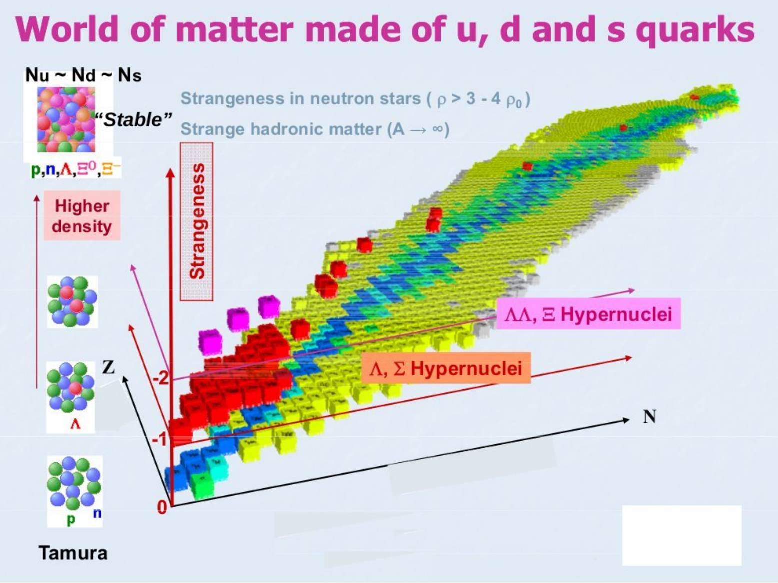
- Test models of baryon-baryon and meson-baryon interactions (meson exchange models, quark models, chiral models, ...)
- Test nuclear models (RMF,EDF, shell model,...)
- Test models of hadrons (SU(3)symmetry, quark models ...)
- Hypernuclear production – test reaction mechanisms
- Hypernuclear decays → study of weak interaction

Hyperon X Nucleon → no Pauli blocking →
Hyperon can penetrate deep into the nuclear interior, probe the nuclear interior

Implications for astrophysics (compact stars), HI collisions (strangeness production, medium modification od hadrons)

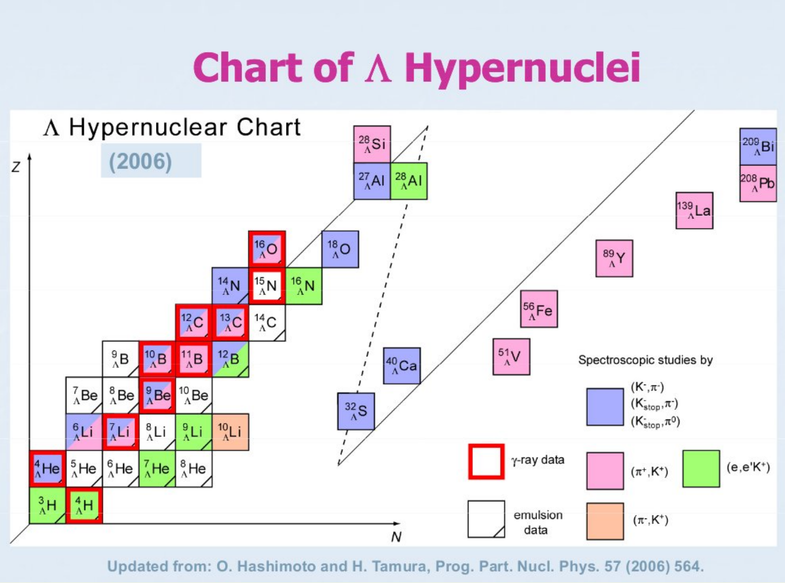
Λ *hypernuclei*

- $>$ 30 Λ-hypernuclei:



Λ *hypernuclei*

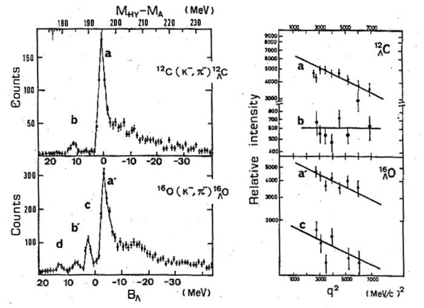
- > 30 Λ-hypernuclei:



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

Λ hypernuclei

- (K^-, π^-) reaction (emulsions, CERN, BNL, KEK, Frascati, JParc):



$$a = a' = (p_{3/2}^{-1}, p_{3/2}^{\Lambda})_{J=0^+} \qquad B_\Lambda(a) = 0 \text{ MeV},\ B_\Lambda(a') = -3.5 \text{ MeV}$$

$$b = b' = (p_{3/2}^{-1}, s_{1/2}^{\Lambda})_{J=1^-} \qquad B_\Lambda(b) = 11 \text{ MeV},\ B_\Lambda(b') = 7 \text{ MeV}$$

$$c = (p_{1/2}^{-1}, p_{1/2}^{\Lambda})_{J=0^+} \qquad B_\Lambda(c) = 2.5 \text{ MeV}$$

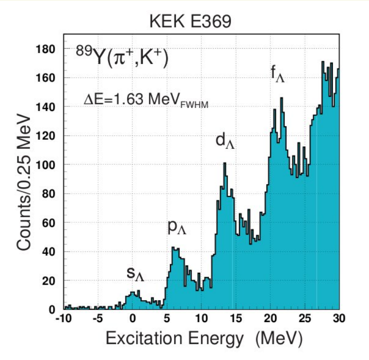
$$d = (p_{1/2}^{-1}, s_{1/2}^{\Lambda})_{J=1^-} \qquad B_\Lambda(d) = 13 \text{ MeV}$$

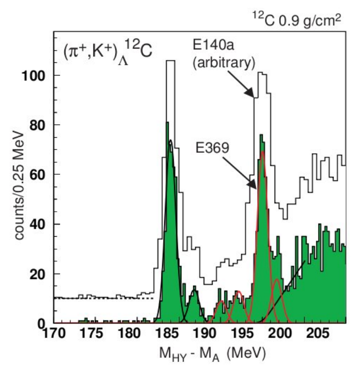
$B_\Lambda(b') - B_\Lambda(d) = 6$ MeV (n SO splitting), $B_\Lambda(a') - B_\Lambda(c) = 6$ MeV (n + Λ SO splitting)

$\Rightarrow \Delta(p_{1/2}^{\Lambda} - p_{3/2}^{\Lambda}) \leq 0.3$ MeV

Λ *hypernuclei*

- (π^+, K^+) reaction (BNL, KEK):





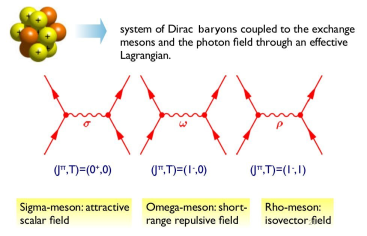
Hotchi et al, PRC 64 (2001) 044302

- Textbook example of single-particle structure
- Λ hyperon bound by ∼ 28 MeV in nuclear matter
- Negligible spin-orbit splitting

Λ *hypernuclei*

- RMF calculations (J.M., B.K. Jennings, PRC (1994)):

  (+ quark model + $Y\omega$ tensor coupling $\frac{f_{\omega Y}}{2M_Y}\bar{\Psi}_Y\sigma^{\mu\nu}\partial_\nu V_\mu \Psi_Y$)

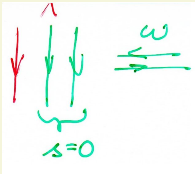


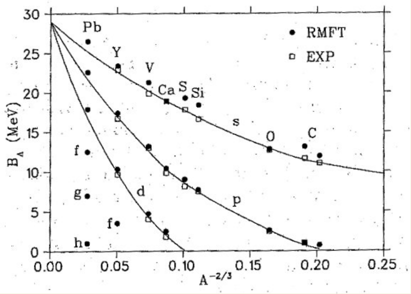
system of Dirac baryons coupled to the exchange mesons and the photon field through an effective Lagrangian.

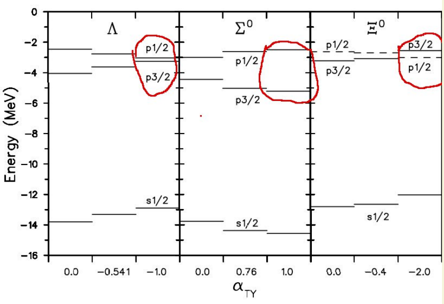
Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive field

Rho-meson: isovector field







Λ hypernuclei

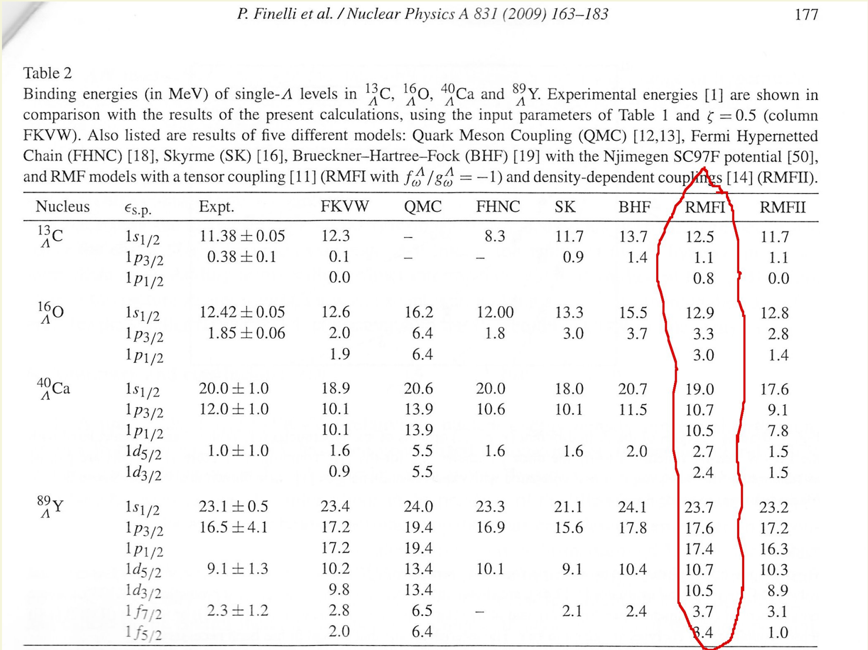
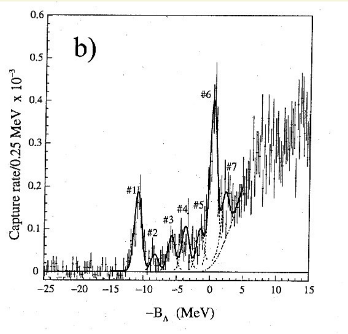


Table 2
Binding energies (in MeV) of single-Λ levels in ${}^{13}_{\Lambda}$C, ${}^{16}_{\Lambda}$O, ${}^{40}_{\Lambda}$Ca and ${}^{89}_{\Lambda}$Y. Experimental energies [1] are shown in comparison with the results of the present calculations, using the input parameters of Table 1 and $\zeta = 0.5$ (column FKVW). Also listed are results of five different models: Quark Meson Coupling (QMC) [12,13], Fermi Hypernetted Chain (FHNC) [18], Skyrme (SK) [16], Brueckner–Hartree–Fock (BHF) [19] with the Njimegen SC97F potential [50], and RMF models with a tensor coupling [11] (RMFI with $f_{\omega}^{\Lambda}/g_{\omega}^{\Lambda} = -1$) and density-dependent couplings [14] (RMFII).

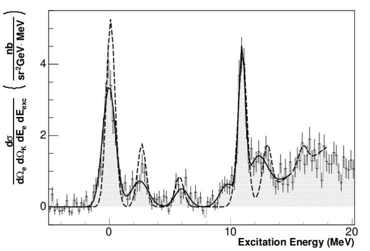
Nucleus	$\epsilon_{\text{s.p.}}$	Expt.	FKVW	QMC	FHNC	SK	BHF	RMFI	RMFII
${}^{13}_{\Lambda}$C	$1s_{1/2}$	11.38 ± 0.05	12.3	–	8.3	11.7	13.7	12.5	11.7
	$1p_{3/2}$	0.38 ± 0.1	0.1	–	–	0.9	1.4	1.1	1.1
	$1p_{1/2}$		0.0					0.8	0.0
${}^{16}_{\Lambda}$O	$1s_{1/2}$	12.42 ± 0.05	12.6	16.2	12.00	13.3	15.5	12.9	12.8
	$1p_{3/2}$	1.85 ± 0.06	2.0	6.4	1.8	3.0	3.7	3.3	2.8
	$1p_{1/2}$		1.9	6.4				3.0	1.4
${}^{40}_{\Lambda}$Ca	$1s_{1/2}$	20.0 ± 1.0	18.9	20.6	20.0	18.0	20.7	19.0	17.6
	$1p_{3/2}$	12.0 ± 1.0	10.1	13.9	10.6	10.1	11.5	10.7	9.1
	$1p_{1/2}$		10.1	13.9				10.5	7.8
	$1d_{5/2}$	1.0 ± 1.0	1.6	5.5	1.6	1.6	2.0	2.7	1.5
	$1d_{3/2}$		0.9	5.5				2.4	1.5
${}^{89}_{\Lambda}$Y	$1s_{1/2}$	23.1 ± 0.5	23.4	24.0	23.3	21.1	24.1	23.7	23.2
	$1p_{3/2}$	16.5 ± 4.1	17.2	19.4	16.9	15.6	17.8	17.6	17.2
	$1p_{1/2}$		17.2	19.4				17.4	16.3
	$1d_{5/2}$	9.1 ± 1.3	10.2	13.4	10.1	9.1	10.4	10.7	10.3
	$1d_{3/2}$		9.8	13.4				10.5	8.9
	$1f_{7/2}$	2.3 ± 1.2	2.8	6.5	–	2.1	2.4	3.7	3.1
	$1f_{5/2}$		2.0	6.4				3.4	1.0

Λ *hypernuclei*

- $(K^-_{\text{stop}}, \pi^-)$ reaction (FINUDA, PLB 622 (2005) 35):
- $(e, e'K)$ reaction (JLab, PRL 99 (2007) 052501):



Λ binding energy spectrum in ${}^{12}_{\Lambda}$C

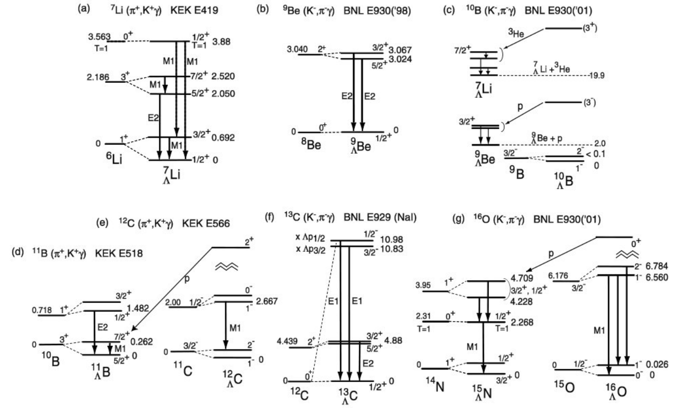


${}^{12}_{\Lambda}$B excitation spectrum

Λ *hypernuclei*

- γ spectroscopy (BNL, KEK)

  $\Rightarrow$ spin dependence of the effective ΛN interaction in the nuclear p shell



Level schemes of Λ hypernuclei from recent γ-ray measurements

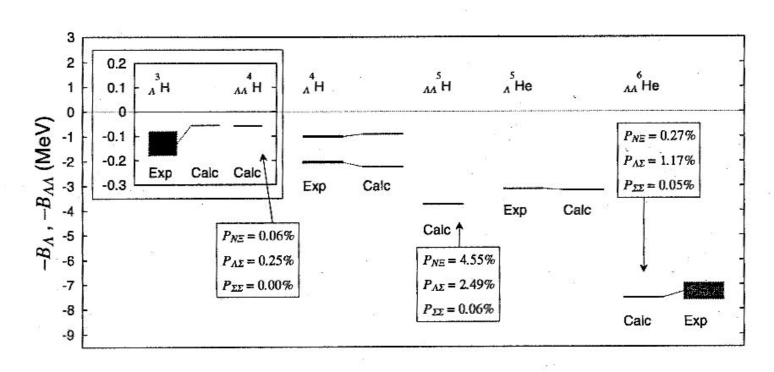
H. Tamura, Nucl. Phys. A 804 (2008) 73; 827 (2009) 153c [PANIC08]

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\, s_N \cdot s_\Lambda + V_{LS}(r)\, l_{N\Lambda} \cdot (s_\Lambda + s_N) + V_{ALS}(r)\, l_{N\Lambda} \cdot (s_\Lambda - s_N) + V_T(r)\, S_{12}$$

D.J. Millener, Nucl. Phys. A 804 (2008) 84

Λ *hypernuclei*

- s-shell Λ hypernuclei



Nemura et al, PRL 89 (2002) 142504 (including $\Lambda N \to \Sigma N$ and $\Lambda\Lambda \to \Xi N$ mixings)
variational approach

Hiyama et al, PRC 65 (2002) 011301(R) - Jacobi-coordinate Gaussian basis

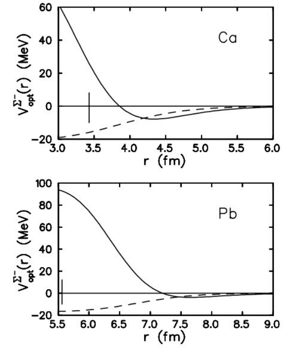
Nogga et al, PRL 88 (2002) 172501 - Faddeev + Faddeev-Yakubovsky

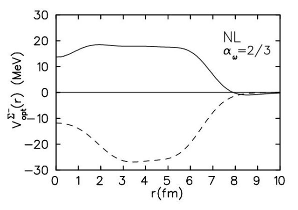
Σ *hypernuclei*

- $^{9}\mathrm{Be}(K^-,\pi^-)^{9}_{\Sigma^-}\mathrm{Be}$ (Bertini (80), CERN) + further narrow Σ-nuclear resonance states in the continuum (KEK, BNL): $^{4}_{\Sigma}\mathrm{He}$, $^{6}_{\Sigma}\mathrm{Li}$, $^{12}_{\Sigma}\mathrm{C}$, $^{16}_{\Sigma}\mathrm{O}$ (limited statistics ⇒ contradictory results)
- Narrow states X widths about $10 - 20$ MeV due to $\Sigma N \rightarrow \Lambda N$
- 80's – many attempts to produce Σ-hypernuclear states and to explain narrow widths

Σ *hypernuclei*

- Σ-nucleus interaction:
  (J.M., Friedman, Gal, Jennings, NPA 594 (1995) 311,
  E. Friedman, A. Gal, Phys. Rept. 452 (2007) 89)

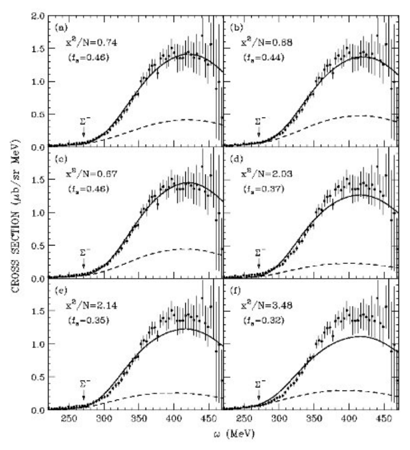




- Σ hyperons are not bound in nuclei except for $^{4}_{\Sigma}$He
- Sawafta et al, PRL 83 (1999) 25; Noumi et al, PRL 89 (2002) 072301

Σ *hypernuclei*

- DWIA calculations (Harada & Hirabayashi, NPA 759 (2005) 143)



^{28}Si(π^-, K^+) spectrum from KEK-E438, using 6 Σ-nucleus potentials,

(a)-(c) with inner repulsion, (d)-(f) fully attractive

Ξ *hypernuclei*

- Ξ-nucleus interaction:

- no established yet QBS
- $^{12}\mathrm{C}(K^-, K^+)$ spectra (KEK -E224, BNL-E885) → $V_\Xi \approx 14\ \mathrm{MeV}$
- Calculations of light Ξ hypernuclei (Hiyama et al, PRC 78 (2008) 054316).
- Spectroscopic study of Ξ hypernucleus $^{12}_{\Xi}\mathrm{B}$ ... (T. Nagae), A 'Day-1' experiment E05 at J-Parc

Multi-strange baryonic systems

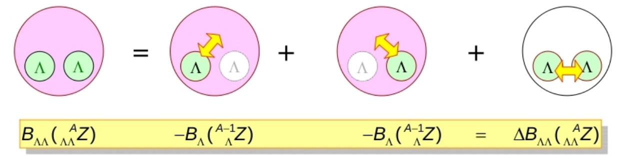
One can envisage bound many-body systems containing more baryons from the SU(3) octet: N, Λ, Σ, Ξ

- Multiply strange nuclear systems

  extension of conventional shell model picture to systems with larger number of hyperons
  - of interest for astrophysics (neutron stars)
  - of interest for HI collisions
  - their study = source of information about $B-B$ interactions

- Unfortunately, only $\Lambda\Lambda$ hypernuclei known (+ mutually contradictory info):

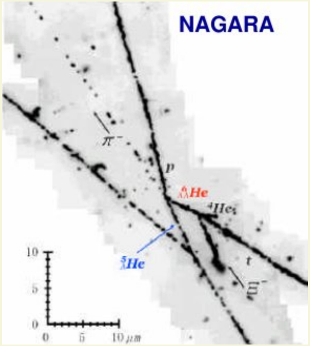
  ${}^{4}_{\Lambda\Lambda}$H (?), ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B



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

ΛΛ *hypernuclei*

$^{6}_{\Lambda\Lambda}\text{He}$ (Prowse 66), $^{10}_{\Lambda\Lambda}\text{Be}$ (Danysz 63), $^{13}_{\Lambda\Lambda}\text{B}$ (KEK-E176 91) →
$\Delta B_{\Lambda\Lambda} \sim 4.3 - 4.8$ MeV



Takahashi et al, PRL 87 (2001) 212502

$$\Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He}) = B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}(^{5}_{\Lambda}\mathrm{He}) \approx 1 \text{ MeV}$$

Multi-strange baryonic systems

RMF calculations

- hidden-strangeness mesons introduced – couple only to hyperons: scalar σ^* (975 MeV) and vector Φ (1020 MeV) (originally introduced to strengthen the $\Lambda\Lambda$ interaction)
- RMF model predicts a possibility of forming bound systems with appreciable number of hyperons
- The dependence of E_B/A, density distributions, r.m.s. radii, on the number of hyperons $\longleftarrow$ delicate interplay between the effect of Pauli blocking (Y, N distinquishable) and weaker YN interactions
- First calculations – only mixtures of Λ and N
  $E_B/A \approx 9$ MeV, $f_s = |S|/A \leq 0.2$

$\Sigma N \rightarrow \Lambda N$ $(Q \approx 78\text{MeV})$
$\Xi N \rightarrow \Lambda\Lambda$ $(Q \approx 26\text{MeV})$
$\Omega N \rightarrow \Lambda\Xi$ $(Q \approx 178\text{MeV})$

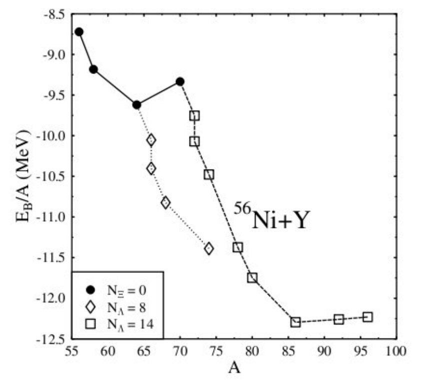
Multi-strange baryonic systems

HOWEVER !!

- For some critical number of Λ's in a system:
  $\Lambda\Lambda \rightarrow \Xi N$ energetically favorable due to Pauli blocking of Λ's
- It is necessary to include Ξ !! (Ξ-nucleus potential ?)
- $\Rightarrow$ $\{$ N, Λ, $\Xi\}$ configurations
  $\rho \approx (2-3)\rho_0$, $f_s = |S|/A \approx 1$, $|Z|/A \ll 1$

  $E_B/A \approx (10-20)$ MeV

Multi-strange baryonic systems

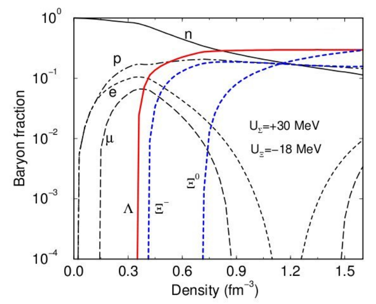


J. Schaffner, C.B. Dover, A. Gal, C. Greiner, H. Stöcker, PRL 71 (1993) 1328.

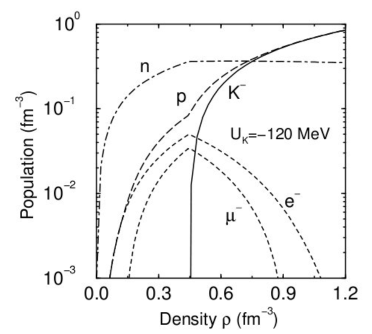
$\Xi N \to \Lambda\Lambda$ ($\approx$ 25 MeV in free space) is Pauli blocked

Strange hadronic matter

- neutron star structure



Schaffner-Bielich, NPA 804 (2008) 309



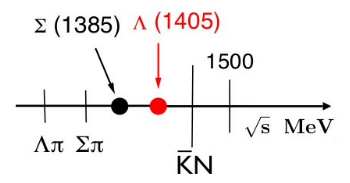
Glendenning, Schaffner-Bielich,
PRC 60 (1999) 025803

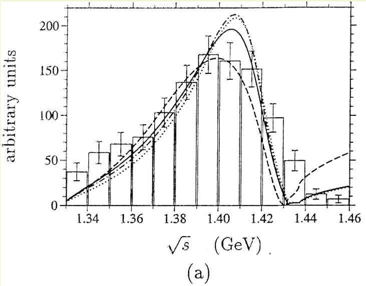
- kaon condensation could occur at $\rho \gtrsim 3\rho_0$, $l^- \to K^- + \nu_l$ $(\omega_{K^-} \leq 200\ \text{MeV})$

$\bar{K}N$ *interaction*

- $\bar{K}N$ interaction

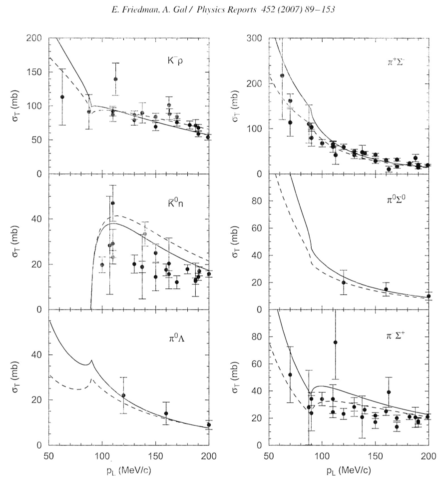
  strongly attractive $\Leftarrow \exists\ I = 0\ \Lambda(1405)\ \pi\Sigma$ resonance, 27 MeV below K^-p threshold





$\bar{K}N$ interaction

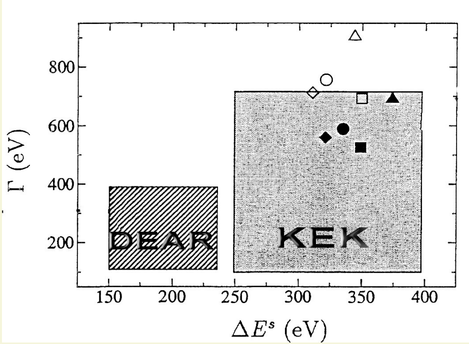
- Scattering data



E. Friedman, A. Gal / Physics Reports 452 (2007) 89–153

$\bar{K}N$ interaction

- $K^{-}p$ atom

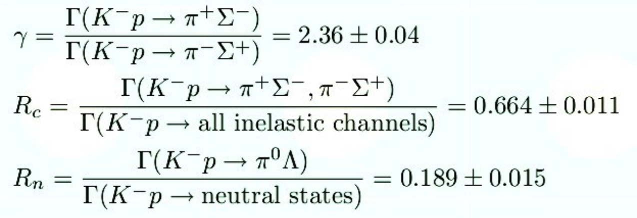


- Siddharta:

$$\mathbf{\Delta E = 305 \pm 31\ eV}$$
$$\mathbf{\Gamma = 512 \pm 77\ eV}$$

$\bar{K}N$ *interaction*

- Threshold branching ratios:



$$\gamma = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \to \text{all inelastic channels})} = 0.664 \pm 0.011$$

$$R_n = \frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutral states})} = 0.189 \pm 0.015$$

Kaonic nuclei

- $\bar{K}$-nucleus interaction

  strongly attractive and absorptive ⇐ kaonic atom level shifts and widths

  ? optical potential depth:

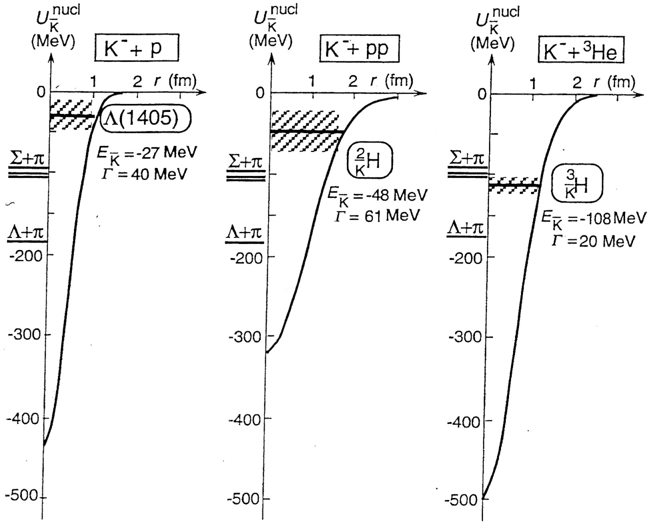
  $\mathrm{Re}V_{opt} \simeq (\mathbf{150}-\mathbf{200})$ MeV ← phenomenological models
  $\mathrm{Re}V_{opt} \simeq (\mathbf{50}-\mathbf{60})$ MeV ← chiral models

  $\Rightarrow \exists$ of $\bar{K}$-nuclear states

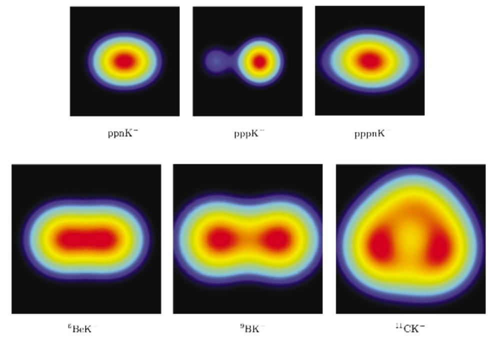
  ? sufficiently narrow to allow identification by experiment

Motivation

T. Yamazaki, Y. Akaishi / Physics Letters B 535 (2002) 70–76



Motivation



- $(2N)\bar{K}$, $(3N)\bar{K}$, $(4N)\bar{K}$, $(8N)\bar{K}$, ... (Akaishi, Yamazaki, Doté *et al.*)
  large polarization effects $\rho \simeq (4-8)\cdot\rho_0$
  $B_{\bar{K}} \gtrsim 100$ MeV, $\Gamma_{\bar{K}} \simeq (20-35)$ MeV

Status Quo

- K^- capture in Li and ^{12}C (FINUDA, PRL (2005)): $B = 115 \pm 6 \pm 4$ MeV, $\Gamma = 67 \pm 14 \pm 3$ MeV

vs.

- $K^- pN \rightarrow \Lambda N + FSI$ (Magas *et al.*, PRC (2006))

vs.

- K^- stopped in ^{6}Li $\rightarrow K^- ppn$ cluster, $B = 58 \pm 6$ MeV, $\Gamma \simeq 30$ MeV
  (FINUDA, PLB (2007) vs. Magas *et al.*, arXiv:0801.4504)

?

- $\bar{p}$ annihilation on ^{4}He (Obelix, LEAR) $\rightarrow K^- pp$: $B \simeq 160$ MeV, $\Gamma \simeq 24$ MeV
  $\rightarrow K^- ppn$: $B = 121 \pm 15$ MeV, $\Gamma < 60$ MeV
  (Bendiscioli *et al.*, NPA (2007))
- $pp \rightarrow K^+ \Lambda p$ (DISTO) $\rightarrow K^- pp$: $B = 105 \pm 118$ MeV
  (T. Yamazaki *et al* EXA08, arXiv: 0810.5182 [nucl-ex])

?

$K^- pp$ *quasibound state*

- Coupled-channel calculations of a $\bar{K}NN - \pi\Sigma N$ system

  (Shevchenko, Gal, JM, PRL 98 (2007) 082301.)

- 3-body Faddeev equations (in AGS form):

$$\begin{aligned} U_{11} &= \phantom{G_0^{-1}} + T_2\, G_0\, U_{21} + T_3\, G_0\, U_{31} \\ U_{21} &= G_0^{-1} + T_1\, G_0\, U_{11} + T_3\, G_0\, U_{31} \\ U_{31} &= G_0^{-1} + T_1\, G_0\, U_{11} + T_2\, G_0\, U_{21}, \end{aligned}$$

U_{ij} describe elastic and re-arrangement processes:

$$\begin{aligned} U_{11} &: \; 1 + (23) \rightarrow 1 + (23) \\ U_{21} &: \; 1 + (23) \rightarrow 2 + (31) \\ U_{31} &: \; 1 + (23) \rightarrow 3 + (12) \end{aligned}$$

- $\bar{K}N$ strongly coupled with $\pi\Sigma$ via $\Lambda(1405) \Rightarrow \pi\Sigma$ channel included

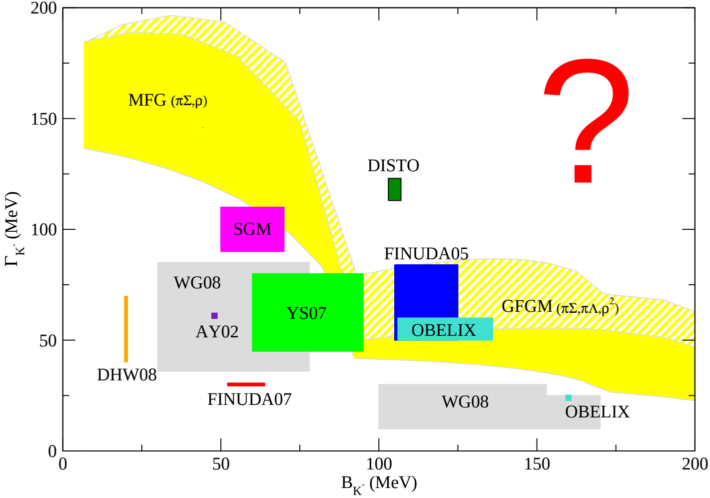
particle channels α:	$1 : (\bar{K}NN)$	$2 : (\pi\Sigma N)$	$3 : (\pi N\Sigma)$
$i = 1$	NN	ΣN	ΣN
$i = 2$	$\bar{K}N$	πN	$\pi\Sigma$
$i = 3$	$\bar{K}N$	$\pi\Sigma$	πN

K^-pp *quasibound state*

Table: Calculated K^-pp binding energies and widths (in MeV)

	single channel		coupled channel		
	AY	DHW	SGM	IS	WG
B	48	17-23	50-70	60 - 95	40-80
Γ	61	40-70	90-110	45-80	40-85

Status Quo


200
150
100
50
0
0
50
100
150
200
Γ_{K^-} (MeV)
B_{K^-} (MeV)
MFG ($\pi\Sigma,\rho$)
SGM
WG08
AY02
YS07
DHW08
FINUDA07
DISTO
FINUDA05
OBELIX
GFGM ($\pi\Sigma,\pi\Lambda,\rho^2$)
WG08
OBELIX
?

RMF Methodology

- Larger K^--nuclear systems

Relativistic mean field model for a system of **nucleons** , K **mesons**, and **hyperons** interacting through the exchange of σ, σ^*, ω, ρ, ϕ and photon fields:

$$\mathscr{L} = \mathscr{L}_{RMF} + \mathscr{L}_K + \mathscr{L}_Y$$

where

$$\begin{aligned} \mathscr{L}_{RMF} &= \text{standard relativistic mean field lagrangian density} \\ \mathscr{L}_K &= (\mathcal{D}_\mu K)^\dagger\,(\mathcal{D}^\mu K) - m_K^2 K^\dagger K - g_{\sigma K} m_K\,\sigma\,K^\dagger K - g_{\sigma^* K} m_K\,\sigma^*\,K^\dagger K\,, \\ \mathscr{L}_Y &= \bar{\psi}_Y[\mathrm{i}\not{D} - (m_Y - g_{\sigma Y}\sigma - g_{\sigma^* Y}\sigma^*)]\psi_Y\,, \end{aligned}$$

with covariant derivative:

$$\mathcal{D}_\mu = \partial_\mu + \mathrm{i}\,g_{\omega K}\,\omega_\mu + \mathrm{i}\,g_{\rho K}\,\vec{I}\cdot\vec{\rho}_\mu + \mathrm{i}\,g_{\phi K}\,\phi_\mu + \mathrm{i}\,e\,(I_3 + \tfrac{1}{2}Y)A_\mu\,.$$

RMF Methodology

$+$ **antikaons**:

$$(-\nabla^2 - E_{K-}^2 + m_K^2 + \Pi_{K-})K^- = 0$$

$$\begin{aligned}\mathrm{Re}\,\Pi_{K-} &= -\,g_{\sigma^* K}\, m_K\, \sigma^* - g_{\sigma K}\, m_K\, \sigma - 2\, E_{K-}(g_{\omega K}\, \omega + g_{\rho K}\, \rho + g_{\phi K}\, \phi + e\, A) \\ &\quad - (g_{\omega K}\, \omega + g_{\rho K}\, \rho + g_{\phi K}\, \phi + e\, A)^2\end{aligned}$$

$$\mathrm{Im}\,\Pi_{K-} = (0.7\, f_{1\Sigma} + 0.1\, f_{1\Lambda})W_0\, \rho_N(r) + 0.2\, f_{2\Sigma}\, W_0\, \rho_N^2(r)/\tilde{\rho}_0$$

f_{iY} kinematical suppression factors
(reduced phase space)

W_0 constrained by kaonic atom data

Absorption through:

- pionic conversion modes $\propto \rho_N(r)$

  $\bar{K}N \rightarrow \pi\Sigma$+90 MeV, $\pi\Lambda$+170 MeV (70%, 10%)

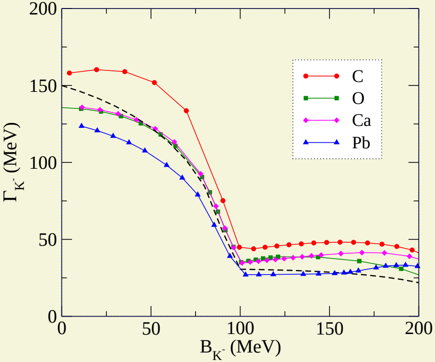
- nonmesonic modes $\propto \rho_N^2(r)$

  $\bar{K}NN \rightarrow YN$+240 MeV (20%)

Γ_{K-} width $\Leftarrow$ phase space suppression x density enhancement

Single-K^- nuclei

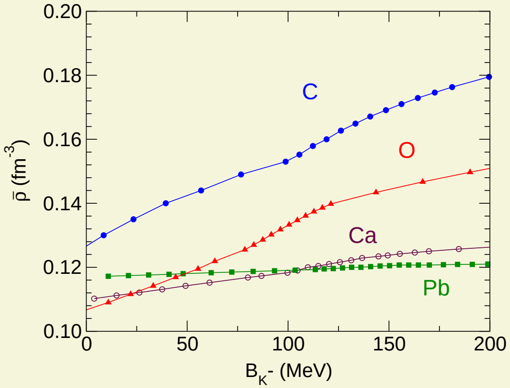
- Γ_{K^-} follows the dependence sf(B_{K^-})



The K^- decay widths Γ_{K^-} in ${}^{12}_{K^-}$C, ${}^{16}_{K^-}$O, ${}^{40}_{K^-}$Ca, and ${}^{208}_{K^-}$Pb as function of the K^- binding energy B_{K^-}.

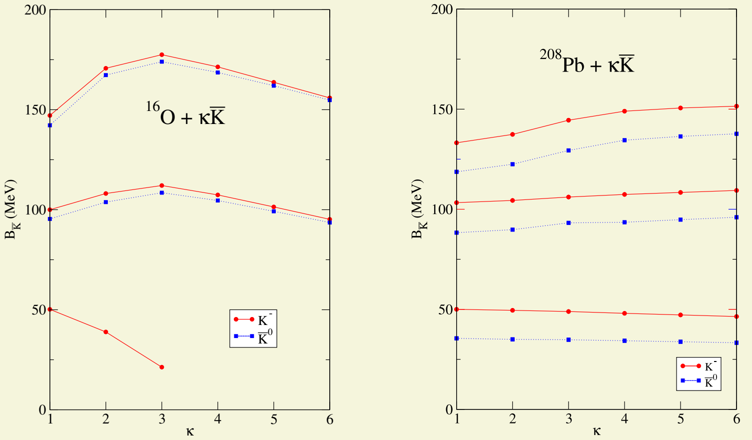
The dashed line indicates a static nuclear matter calculation.

Single-K^- nuclei



Average nuclear density $\bar{\rho}$ as function of the K^- binding energy.

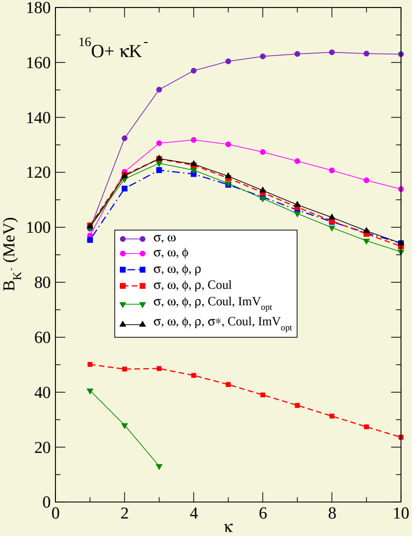
Multi-$\bar{K}$ nuclei



The $\bar{K}$ binding energies as functions of the number κ of antikaons.

- saturation observed across the periodic table
- $B_{\bar{K}} << m_K + m_N - m_\Lambda \gtrsim 320$ MeV, far away from kaon condensation

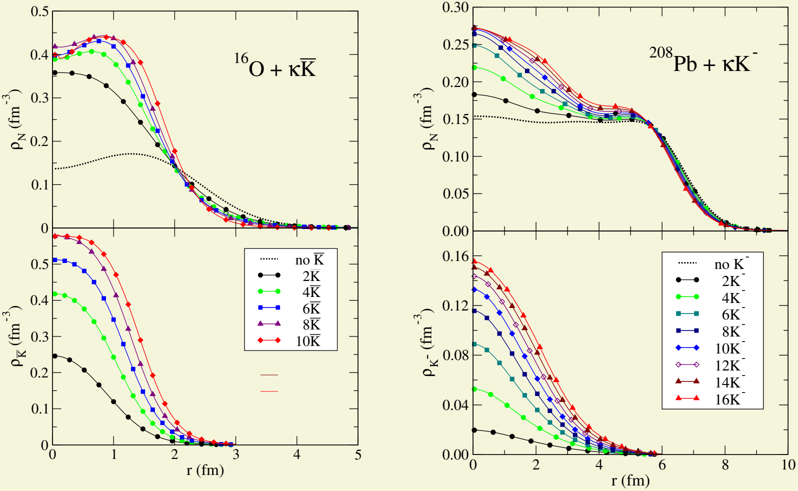
Multi-$\bar{K}$ nuclei



The K^- binding energy as a function of the number κ of antikaons.

- saturation occurs for any boson-field composition
  (when ω-field present ⇒ repulsion)

Multi-$\bar{K}$ nuclei



Nuclear (ρ_N) and $\bar{K}$ ($\rho_{\bar{K}}$) density distributions for various numbers κ of antikaons.

Multi-$\bar{K}$ hypernuclei

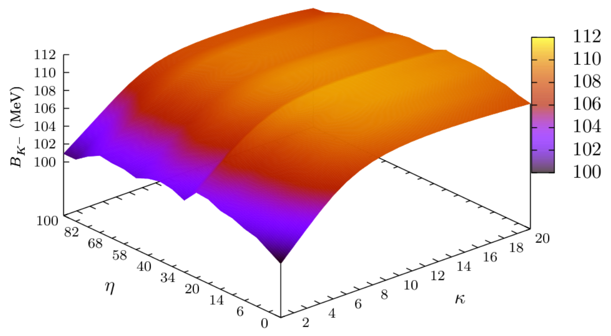
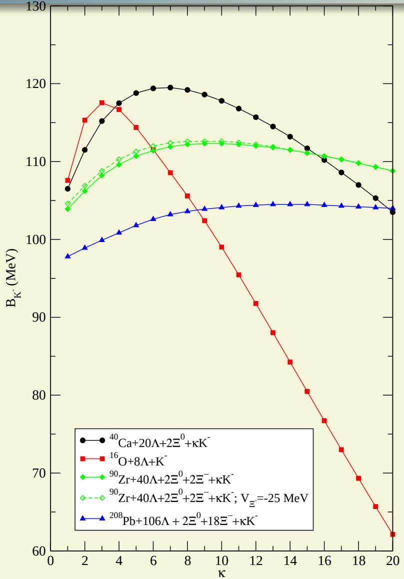


Fig. 17 The $\bar{K}$ binding energy $B_{\bar{K}}$ in ^{208}Pb as a function of the number κ of antikaons and η of Λ hyperons.

Multi-$\bar{K}$ hypernuclei



The $\bar{K}$ binding energy $B_{\bar{K}}$ in ${}^{A}\mathrm{Z} + \eta\Lambda + \mu_0\Xi^0 + \mu_-\Xi^- + \kappa K$ as a function of the number κ of antikaons.

Summary

- Λ hyperon bound by 28 MeV in nuclear matter, spin-orbit splitting → 0
  Few-body Λ (and $\Lambda\Lambda$) hypernuclei - $\Sigma N \rightarrow \Lambda N$ important
  p-shell hypernuclei - effective ΛN interaction determined
  (exp. JLab, FINUDA, planned JParc, HypHI @ GSI (FAIR))
- more data on $\Lambda\Lambda$ hypernuclei needed → PANDA@GSI
- Σ hyperons are not bound in nuclei except for ${}^{4}_{\Sigma}\mathrm{He}$
- Ξ hyperons perhaps bound by ≈ 14 MeV in nuclear matter
  (planned exp. JParc)
- $\bar{K}$ nuclei → the issue is far from being resolved
  (searches for $K^{-}pp$ are underway in GSI and JParc)
- kaon condensation is unlikely to occur in strong-interaction self-bound strange hadronic matter