On bound states of hadrons in nuclei

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Physics Symposium @ 26th CBM Week, Prague, September 16, 2015

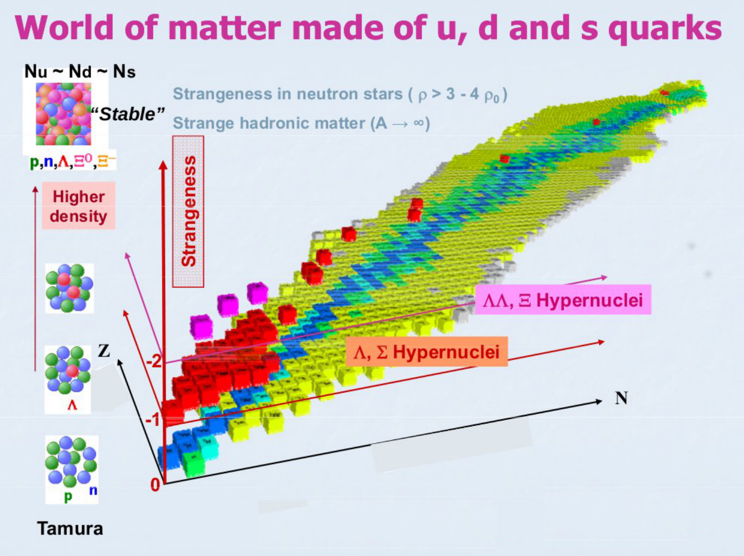
Prelude

There are good reasons to study interactions of hadrons (not only N) with the nuclear medium:

- free-space and in-medium HN interactions ($H = Y$, K, η) $\rightarrow$ test of interaction models (meson exchange, chiral)
- test of nuclear models
  hyperon X nucleon → no Pauli blocking → hyperon can penetrate deep into the nuclear interior, probe it and test nuclear response
- hypernuclear production - test of reaction mechanisms
- hypernuclear decays - study of weak interaction
- nature of resonances $\Lambda(1405)$, $\Sigma(1385)$, $N^*(1535)$
- possible existence of $K^-(\eta)$ nuclear states
- in-medium modifications, strangeness production in HI collisions
- structure of compact stars

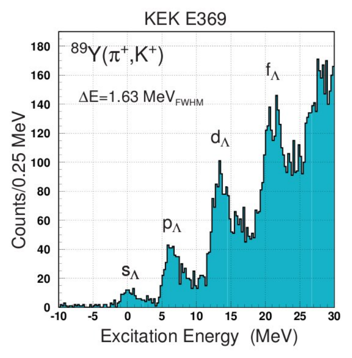
Hypernuclei

- >30 Λ-hypernuclei:

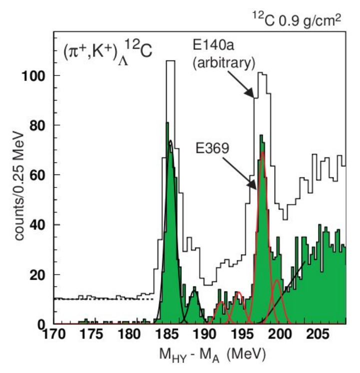


Λ *hypernuclei*

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



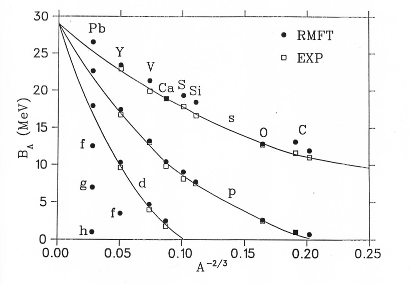
Hotchi et al, PRC 64 (2001) 044302

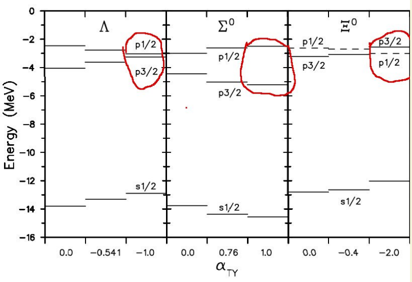


- Textbook example of single-particle structure
- Λ hyperon bound by $\sim$ 28 MeV in nuclear matter
- Negligible spin-orbit splitting

Λ *hypernuclei*

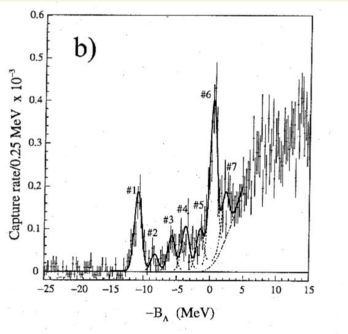
- RMF calculation of hypernuclei - small SO splitting explained
  J.M., B.K. Jennings, PRC (1994)





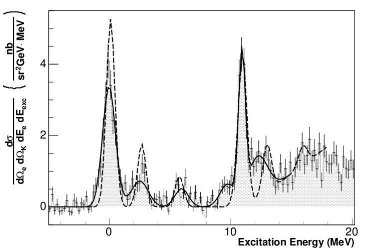
Λ *hypernuclei*

- $(K^-_{\rm stop}, \pi^-)$ reaction (FINUDA, PLB 622 (2005) 35):



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

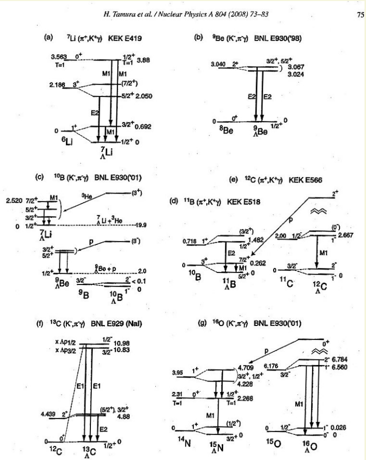
- $(e, e'K)$ reaction (JLab, PRL 99 (2007) 052501):



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

Λ *hypernuclei*

- γ spectroscopy (BNL, KEK)
  $\Rightarrow$ spin dependence of the effective ΛN interaction in the nuclear p shell



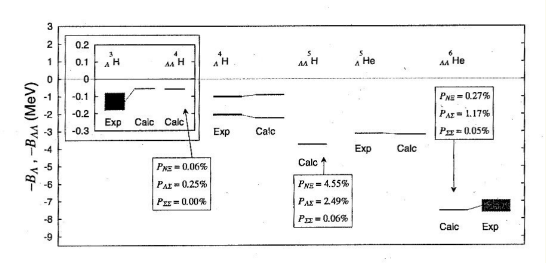
H. Tamura et al. / Nuclear Physics A 804 (2008) 73–83 75

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

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

Λ *hypernuclei*

- s-shell Λ hypernuclei



Nemura et al, PRL 89 (2002) 142504 (+ $\Lambda N \to \Sigma N$ and $\Lambda\Lambda \to \Xi N$) - variational approach
Hiyama et al, PRC 65 (2002) 011301(R) - Jacobi-coordinate Gaussian basis
Nogga et al, PRL 88 (2002) 172501 - Faddeev + Faddeev-Yakubovsky

- s-shell + p-shell Λ hypernuclei

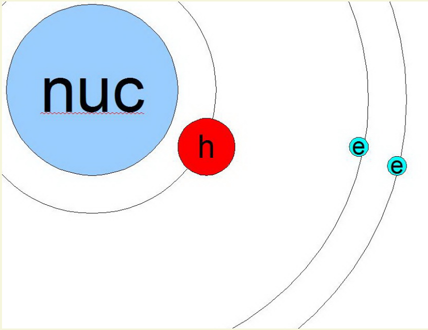
Isaka et al, PRC (2014,2015) - AMD
Schaefer et al, EPJ Web Conf.(2015)- FMD
Gazda et al, FBS (2014), PRL (2014) - NCSM

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*

- Exotic atom $(h = \pi^-,\ \bar{p},\ K^-,\ \Sigma^-,\ \Xi^-)$



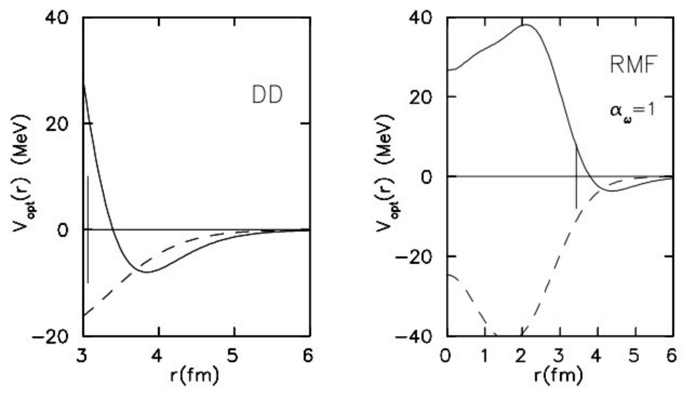
$\longrightarrow \varepsilon,\ \Gamma \longrightarrow V_{\mathrm{opt}}$

	$\mathrm{Re}\,V_{\mathrm{opt}}$	$\mathrm{Im}\,V_{\mathrm{opt}}$ (absorptive)
π^-	repulsive	moderate
K^-	attractive	strong
$\bar{p}$	attractive	strong
Σ^-	repulsive	moderate

Σ *hypernuclei*

- Σ-nucleus interaction:

  (J.M., Friedman, Gal, Jennings, NPA 594 (1995) 311)



- 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
- DWIA calculations for (π^-, K^+) spectra (Harada & Hirabayashi, NPA 759 (2005) 143)

Ξ *hypernuclei*

- Ξ-nucleus interaction:

- $^{12}\mathrm{C}(K^-, K^+)$ spectra (KEK -E224, BNL-E885) → $V_\Xi \approx 14\ \mathrm{MeV}$
- Calculations of light Ξ hypernuclei (Motoba et al)
- Spectroscopic study of Ξ hypernucleus $^{12}_{\Xi}\mathrm{B}$ ... (T. Nagae), A 'Day-1' experiment E05 at J-Parc

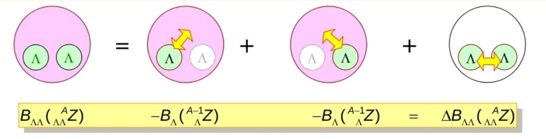
Multi-strange baryonic systems

One can envisage bound many-body systems containing more baryons from the SU(3) octet:

N, Λ, Σ, Ξ

- Multiply strange nuclear systems
  - of interest for astrophysics (neutron stars)
  - of interest for HI collisions
  - their study = source of information about $B - B$ interactions

- Unfortunately, only few ΛΛ hypernuclei known:
  ${}^{4}_{\Lambda\Lambda}$H (?), ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B

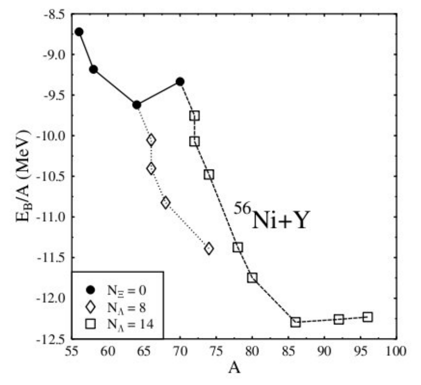


$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) \approx 1 \text{ MeV}$$

Takahashi et al, PRL 87 (2001) 212502

Multi-strange baryonic systems

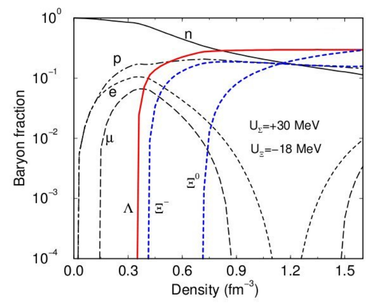
- RMF model predicts a possibility of forming bound systems with appreciable number of hyperons
- Delicate interplay between the effect of Pauli blocking $(Y, N$ distinquishable$)$ and weaker YN interactions $\rightarrow$
  $\{N, \Lambda$, and $\Xi\}$ configurations: $\rho \approx (2-3)\rho_0$, $f_s = |S|/A \approx 1$, $|Z|/A \ll 1$



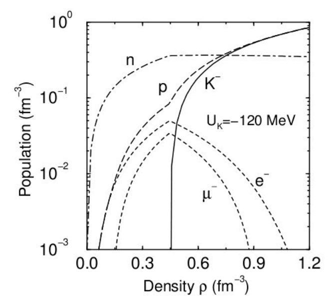
$\Xi N \rightarrow \Lambda\Lambda$ ($\approx$ 25 MeV in free space) is Pauli blocked

Neutron star

- neutron star structure



Schaffner-Bielich, NPA 804 (2008) 309



Glendenning, Schaffner-Bielich PRC 60 (1999) 025803

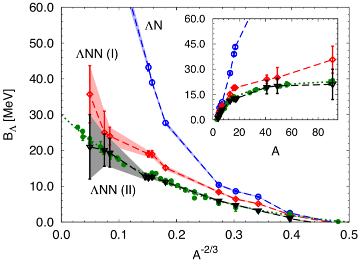
- hyperons (or even kaons) could occur at $\rho \gtrsim 3\rho_0 \rightarrow M_{NS} \leq 1.5 M_\odot$
- but - P.B. Demorest et al, Nature 467 (2010) 1081 - M(J1614-2230) $= 1.97 \pm 0.04$ $M_\odot$
  J. Antoniadis et al, Science 340 (2013) 1233232 - M(J0348-0432) $= 2.01 \pm 0.04$ $M_\odot$
- (?) need for repulsive 3body YNN and YYN forces to make EOS stiff

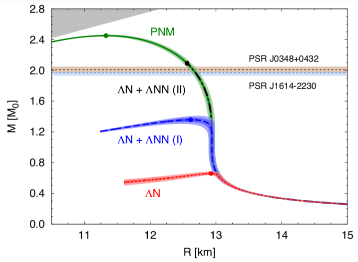
  → hyperons appear in NS at much larger densities (if at all)

3-body ΛNN forces

- phenomenological Usmani $V_{\Lambda N}$ and $V_{\Lambda NN}$ forces

  Lonardoni, Pederiva, Gandolfi, PRC (2013, 2014)





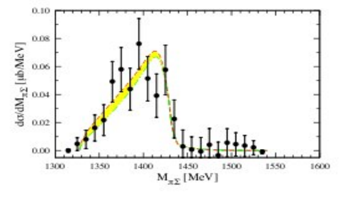
$\bar{K}N$ *interaction*

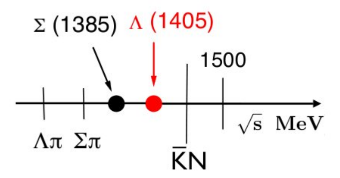
- $\bar{K}N$ interaction

  strongly attractive + strongly coupled to $\pi\Sigma$

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

  (PDG: $M = 1405 \pm 5$ MeV, $\Gamma = 40 \pm 10$ MeV)





	I=0	I=1
NN	**deuteron (2 MeV)**	**attractive**
$\bar{K}N$	Λ(1405) **(15-30 MeV)**	**attractive**

$\bar{K}$-*nucleus interaction*

- $\bar{K}$-nucleus interaction

  strongly attractive and absorptive $\Leftarrow$ kaonic atom level shifts and widths

  ? optical potential depth:

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

  $\mathrm{Im}V_{opt} \simeq (\mathbf{60}-\mathbf{70})$ MeV

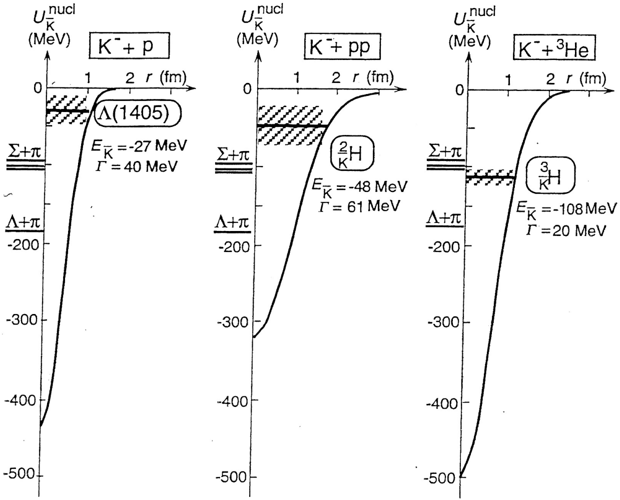
  (E. Friedman, A. Gal, NPA 881 2012 (150), NPA 899 (2013) 60: self-consistent subthreshold K^-N amplitudes + K^--multinucleon interactions are needed!)

- $\Rightarrow$ Do $\bar{K}$-nuclear states exist?

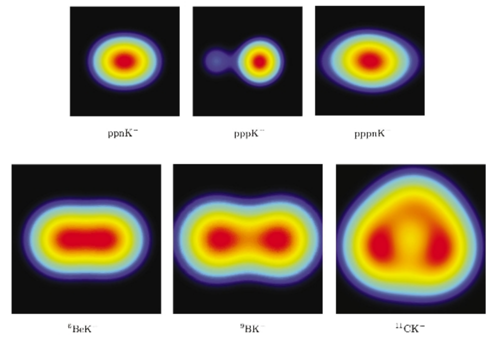
  Are they sufficiently narrow to be identified in experiment

$\bar{K}$ nuclear states ?

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 $\rho \simeq (4-8)\rho_0$
  $B \gtrsim 100$ MeV, $\Gamma \simeq (20-35)$ MeV

$\bar{K}$ *nuclear states - Status Quo*

- ? K^- capture in Li and ^{12}C (FINUDA) →
  $K^-pp:\ B = 115 \pm 6 \pm 4$ MeV, $\Gamma = 67 \pm 14 \pm 3$ MeV
  (M. Angello *et al.*, PRL 94 (2005) 212303)

- ? $\bar{p}$ annihilation on ^{4}He (Obelix, LEAR) →
  $K^-pp:\ B \simeq 160$ MeV, $\Gamma \simeq 24$ MeV
  (G. Bendiscioli *et al.*, NPA 789 (2007) 222)

- ? $pp \to K^+\Lambda p$ (DISTO) →
  $K^-pp:\ B \simeq 105$ MeV, $\Gamma \simeq 118$ MeV
  (T. Yamazaki *et al*, PRL 104 (2010) 132502)

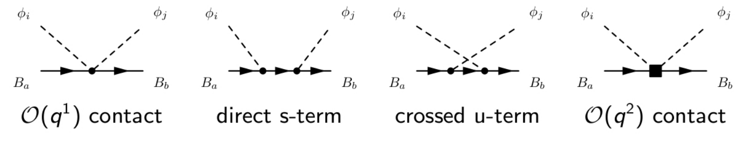
- current status @ HYP2015
  $pp \to (K^-pp) + K^+$ (GSI) - no candidates
  $\pi + d \to (K^-pp) + K^+$ (E27, JPARC) - K^-pp:
  $B = 95\ ^{+18}_{-17}\ \text{(stat.)}\ ^{+30}_{-21}\ \text{(syst.)}$ MeV, $\Gamma = 162\ ^{+87}_{-45}\ \text{(stat.)}\ ^{+66}_{-78}\ \text{(syst.)}$ MeV

$\bar{K}N$ *interactions*

- chiral $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ meson-baryon effective Lagrangian for $\{\pi, K, \eta\} + \{N, \Lambda, \Sigma, \Xi\}$
- $\exists$ resonances (e.g. $\Lambda(1405)$) $\Rightarrow$ χPT not applicable $\rightarrow$
- nonperturbative coupled-channel resummation techniques

$$T_{ij} = V_{ij} + V_{ik} G_{kl} T_{lj}, \quad V_{ij} \text{ derived from } \mathcal{L}_\chi$$

Effective potentials match the chiral meson-baryon amplitudes up to NLO order

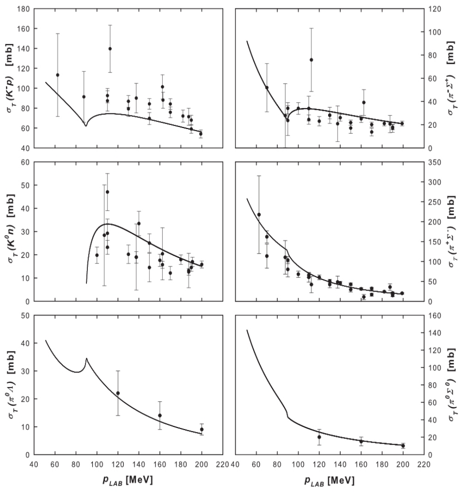


$\bar{K}N$ *interactions*

- $S = -1$ sector ($\bar{K}N$ related channels involved):
  $\pi\Lambda$, $\pi\Sigma$, $\bar{K}N$, $\eta\Lambda$, $\eta\Sigma$, $K\Xi$
- Model parameters (NLO d-couplings, inverse interaction ranges) fixed in fits to low-energy meson-nucleon data:
    - kaonic hydrogen data (SIDDHARTA)
    - $K^{-}p$ threshold branching ratios
    - $K^{-}p$ low energy X-sections

$K^- p$ Data

$K^- p$ scattering:



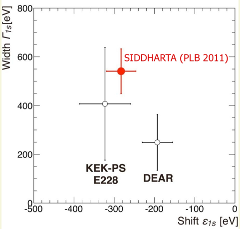
Threshold branching ratios:

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

$$R_c = \frac{\Gamma(K^- p \to \text{charged})}{\Gamma(K^- p \to \text{all})} = 0.664 \pm 0.011$$

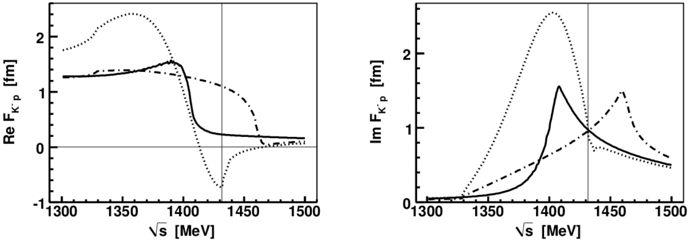
$$R_n = \frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutral})} = 0.189 \pm 0.015$$

Kaonic hydrogen:



Chiral K^-N scattering amplitudes

- Strong energy dependence of $f_{K^-p}(\sqrt{s}) = 1/2(f_{KN}^{I=0} + f_{KN}^{I=1})$ affected by the $I = 0$ $\Lambda(1405)$



dotted - in vacuum, dot-dashed - Pauli blocked, continuous - Pauli blocked + hadron selfenergies

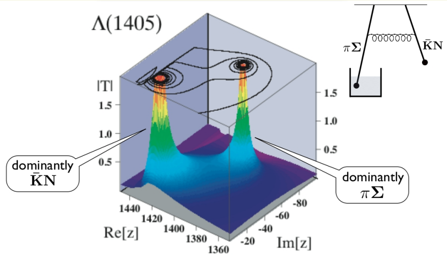
- In-medium K^-p interaction is relatively weak at threshold but becomes stronger when going subthreshold

$\bar{K}N$ *interaction*

- Λ(1405) – dynamically generated 2body resonance

  coupled channel chiral approach → strongly correlated $\bar{K}N - \pi\Sigma$ dynamics provides 2 resonance poles

  Λ(1405) is NOT a simple bound state but emerges from the complex interplay of the strongly coupled $\bar{K}N$ and $\pi\Sigma$ channels



- Pole positions from chiral SU(3) coupled-channels calculation with SIDDHARTA threshold constraints:

$$\begin{array}{ll} \mathbf{E_1 = 1424 \pm 15\ MeV} & \mathbf{E_2 = 1381 \pm 15\ MeV} \\ \mathbf{\Gamma_1 = 52 \pm 10\ MeV} & \mathbf{\Gamma_2 = 162 \pm 15\ MeV} \end{array}$$

Y. Ikeda, T. Hyodo, W.W.: Nucl. Phys. A 881 (2012) 98

K^-pp *quasibound state*

K^-pp binding energies and widths (in MeV) – chiral, E-dependent approach

	var.[1]	var.[2]	Fad.[3]	Fad.[4]
B	16	17-23	9-16	32
Γ	41	40-70	34-46	49

1. N. Barnea, A. Gal, E.Z. Liverts, PLB 712 (2012) 132
2. A. Dote, T. Hyodo, W. Weise, NPA 804 (2008) 197, PRC 79 (2009) 014003
3. Y. Ikeda, H. Kamano, T. Sato, PTP 124 (2010) 533

4 J. Revai, N.V. Shevchenko, PRC 90 (2014) 034004

K^-pp binding energies and widths (in MeV) – phenomenological, E-independent approach

	var.[5]	Fad.[6]	Fad.[7]	var.[8]	Fad.[9]
B	48	50-70	60-95	40 -80	47
Γ	61	90-110	45 - 80	40 - 85	50

5. T. Yamazaki, Y. Akaishi, PLB 535 (2002) 70
6. N.V. Shevchenko, A. Gal, J. Mares, PRL 98 (2007) 083201
7. Y. Ikeda, T. Sato, PRC 76 (2007) 035203, PRC 79 (2009) 035201
8. S. Wycech, A.M. Green, PRC 79 (2009) 014001
9. J. Revai, N.V. Shevchenko, PRC 90 (2014) 034004

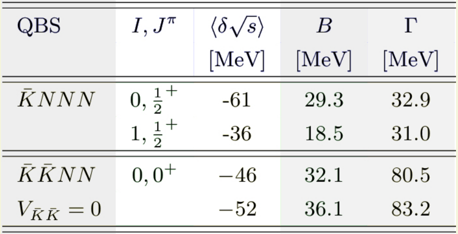
- Binding energies:

phenomenological models:	$K^-p \to 27$ MeV,	$K^-pp \to 50-100$ MeV
chiral (E-dependent) models:	$K^-p \to 10-13$ MeV,	$K^-pp \to 10-30$ MeV

$\bar{K}$ *in few-body systems*

- $\bar{K}NNN$ and $\bar{K}\bar{K}NN$

  N. Barnea, A. Gal, E.Z. Liverts, PLB 712 (2012)



QBS	I, J^π	$\langle\delta\sqrt{s}\rangle$ [MeV]	B [MeV]	Γ [MeV]
$\bar{K}NNN$	$0, \frac{1}{2}^+$	-61	29.3	32.9
	$1, \frac{1}{2}^+$	-36	18.5	31.0
$\bar{K}\bar{K}NN$	$0, 0^+$	-46	32.1	80.5
$V_{\bar{K}\bar{K}} = 0$		-52	36.1	83.2

- T. Yamazaki, Y. Akaishi, PRC 65 (2002) 044005, PLB 587 (2004) 167:

  $B(\bar{K}NNN) \sim 100$ MeV, $B(\bar{K}\bar{K}NN) \sim 120$ MeV !

- Y. Kanada-En'yo, D. Jido, PRC 78 (2008) 025212:

  $B(\bar{K}\bar{K}N) = 10$ - 32 MeV, $\Gamma(\bar{K}\bar{K}N)$=40 - 60 MeV

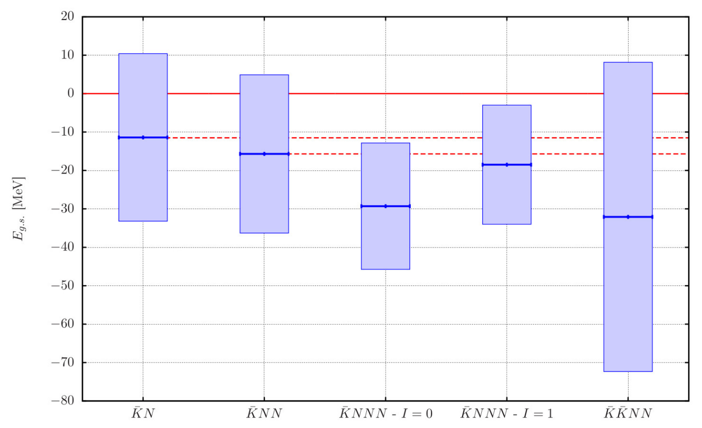
- N.V. Shevchenko, J. Haidenbauer, arXiv:1507.08839v1[nucl-th]:

  $B(\bar{K}\bar{K}N) = 12$ - 26 MeV, $\Gamma(\bar{K}\bar{K}N)$=61 - 102 MeV

$\bar{K}$ *in few-body systems*

- $\bar{K}N \to \bar{K}\bar{K}NN$ systems

  N. Barnea, A. Gal, E.Z. Liverts, PLB 712 (2012)



Binding energies and $\bar{K}N \to \pi Y$ widths of $\bar{K}$ and $\bar{K}\bar{K}$ few-body quasi-bound states.

$\bar{K}$ in many-body systems

- K.-G. equation

  $$\left[\omega_K^2 + \vec{\nabla}^2 - m_K^2 - \Pi_K(\vec{p}_K, \omega_K, \rho)\right] \phi_K = 0$$

  complex energy $\omega_K = m_K - B_K - \mathrm{i}\Gamma_K/2 - V_C$

- self-energy operator $\Pi_K(\vec{p}_K, \omega_K, \rho)$
  constructed microscopically from a chiral model

- $\bar{K}$ in a nucleus $\Rightarrow$ polarized (compressed) $\rho \longrightarrow \Pi_K(\rho)$
  $\Rightarrow$ self-consistent solution

$\bar{K}$ *in many-body systems*

- Selfenergy operator

$$\Pi_K = 2\,\omega_K V_K == -4\pi \frac{\sqrt{s}}{m_N} F_{KN}(\vec{p}, \sqrt{s}, \rho)\,\rho$$

- $F_{KN} = \bar{K}N$ scattering amplitude with **two-body arguments:**

$\vec{p} = \bar{K}N$ relative momentum, $\sqrt{s}$ $(s = (E_K + E_N)^2 - (\vec{p}_K + \vec{p}_N)^2)$

- $\bar{K}N$ c.m. frame → $\bar{K}$–nucleus c.m. frame $\Rightarrow \vec{p}_K + \vec{p}_N \neq 0$

$$\Rightarrow \sqrt{s} \sim E_{th} - B_N \frac{\rho}{\bar{\rho}} - \xi_N B_K \frac{\rho}{\rho_0} - \xi_N T_N \left(\frac{\rho}{\rho_0}\right)^{2/3} + \xi_K \mathrm{Re} V_K(\rho)$$

- $\rho =$ nucl. medium density (RMF calculations)

- $V_K, B_K \Rightarrow$ self-consistent solution

$\bar{K}N$ *scattering amplitude*

- Chiral coupled-channels model:

  A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115 ← NLO model (SIDDHARTA data)

  multi-channel L.-Sch. equation:

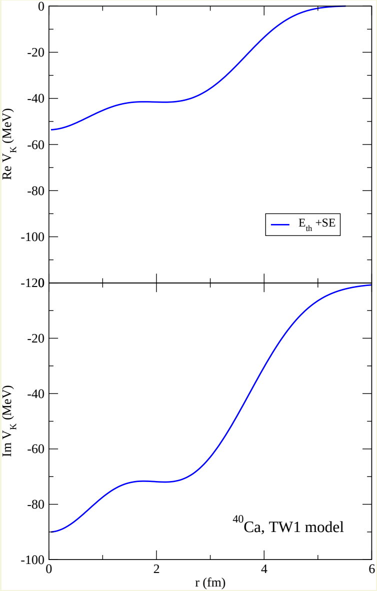
  $T_{ij} = V_{ij} + V_{ik} G_{kl} T_{lj}$

  V_{ij} in separable form, $G = \frac{1}{E - H_0 - \Pi(\sqrt{s}, \rho)}$

  '+SE' option: hadron **self-energies** Π in G_{ij}

  ⇒ self-consistency in V_K

K^- *potentials*



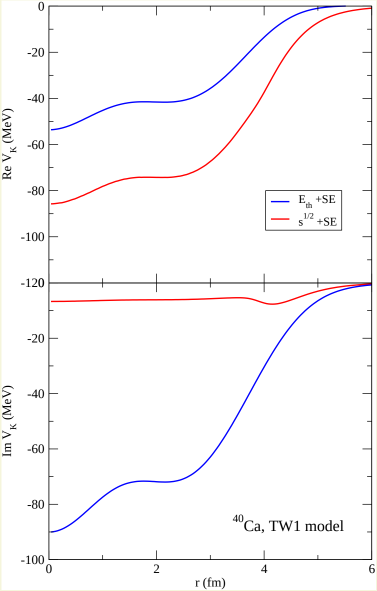
$$\sqrt{s}=E_{th} \;\&\; F_{KN} = F_{KN}(\Pi_K)$$

amplitude with selfenergies at threshold

Binding energies and widths of 1*s* K^- states (TM1 model)

	^{12}C	^{16}O	^{40}Ca	^{90}Zr	^{208}Pb
B_K	(-0.9)	6.4	25.0	39.0	53.4
Γ_K	(137.6)	120.2	141.8	141.0	129.1

K^- potentials



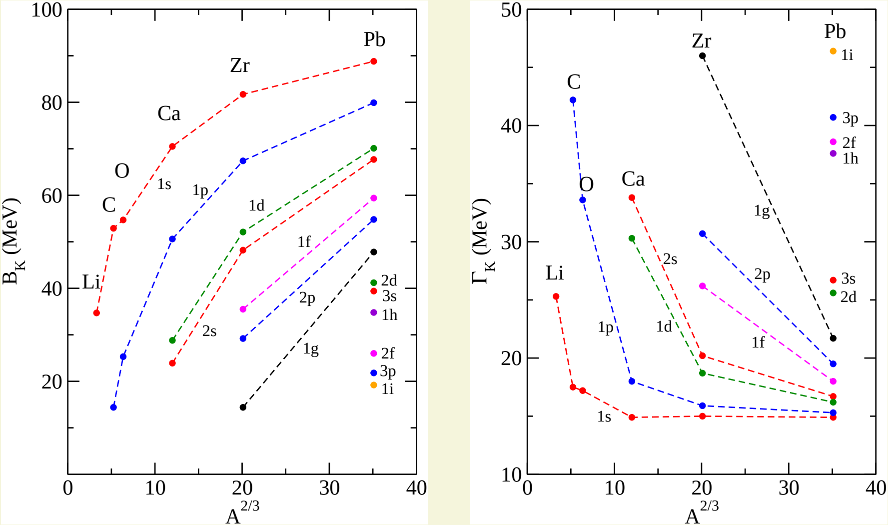
$$B_K \Leftrightarrow V_K(\sqrt{s}) \;\&\; F_{KN} = F_{KN}(\Pi_K)$$

amplitude with selfenergies and selfconsistence in K.–G. Eq.

Binding energies and widths of 1s K^- states (TM1 model)

	^{12}C	^{16}O	^{40}Ca	^{90}Zr	^{208}Pb
B_K	42.4	44.9	58.8	68.9	76.3
Γ_K	16.5	16.2	12.0	11.5	11.3

Excited K^- nuclear states



Binding energies (left panel) and widths (right panel) of K^-–nuclear states, calculated selfconsistently using '+SE' NLO30 amplitudes; $K^- NN \to YN$ not included.

K^- nuclear states

- 2N absorption
  $\bar{K}NN \to YN$ (20%) nonmesonic modes
- phenomenological term added:

$$+\mathrm{Im}\,\Pi_K = 0.2 f_{2Y}\, W_0\, \rho_N^2(r)$$

f_{2Y} kinematical suppression factors
(reduced phase space)

W_0 constrained by kaonic atom data

The effect of 2N absorption (CS30 model):

		C	O	Ca	Zr	Pb
$\sqrt{s}$+SE+dyn.	B_K	55.7	56.0	70.2	80.5	87.0
	Γ_K	12.3	12.1	10.8	10.9	10.8
$\sqrt{s}$+SE+dyn.+2N	B_K	54.0	55.1	67.6	79.6	86.3
	Γ_K	44.9	53.3	65.3	48.7	47.3

η nuclear states - Status Quo

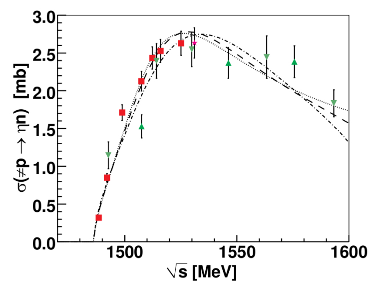
- Haider, Liu (PLB 172 (1986) 257, PRC 34 (1986) 1845)
  moderate attractive ηN interaction with scattering length $a_{\eta N} \sim 0.27 + i0.22$ fm $\Rightarrow \exists$ of η nuclear bound states (starting ^{12}C)
- Numerous studies since then yielding Re$a_{\eta N}$ from 0.2 fm to 1 fm
  chiral coupled channel models - Re$a_{\eta N} < 0.3$ fm;
  K matrix methods fitting πN and γN reaction data in the $N^*(1535)$ resonance region - Re$a_{\eta N} \sim 1$ fm $\rightarrow$ bound states already in He isotopes
- Strong final-state interaction have been noted in $p-$ and d-initiated η production (COSY-ANKE, COSY-GEM, LNS-SPES2,3,4)
- $^{25}_{\eta}Mg$? (COSY-GEM, PRC 79 (2009) 012201(R))
  $p +^{27}\mathrm{Al} \rightarrow^{25}_{\eta} \mathrm{Mg} +^{3} \mathrm{He};\qquad ^{25}_{\eta}\mathrm{Mg} \rightarrow (\pi^- + p) + X$
  $B_\eta = 13.1 \pm 1.6$ MeV and $\Gamma_\eta = 10.2 \pm 3.0$ MeV.
- But NO decisive experimental evidence so far.
  (negative results for $^3_\eta$He (photoproduction on ^{3}He - MAMI, PLB 709 (2012) 21.)
  and for $^4_\eta$He ($dd \rightarrow^3 \mathrm{He}p\pi$ - WASA@COSY PRC 87 (2013)035204.)

ηN *interactions*

- Channels involved in the chiral SU(3) coupled-channel approach: πN, ηN, $K\Lambda$, $K\Sigma$ $\quad (S = 0)$
- Model parameters (NLO d-couplings, inverse interaction ranges) fixed in fits to low-energy meson-nucleon data:
  - $S = 0$ sector (ηN related channels)
    - πN amlitudes from SAID database (S_{11} and S_{31} partial waves)
    - $\pi N \to \eta N$ production X-sections

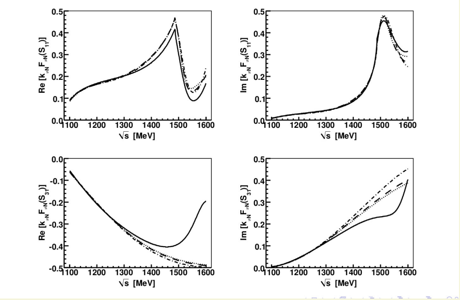
$\eta - N\ (\pi N)$ *Data*

$\pi N \to \eta N$ production X-section:



πN amplitudes from SAID database:

(S_{11} and S_{31} partial waves)



$\bar{K}N$ *vs.* ηN *amplitudes*

- Strong energy dependence of the scattering amplitudes !

	$E_{\rm th}$ (MeV)	resonance
$\bar{K}N$	1434	$\Lambda(1405)$
ηN	1486	$N^*(1535)$

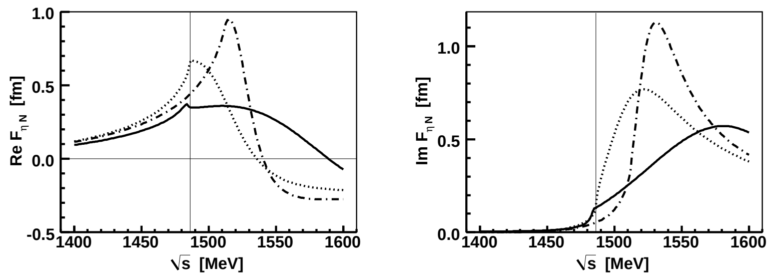
$\bar{K}N$ case - $\Lambda(1405)$ resonance below threshold

vs.

ηN case - $N^*(1535)$ resonance above threshold

ηN scattering amplitudes

- Energy dependence of $f_{\eta N}(\sqrt{s}) \longleftarrow N^*(1535)$

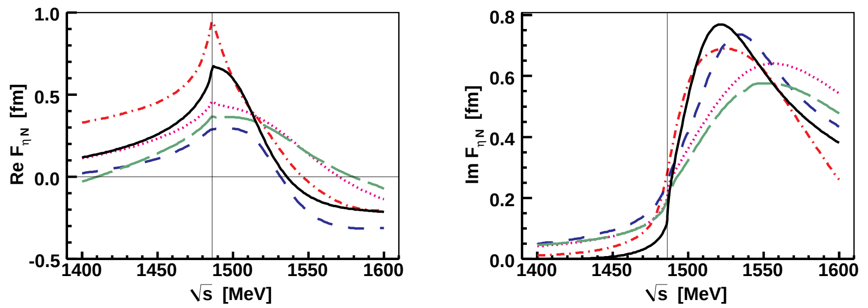


dotted curve: free-space, dot-dashed: Pauli blocked, full: Pauli blocked + hadron selfenergies

- Nuclear medium reduces the ηN attraction at threshold, the amplitude becomes smaller when going subthreshold

η nuclear states

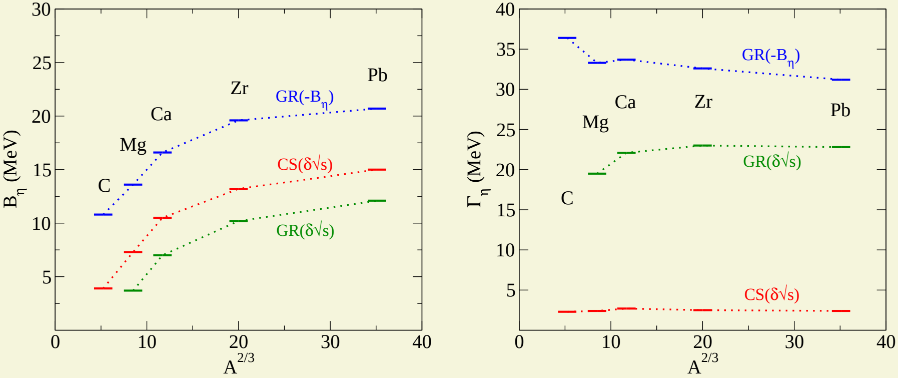
- ηN amplitude for various models:



line	$a_{\eta N}$ [fm]	model
dotted	0.46+i0.24	*N. Kaiser, P.B. Siegel, W. Weise, PLB 362 (1995) 23*
short-dashed	0.26+i0.25	*T. Inoue, E. Oset, NPA 710 (2002) 354 (GR)*
dot-dashed	0.96+i0.26	*A.M. Green, S. Wycech, PRC 71 (2005) 014001 (GW)*
long-dashed	0.38+i0.20	*M. Mai, P.C. Bruns, U.-G. Meißner, PRD 86 (2012) 094033 (M2)*
full	0.67+i0.20	*A. Cieply, J. Smejkal, Nucl. Phys. A 919 (2013) 334 (CS)*

η nuclear states

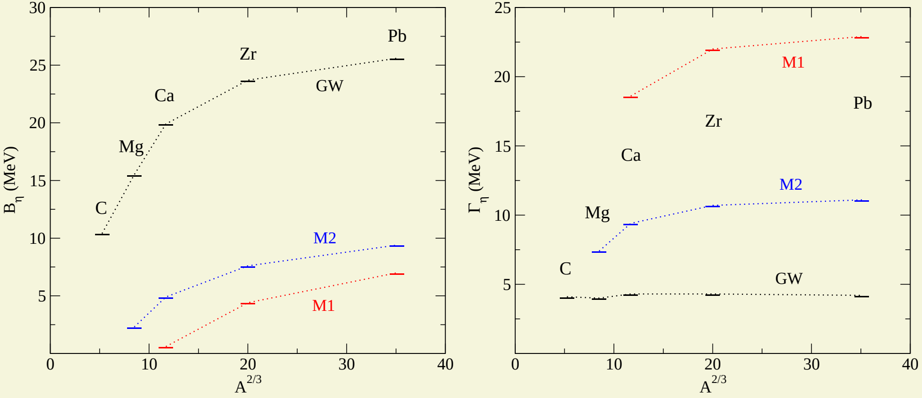
- Sensitivity to the energy shift:
  selfconsistent $\delta\sqrt{s}$ reduces both 1s B_η and Γ_η



- GR widths too large to resolve η bound states !

η nuclear states

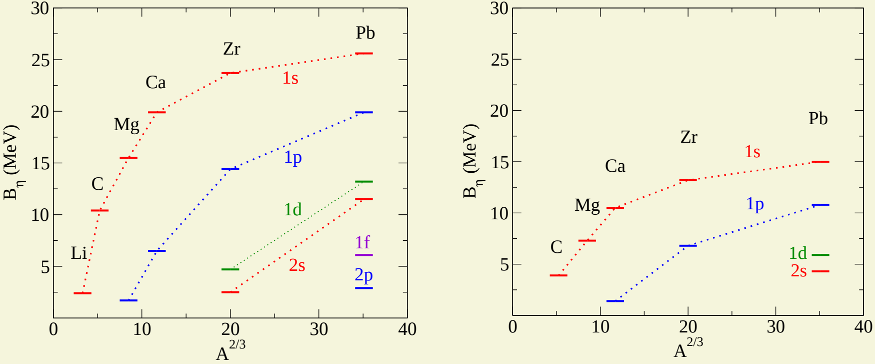
- Model dependence:



- Larger Re $a_{\eta N}$ gives larger B_η **vs.** no relation between Im $a_{\eta N}$ and Γ_η

η nuclear states

- Predictions of GW (left) and CS (right) models:
  all states in selected nuclei are shown; both models give small widths



Summary

Hyperons in nuclear systems

- Λ hyperon bound by 28 MeV in nuclear matter, spin-orbit splitting → 0
  Few-body Λ (and $\Lambda\Lambda$) hypernuclei - $\Sigma N \to \Lambda N$ important
  ? - 3-body YNN forces, charge symmetry breaking in mirror hypernuclei
  p-shell hypernuclei - effective ΛN interaction determined
  (exp. JLab, FINUDA, planned JParc, HypHI @ GSI (FAIR))
- more data on $\Lambda\Lambda$ hypernuclei needed → PANDA(FAIR)
- 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)

Summary

$\bar{K}$ in few-body systems

- Theory: $\bar{K}N - \pi\Sigma$ interaction still ambiguous (nature of $\Lambda(1405)$, subthreshold extrapolation) $\Rightarrow$ different predictions for few-body systems (K^-pp)
- Experiment: K^-pp 'candidates' with different B_K and Γ_K, contradicting theoretical calculations → still under discussion

- $\pi\Sigma$ spectra ($\Lambda(1405)$) - new data from LEPS, CLAS, HADES, AMADEUS ...
- K^-pp bound states - recent and forthcoming experiments:
  $pp \to (K^-pp) + K^+$ (GSI),
  K^{-3}He $\to (K^-pp) + n$ (E15, JPARC),
  $\pi + d \to (K^-pp) + K^+$ (E27, JPARC)
  AMADEUS @ Frascati
- K^-d interaction: ε and Γ in kaonic deuterium (SIDDHARTA 2)

Summary

$\bar{K}$ in many-body systems

- Chiral models give relatively deeply bound $1s$ K^- nuclear states - $B_{K^-} \sim 50 - 90$ MeV (A + model dependence).
- After including $\bar{K}NN \rightarrow YN$ absorption, the decay widths Γ_K are comparable or even larger than the corresponding binding energies B_K for all K^- nuclear quasi-bound states, exceeding considerably the level spacing.

η nuclear bound states

- Large energy shift and rapid decrease of the ηN amplitudes lead to relatively small binding energies and widths of the calculated η nuclear bound states.
- additional width contribution not considered in this work due to $\eta N \rightarrow \pi\pi N$ and $\eta NN \rightarrow NN \Rightarrow$ estimated to add few MeV
- Subthreshold behavior of $f_{\eta N}$ is crucial to decide whether η nuclear states exist, in which nuclei, and if their widths are small enough to be resolved in experiment.