In-medium $\bar{K}$ mesons

from atoms to strange dibaryons

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- $\bar{K}N - \pi Y$ **chiral dynamics and its consequences**
- $\bar{K}$ **nuclear clusters; strange dibaryons**
- $\bar{K}$**-nucleus potentials from** K^- **atoms**
- **No** $\bar{K}$ **condensation on earth**

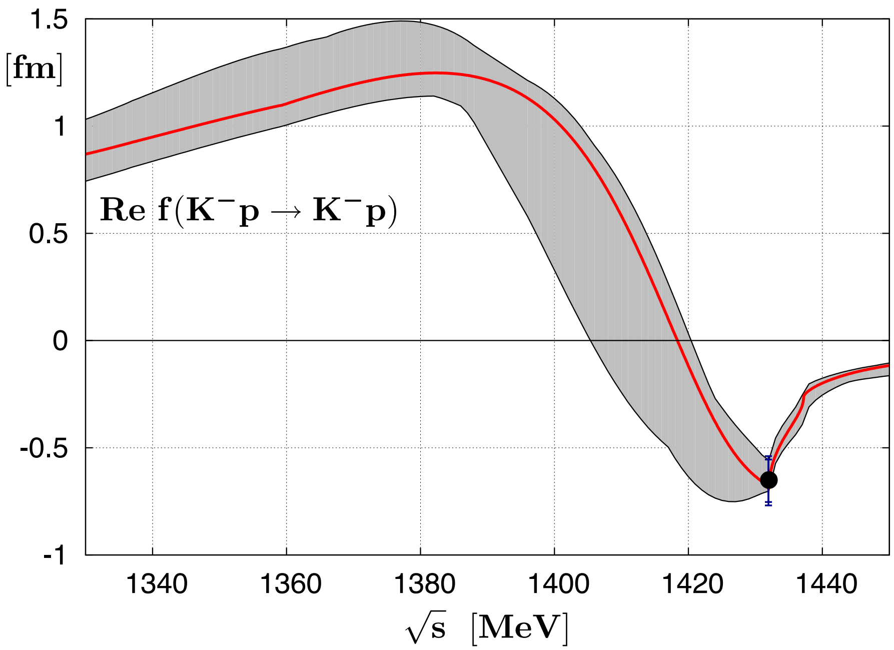
SNP: NPA 881 (2012), HYP12: NPA 914 (2013)

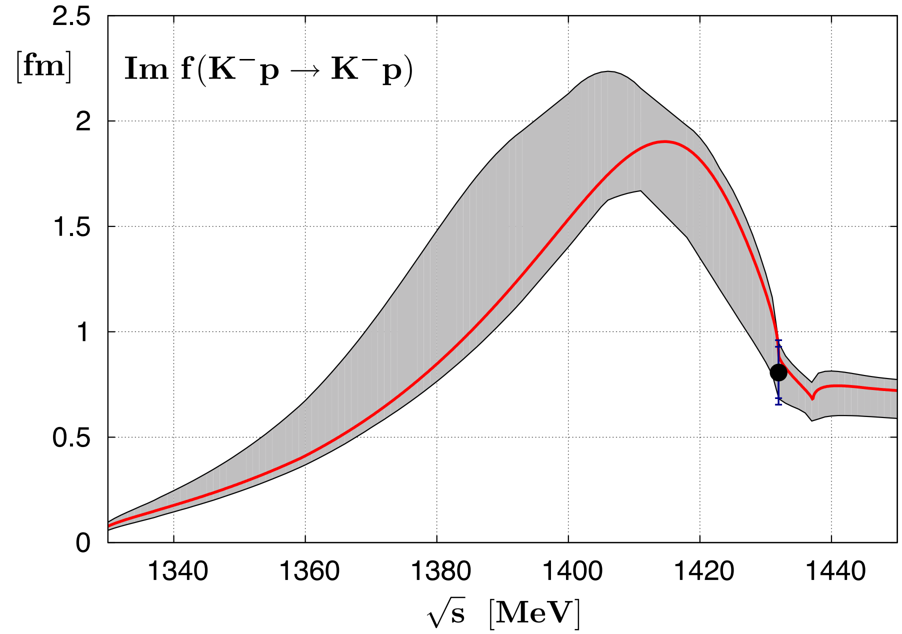
A.Gal, E.Friedman, N.Barnea, A.Cieplý, D.Gazda, J.Mareš

Acta Physica Polonica B 45 (2014) 673-687

$\bar{K}N - \pi Y$ Chiral Dynamics

K^-p scattering amplitude from NLO chiral SU(3) dynamics





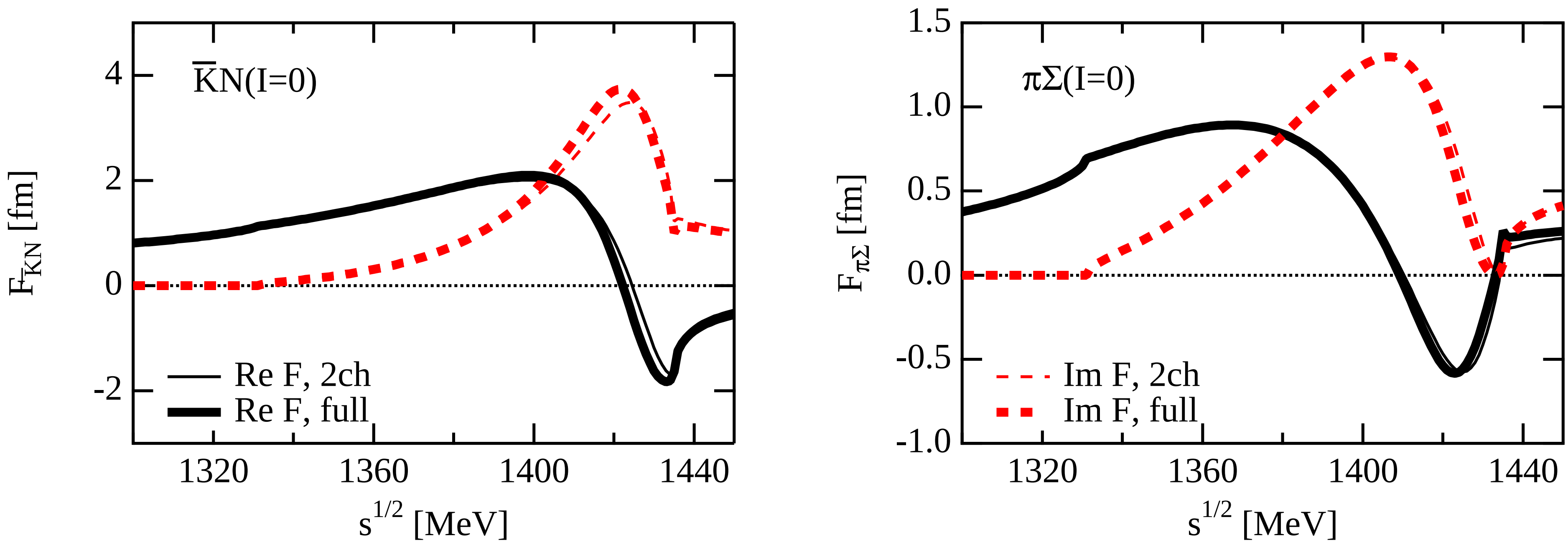
Y. Ikeda, T. Hyodo, W. Weise (IHW), PLB **706** (2011) 63; NPA **881** (2012) 98

Threshold amplitude constrained by SIDDHARTA exp.

Strong subthreshold K^-p attraction; $\Lambda(1405)$ physics;

consequences for kaonic atoms & nuclear clusters

$K^-NN \rightarrow YN$ **absorption not accounted for by this model.**



T. Hyodo, W. Weise, PRC 77 (2008) 035204 $I = 0$ coupled-channel amplitudes

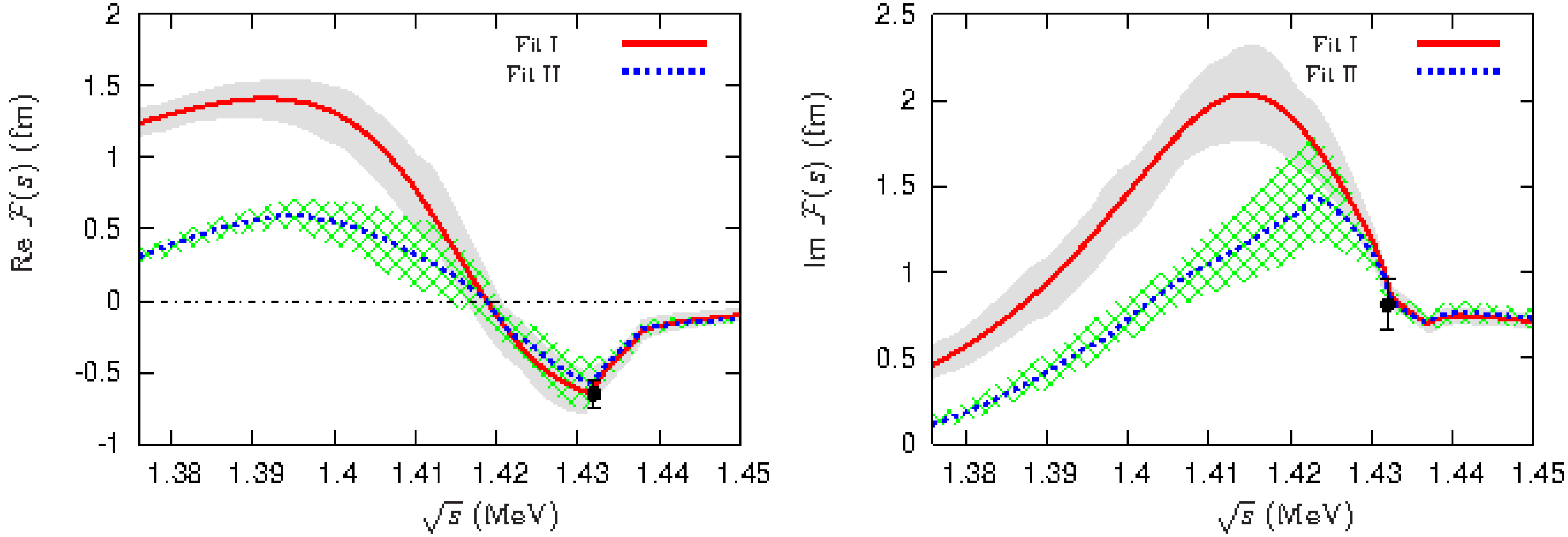
Location of 'resonances': $\bar{K}N \approx 1420$ MeV, $\pi\Sigma \approx 1405$ MeV

$\bar{K}N$ pole relatively narrow, and stable to fit variations.

$\pi\Sigma$ pole broader, unstable, and affects subthreshold.

IHW (2012): $z_{\bar{K}N}$=1424-i26 MeV, $z_{\pi\Sigma}$=1381-i81 MeV

K^-p subthreshold ambiguity



Two NLO chiral-model fits by Guo-Oller, PRC 87 (2013) 035202

- **Fit I: meson-independent $f = 125.7 \pm 1.1$ MeV.**
- **Fit II: physical values for $f_\pi,\ f_K,\ f_\eta$.**
  Will create problems when confronted with K^--atom data.
- **Amplitudes constrained at threshold by SIDDHARTA.**
  $\bar{K}N$ pole robust, $\pi\Sigma$ pole correlated with fit.

$\overline{K}$ nuclear few-body systems

Energy dependence in $\bar{K}$ nuclear few-body systems

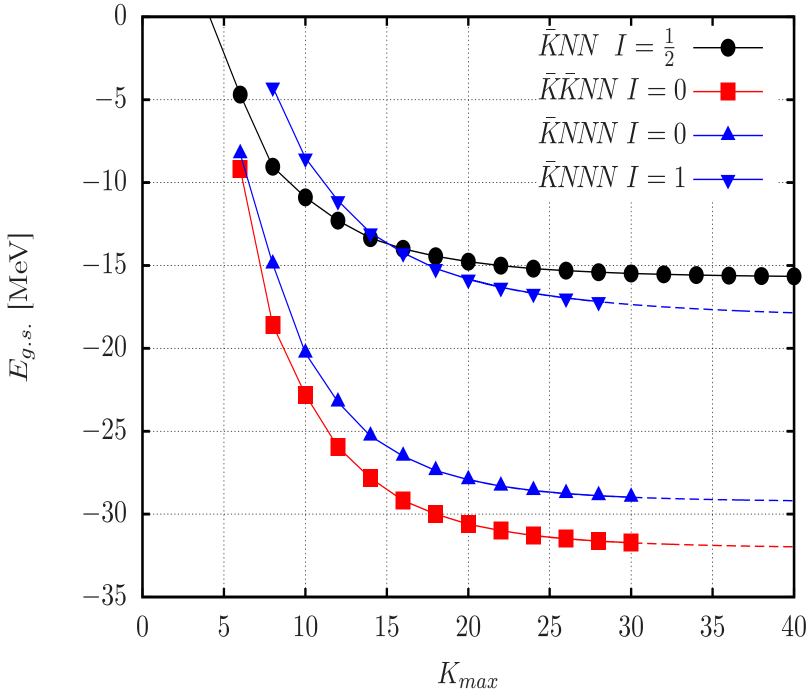
- $\Lambda(1405)$ induces strong energy dependence of the scattering amplitudes $f_{\bar{K}N}(\sqrt{s})$ and the underlying effective single-channel input potentials $v_{\bar{K}N}(\sqrt{s})$.

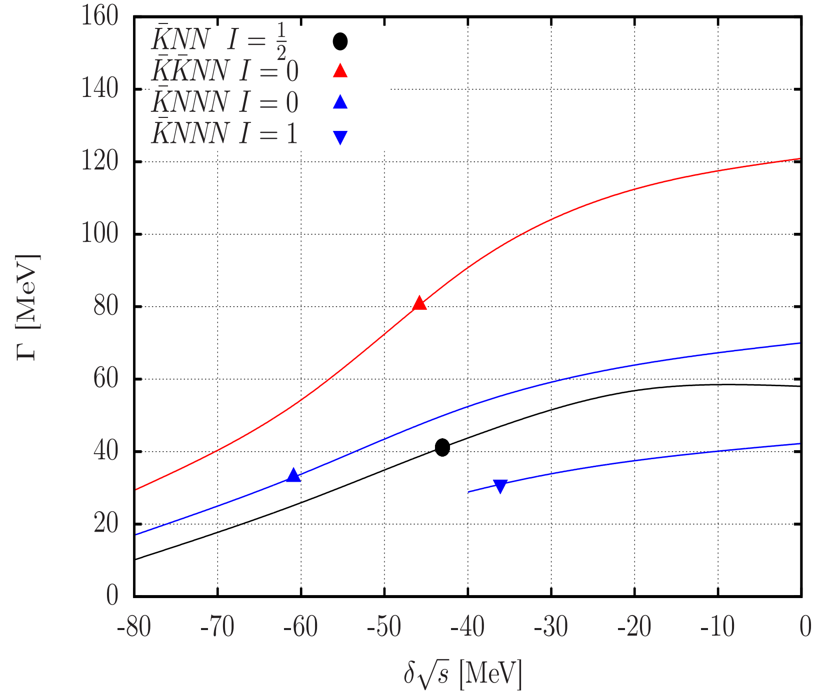
- $s = (\sqrt{s_{\rm th}} - B_K - B_N)^2 - (\vec{p}_K + \vec{p}_N)^2 \le s_{\rm th}$

- Expanding nonrelativistically near $\sqrt{s_{\rm th}} \equiv m_K + m_N$:
$\delta\sqrt{s} = -\frac{B}{A} - \frac{A-1}{A} B_K - \xi_N \frac{A-1}{A} \langle T_{N:N} \rangle - \xi_K \left(\frac{A-1}{A}\right)^2 \langle T_K \rangle$,
$\delta\sqrt{s} \equiv \sqrt{s} - \sqrt{s_{\rm th}}, \;\; B_K = -E_K, \;\; \xi_{N(K)} \equiv \frac{m_{N(K)}}{(m_N + m_K)}$.

- Self-consistency: output $\sqrt{s}$ from solving the Schroedinger equation identical with input $\sqrt{s}$.

3– & 4–body B & Γ calculated self-consistently





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

- Variational calculation in hyperspherical basis controlled by $K_{\rm max}$
- $\bar{K}N$ energy dependence [Hyodo–Weise, PRC 77 (2008) 035204] restrains B & Γ by treating $\delta\sqrt{s_{\bar{K}N}}$ self-consistently
- B(4-body) small w.r.t. non-chiral estimates of over 100 MeV

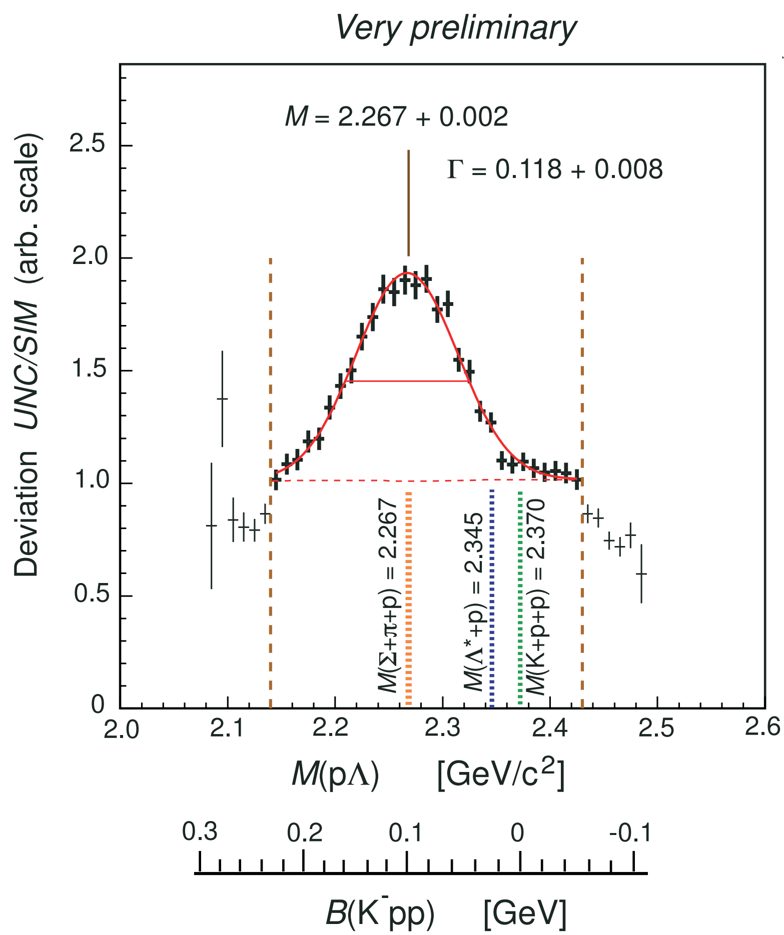
- $\bar{K}NN$: is there an excited $I = 1/2$ quasibound state ($\bar{K}d$, dominantly $I_{NN} = 0$) on top of "K^-pp" g.s. ?
- Barnea, Gal & Liverts do not find such a bound state below the $\Lambda^* N$ threshold at $B = 11.4$ MeV.
- Bayar & Oset [NPA **881** (2012) 127]: **YES**, bound by about 9 MeV, from a peak in $|T_{\bar{K}NN}|^2$ calculated in a fixed-scatterer approximation to Faddeev equations.
- Shevchenko [NPA **890-1** (2012) 50]: **UNLIKELY**, judging from the K^-d scattering length and effective range deduced from a $\bar{K}NN$ Faddeev calculation.
- Shevchenko & Revai [PRC, arXiv:1402.3935]: **NO**, searching for poles in a $\bar{K}NN$ Faddeev calculation.

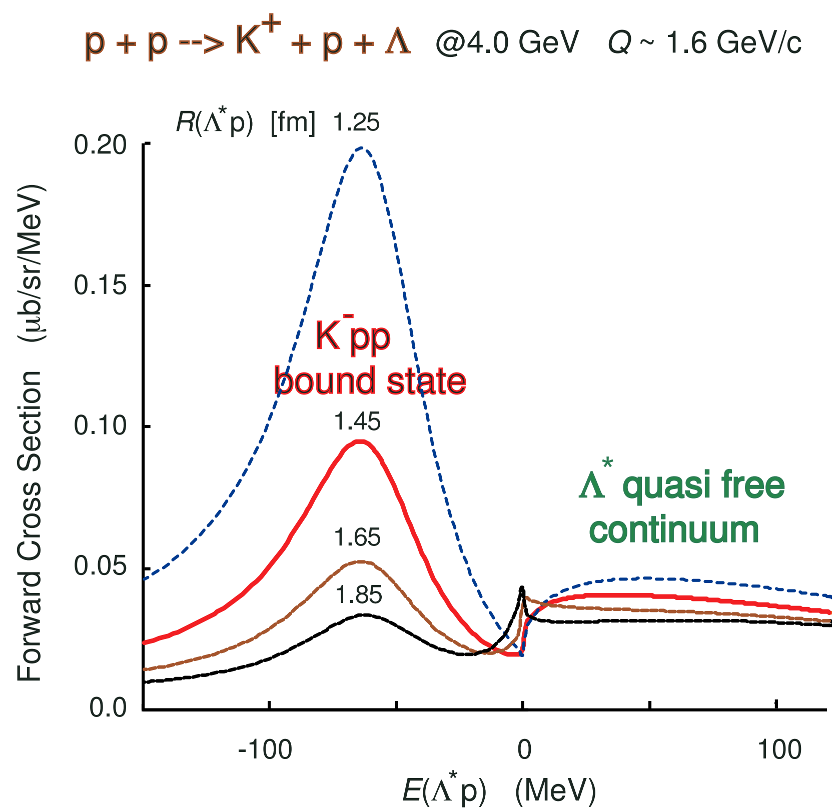
$K^{-}pp$ calculated binding energies & widths

(MeV)	chiral, energy dep. calculations				non-chiral, static calculations			
	var. [1]	var. [2]	Fad. [3]	Fad. [4]	var. [5]	Fad. [6]	Fad. [7]	var. [8]
B	16	17–23	9–16	32	48	50–70	60–95	40–80
Γ	41	40–70	34–46	49	61	90–110	45–80	40–85

Robust binding & large widths; chiral models give weak binding

1. N. Barnea, A. Gal, E.Z. Liverts, PLB **712** (2012)
2. A. Doté, 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, arXiv:1403.0757
5. T. Yamazaki, Y. Akaishi, PLB **535** (2002) 70
6. N.V. Shevchenko, A. Gal, J. Mareš, PRL **98** (2007) 082301
7. Y. Ikeda, T. Sato, PRC **76** (2007) 035203, PRC **79** (2009) 035201
8. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including p waves)





Yamazaki et al. PRL 104 (2010) 132502, DISTO data reanalysis at 2.85 GeV

Broad $K^- pp$ structure in $pp \to \Lambda p K^+$ at $\pi N \Sigma$ threshold

Forthcoming experiments: $pp \to (K^- pp) + K^+$ at GSI

$K^{-3}\mathrm{He} \to (K^- pp) + n$ (E15) & $\pi^+ d \to (K^- pp) + K^+$ (E27) at J-PARC

from $\Lambda(1405)N$ to $\Sigma(1385)N$

- $\Lambda(1405)N$ is in a way a doorway to the quasibound $I = 1/2$, $J^P = 0^-$ $\bar{K}NN$ dibaryon. Lower $\mathcal{S} = -1$ components are $\pi\Lambda N$ and $\pi\Sigma N$, the lowest of which is $\pi\Lambda N$, but it cannot support any strongly attractive meson-baryon s-wave interaction.

- The $\pi\Lambda N$ system can benefit from strong meson-baryon p-wave interactions fitted to the $\Delta(1232) \to \pi N$ and $\Sigma(1385) \to \pi\Lambda$ form factors. Maximize isospin and angular momentum couplings by full alignment: $I = 3/2$, $J^P = 2^+$. In particular, ΛN is in ${}^3S_1$. This is a Pion Assisted Dibaryon, see **Gal & Garcilazo, PRD 78 (2008) 014013.**

- Add the $\pi\Sigma N$ channel [PRC **81** (2010) 055205, and finalized in NPA **897** (2013) 167].
  A $\pi\Lambda N$ resonance about 10–20 MeV below the $\pi\Sigma N$ threshold is found by solving coupled-channel Faddeev equations. Results are sensitive to the pion-baryon p-wave form factors.

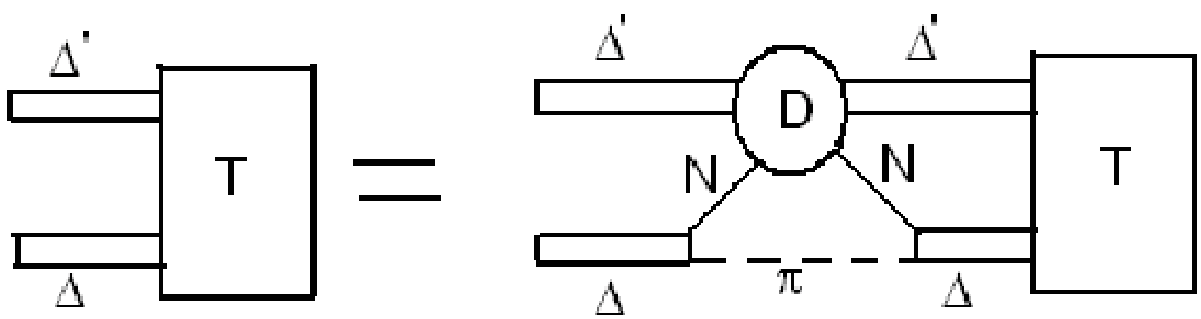
- This resonance is a pion assisted quasibound dibaryon, suggesting doorway states of the type $\Sigma(1385)N$ and $\Delta(1232)Y$, the lower of which is $\Sigma(1385)N$ with $I = 3/2$ and ${}^5S_2$, $J^P = 2^+$. These are different labels from the $I = 1/2$ and ${}^1S_0$, $J^P = 0^-$ for $\Lambda(1405)N$ viewed as a doorway to K^-pp.

- Adding a $\bar{K}NN$ channel does not help, because the leading $^3S_1$ NN configuration is Pauli forbidden.
- Search for this $\mathcal{Y}$ dibaryon at GSI & J-PARC in:
  $p\ +\ p \rightarrow \mathcal{Y}^{++}\ +\ K^0,\quad \mathcal{Y}^{++} \rightarrow \Sigma^+\ +\ p,$
  or $\ \pi^+\ +\ d\ \rightarrow\ \mathcal{Y}^{++}\ +\ K^0,\quad \mathcal{Y}^{++} \rightarrow \Sigma^+\ +\ p.$
- A (π^+, K^+) reaction as in E27 would lead to YN decay states similar to those anticipated in searches of K^-pp. Another possibility at J-PARC or GSI is:
  $\pi^-\ +\ d\ \rightarrow\ \mathcal{Y}^-\ +\ K^+,\quad \mathcal{Y}^- \rightarrow \Sigma^-\ +\ n.$
- **Nonstrange $\mathcal{D}_{IS}$ pion assisted dibaryons**
  πNN: $\mathcal{D}_{12}$**(2150) &** $\mathcal{D}_{21}$**(?);**
  $\pi N\Delta$: $\mathcal{D}_{03}$**(2370) &** $\mathcal{D}_{30}$**(?)**

Pion-assisted $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon

Gal-Garcilazo, PRL 111 (2013) 172301, NPA (2014)

- **Approximate $\pi\pi NN$ problem by $\pi N\Delta'$ problem.**
- **Separable pair interactions: πN Δ-isobar form factor by fitting $\delta(P_{33})$; $N\Delta'$ $\mathcal{D}_{12}(2150)$-isobar form factor by fitting $NN(^1D_2)$ scattering.**
- **3-body S-matrix pole equation reduces to effective $\Delta\Delta'$ diagram:**

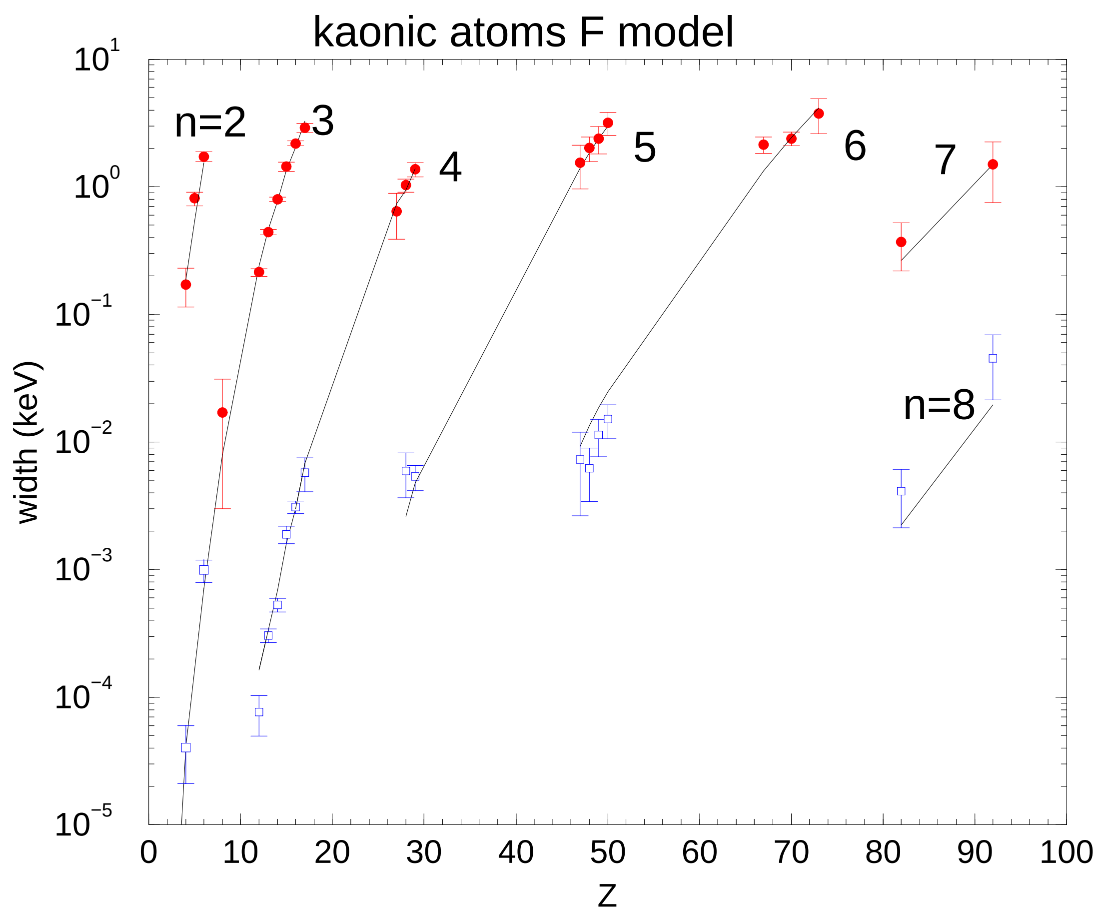


- P_{33} **form factors of size 0.9 & 1.3 fm:**
  $M = 2363 \pm 20$, $\Gamma = 65 \pm 17$ **MeV,**
  in good agreement with WASA@COSY
  (Clement's & Workman's talks here).

- **Although bound w.r.t.** $\Delta\Delta$, $\mathcal{D}_{03}(2370)$ **is resonating w.r.t. the** $\pi - \mathcal{D}_{12}(2150)$ **threshold.**
  The subsequent decay $\mathcal{D}_{12}(2150) \to \pi d$ **is seen in the** πd **Dalitz plot projection.**

- NN**-decoupled dibaryon resonances** $\mathcal{D}_{21}$ **&** $\mathcal{D}_{30}$ **predicted 10–30 MeV higher, respectively;**
  see also Bashkanov-Brodsky-Clement
  "Novel 6q Hidden-Color Dibaryons in QCD"
  PLB 727 (2013) 438 (Bashkanov's poster here).

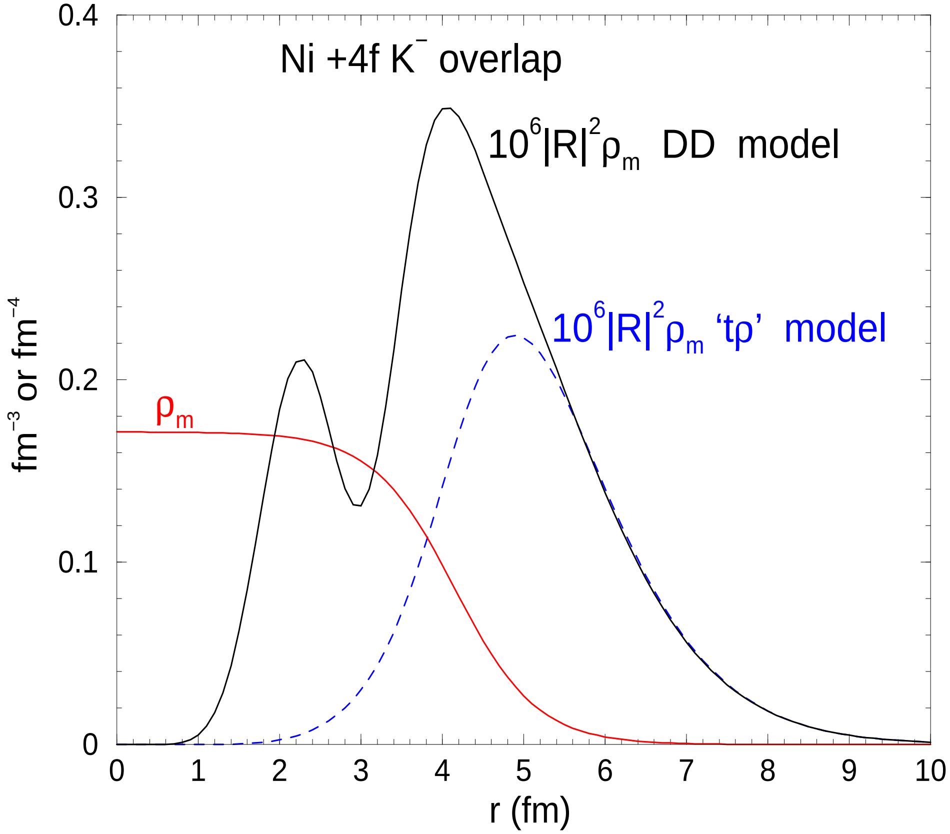
What do K^- atoms tell us?

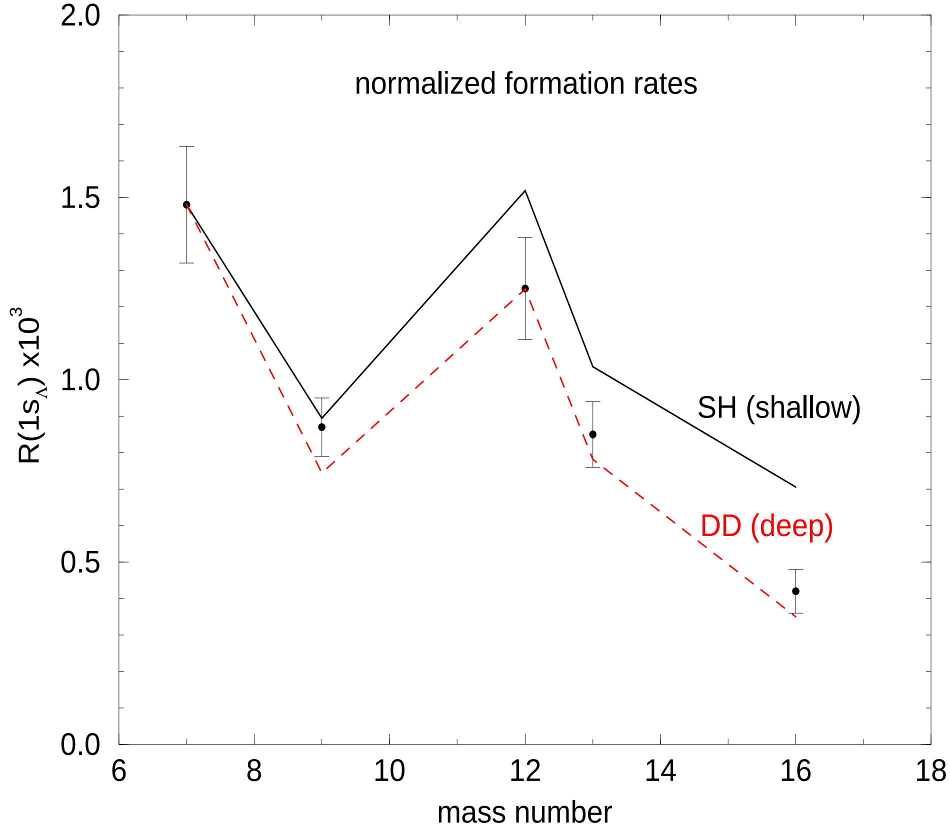


$K^-_{\rm atom}$ widths across the periodic table in model F (deep pot.)

Lowest χ^2 phenom. model, $\chi^2 = 84$ per 65 data points,

J. Mareš, E. Friedman, A. Gal, NPA 770 (2006) 84.





Left: K^--Ni 4f atomic wavefunction overlap with nuclear density for deep potential, revealing a nuclear $\ell = 3$ quasibound state.

Right: FINUDA $1s_\Lambda$ formation rates in $K^-_{\rm stop}$ capture in nuclei [Cieplý-Friedman-Gal-Krejčiřík, PLB 698 (2011) 226].

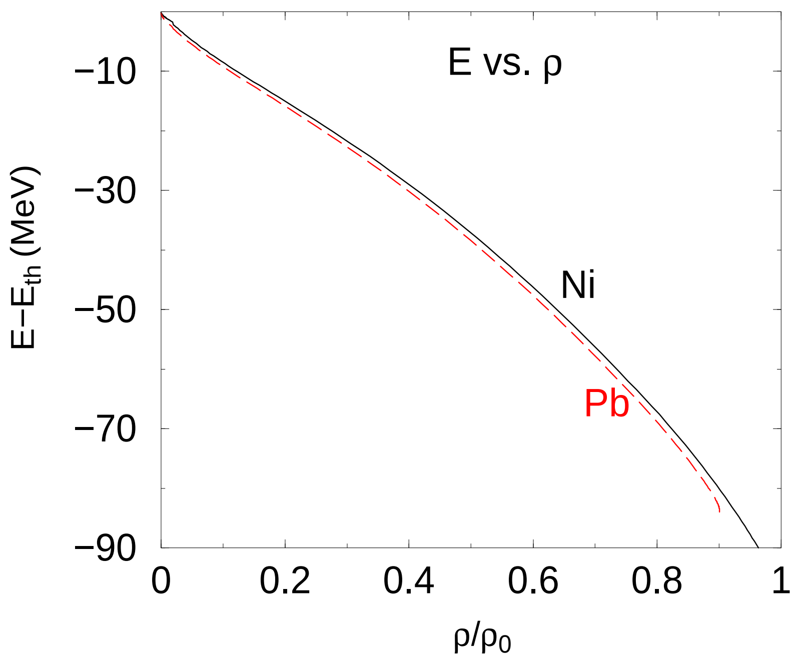
Deep K^- nuclear potential is favored.

Self-consistency requirement imposed in recent K^- atom calculations

[Cieplý-Friedman-Gal-Gazda-Mareš, PLB 702 (2011) 402]:

$$\sqrt{s_{K^-N}} \to E_{\rm th} - B_N - B_K - \xi_N \frac{p_N^2}{2m_N} - \xi_K \frac{p_K^2}{2m_K}$$

$$\xi_{N(K)} = \frac{m_{N(K)}}{(m_N + m_K)} \qquad \frac{p_K^2}{2m_K} \sim -V_{K^-} \approx 100 \text{ MeV}$$

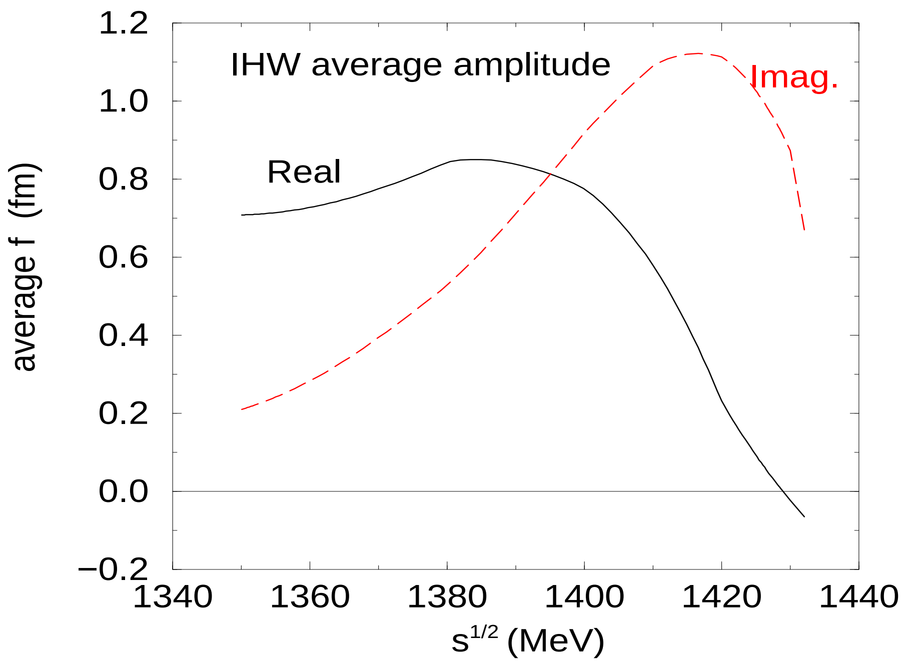


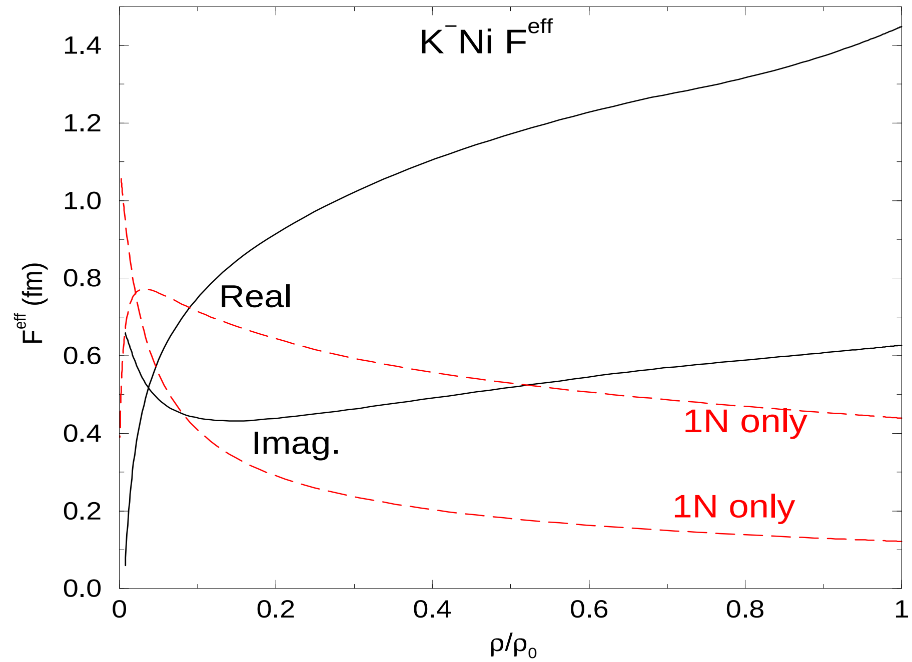
K^- is not at rest!

Friedman-Gal, NPA 899 (2013) 60

K^-N subthreshold energy *vs* nuclear density in K^- atoms.

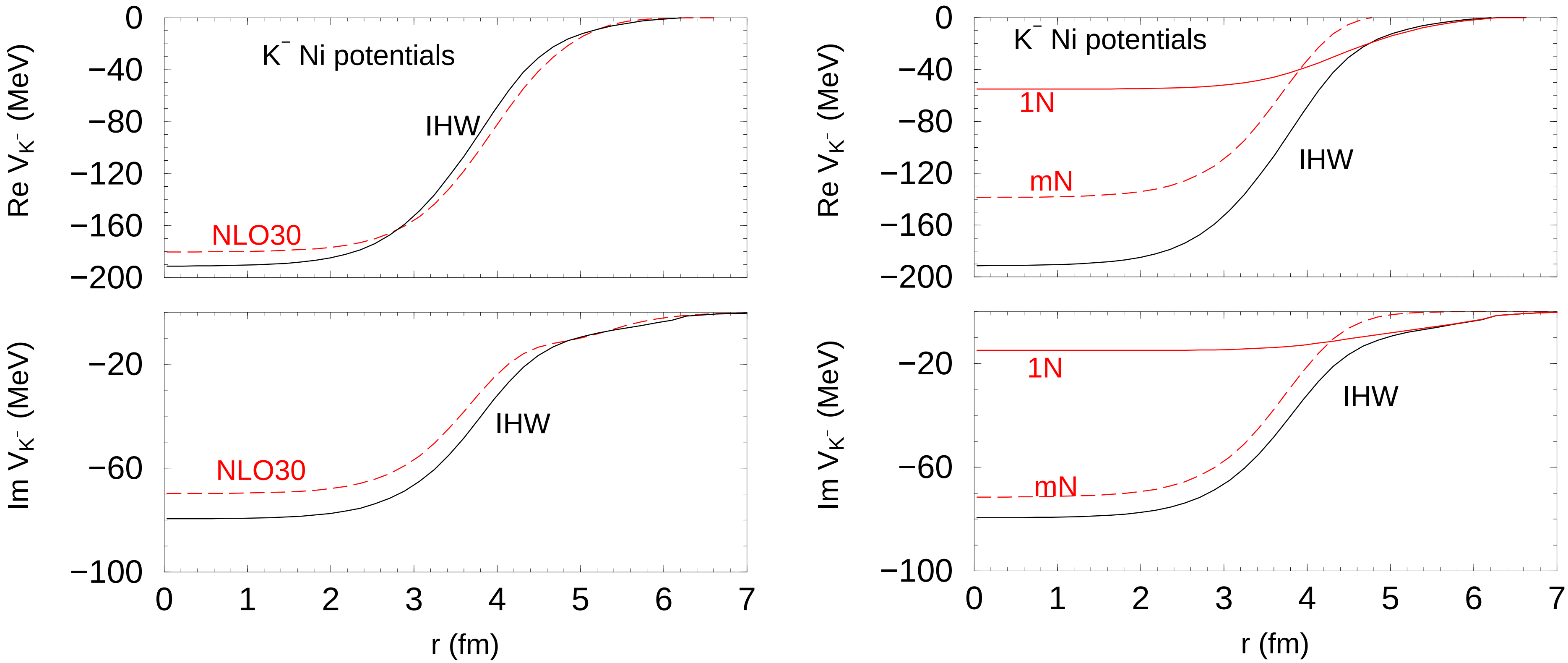
A dominant in-medium effect





Left: IHW free-space input f_{K-N} Right: atomic-fit output $\mathcal{F}^{\rm eff}_{\rm tot}$

- Subthreshold energy shift is applied self consistently to in-medium 1N amplitude plus (2+...)N phenomenological amplitude.
- Multiple-scattering inclusion of in-medium correlations.
- K^--atom best-fit: $\chi^2/{\rm N}_{\rm data} = 118/65$ [Friedman-Gal, NPA 899 (2013) 60].



Kaonic-atom best-fit V_{K^-} for Ni & its non-additive breakdown into in-medium 1N and phenomenological m(any)N contributions.

Upper level sensitive to 1N & lower level to mN terms.

NLO30: A. Cieply, J. Smejkal, NPA **881** (2012) 115 (in-medium).

IHW: Y. Ikeda, T. Hyodo, W. Weise, NPA **881** (2012) 98.

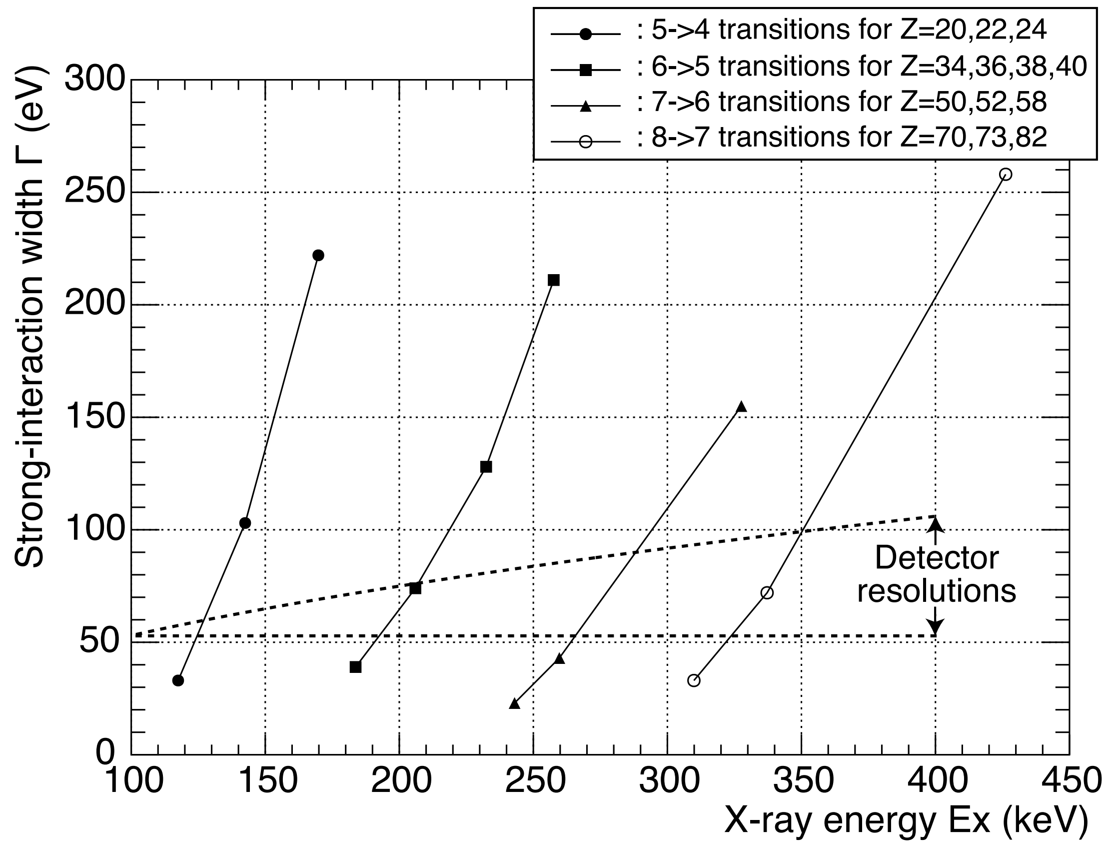
Full and reduced data set fits [$b(\rho_0)$ in fm]

	shallow potential			deep potential		
N	χ^2	Re $b(\rho_0)$	Im $b(\rho_0)$	χ^2	Re $b(\rho_0)$	Im $b(\rho_0)$
65	130	0.62±0.05	0.93±0.04	84	1.44±0.03	0.59±0.03
15	44	0.78±0.13	0.92±0.11	26	1.47±0.05	0.55±0.06

Reduced sets, C(2p) Si(3d) Ni(4f) Sn(5g) Pb(7i), with upper-level yield & lower-level width & shift, preserve features obtained from fits to full data.

Need more accurate measurements in a few atoms.

[E. Friedman, in MESON 2010, IJMPA 26 (2011) 468]

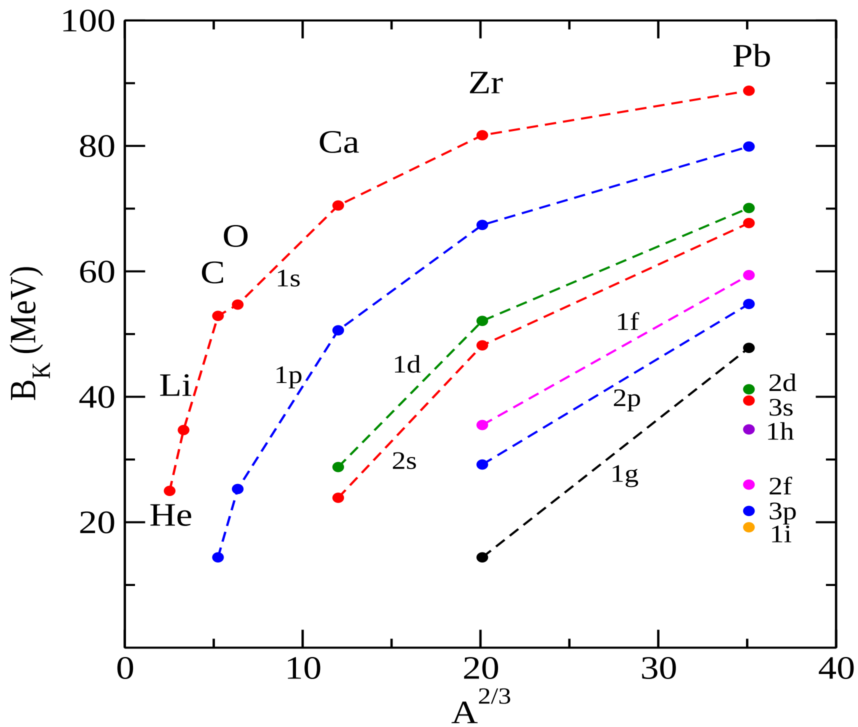


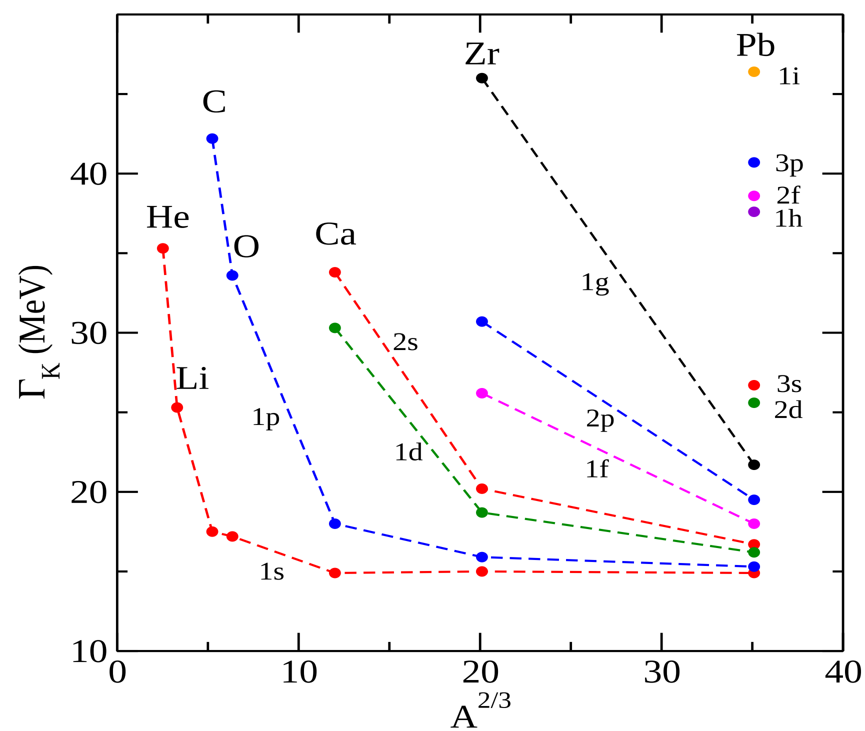
Feasibility of upper-level width measurements, on top of lower-level, vs. detector resolution for superconducting microcalorimeter detectors, normalized at 53 eV width for 100 keV x-ray.

E. Friedman, S. Okada, NPA 915 (2013) 170.

$\overline{K}$ condensation on earth?

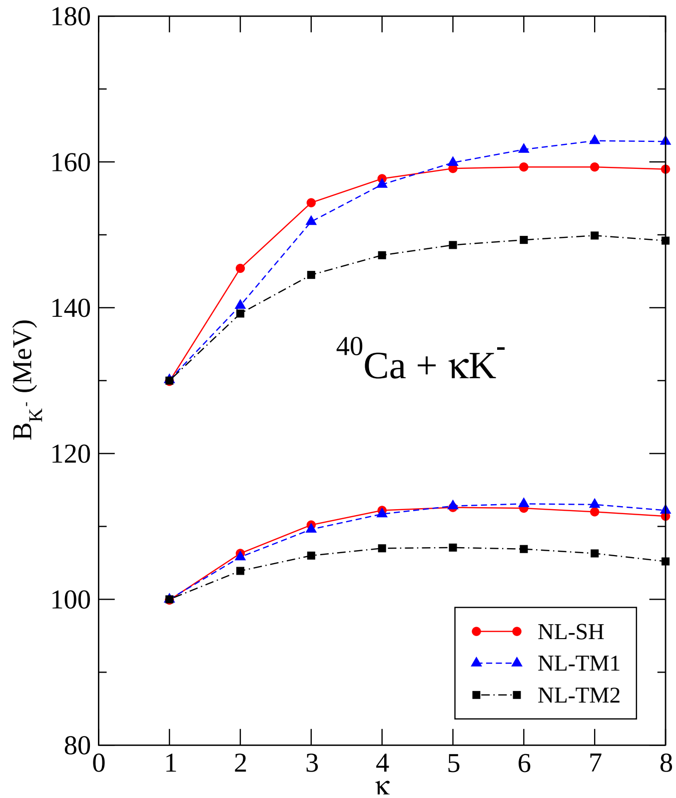
RMF quasibound spectra calculated self-consistently (NLO30 '+ SE')





D. Gazda, J. Mareš, NPA 881 (2012) 159

- NLO30 is a chirally motivated coupled channel separable model with in-medium versions [A. Cieplý, J. Smejkal, NPA 881 (2012) 115]
- Γ_K due only to $K^- N \to \pi Y$ (no $K^- NN \to YN$) decay modes
- Self consistency: deep K^- levels are narrower than shallow ones

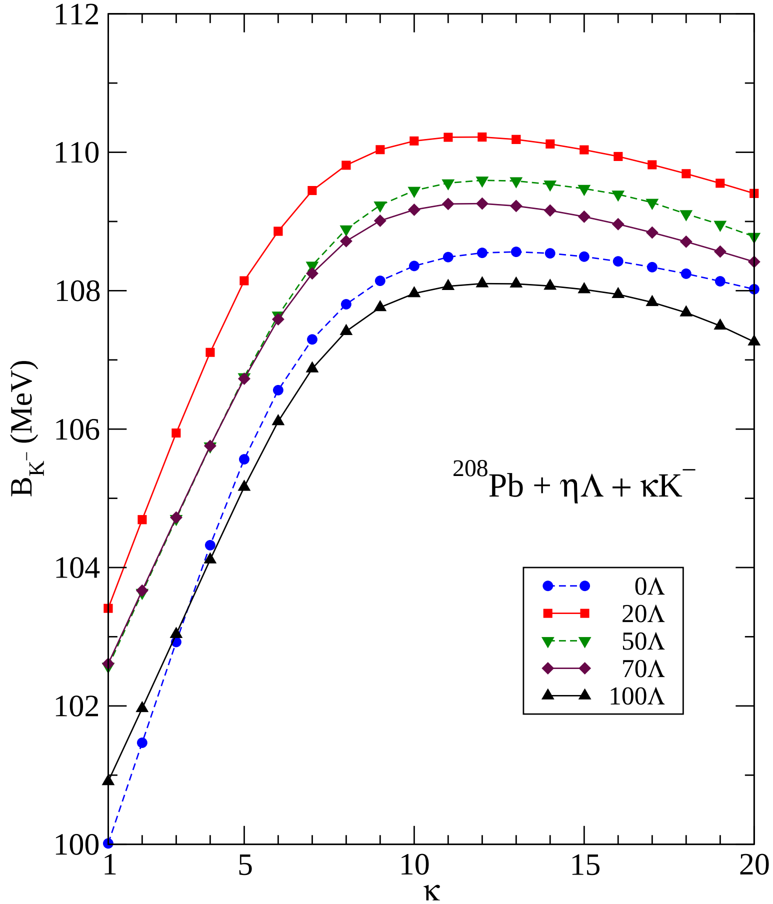


D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for multi-K^- ^{40}Ca nuclei.

Vector-meson repulsion among $\bar{K}$ mesons.

$B_{\bar{K}}(\kappa \to \infty) << (m_K + M_N - M_\Lambda) \approx 320$ MeV.



D. Gazda, E. Friedman, A. Gal, J. Mareš, Phys. Rev C 80 (2009) 035205

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for ${}^{208}\mathrm{Pb} + \eta\Lambda + \kappa K^-$.

$\bar{K}$ mesons do not replace hyperons in stable self-bound strange matter.

Summary

- Large widths, $\Gamma_{\overline{K}} > 50$ MeV, expected for single-$\overline{K}$ quasibound nuclear states. Focus on light systems. K^-pp searches are underway in GSI and J-PARC.
- **Look for $(I = \frac{3}{2}, J^P = 2^+)$ $YN\pi$ dibaryon.**
- Major issues: (i) how deep is $\overline{K}$ nuclear spectrum? (ii) how big is $\Gamma(\overline{K}NN \to YN)$ w.r.t. $\Gamma(\overline{K}N \to \pi Y)$? **Do K^-d atom (SIDDHARTA-II at DAΦNE) & selective K^- atom measurements (JPARC?)**
- $B_{\overline{K}}$ saturates in multi-$\overline{K}$ nuclei and hypernuclei. $\overline{K}$ condensation is unlikely in self-bound matter.
- **Thanks to my collaborators N. Barnea, A. Cieplý, E. Friedman, D. Gazda, J. Mareš**