Multi-$\bar{K}$ (hyper)nuclei

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Hadronic Atoms and Kaonic Nuclei, Trento, 12–16 October, 2009

D.Gazda, E.Friedman, A.Gal, J.Mareš:
arXiv:0906.5344v1 [nucl-th], Phys. Rev. C in press.

Motivation

$\bar{K}N$ interaction

strongly attractive, highly non-perturbative, Λ(1405)

⇓

$\bar{K}$-nucleus interaction

strongly attractive and absorptive ← kaonic atoms

? optical potential depth:

phenomenology V_{opt}=**(150-200)** MeV × chiral models V_{opt}=**(50-60)** MeV

? existence of sufficiently narrow K^- bound states

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kaon propagation in nuclear matter

heavy ion collisions

neutron star structure, ? kaon **condensation**

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Motivation

Kaon condensation in dense matter – neutron stars and heavy ion collisions.

- neutron stars
  weak interactions operative
  $\mu_K = \mu_e \approx 200$ MeV $\Rightarrow e^- \rightarrow K^- + \nu_e$
- laboratory conditions $\sim$ heavy ion collisions
  strong interactions operative
  $B_{\bar{K}} \gtrsim 240$ MeV $\approx m_K + m_N - m_\Sigma \Rightarrow$ precursor phenomena to kaon condensation
  $B_{\bar{K}} \gtrsim 320$ MeV $\approx m_K + m_N - m_\Lambda \Rightarrow \bar{K}$'s relevant degrees of freedom for self-bound systems

. . . does $B_{\bar{K}}$ in multi-$\bar{K}$ system increase enough?

Model

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

$$\mathscr{L} = \mathscr{L}_N + \mathscr{L}_Y + \mathscr{L}_K \ ,$$

where

$$\mathscr{L}_N = \text{standard relativistic mean field lagrangian density}$$

$$\mathscr{L}_Y = \bar{\psi}_Y [\mathrm{i} \not{\mathcal{D}} - (m_Y - g_{\sigma Y}\sigma - g_{\sigma^* Y}\sigma^*)]\psi_Y \ ,$$

$$\mathscr{L}_K = (\mathcal{D}_\mu K)^\dagger \, (\mathcal{D}^\mu K) - m_K^2 K^\dagger K - g_{\sigma K} m_K \, \sigma \, K^\dagger K - g_{\sigma^* K} m_K \, \sigma^* \, K^\dagger K \ ,$$

with $\mathcal{D}_\mu$ given by:

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

baryons (nucleons, hyperons):

$$[-\mathrm{i}\alpha_j \nabla_j + (m_B - g_{\sigma B}\,\sigma - g_{\sigma^* B}\,\sigma^*)\beta + g_{\omega B}\,\omega + g_{\rho B}\,I_3\,\rho + g_{\phi B}\phi + e(I_3 + \tfrac{1}{2}Y)A]\psi_B = \varepsilon\psi_B$$

mesons:

$$\begin{aligned}
(-\nabla^2 + m_\sigma^2)\sigma &= g_{\sigma N}\rho_s + g_2\sigma^2 - g_3\sigma^3 + g_{\sigma K}\,m_K K^* K + g_{\sigma Y}\rho_{sY} \\
(-\nabla^2 + m_\sigma^2)\sigma^* &= g_{\sigma^* K}\,m_K K^* K + g_{\sigma^* Y}\rho_{sY} \\
(-\nabla^2 + m_\omega^2)\omega &= g_{\omega N}\rho_N - g_{\omega K}\rho_{K^-} + g_{\omega Y}\rho_Y \\
(-\nabla^2 + m_\rho^2)\rho &= g_{\rho N}\rho_3 - g_{\rho K}\rho_{K^-} + g_{\rho N}\rho_{3Y} \\
(-\nabla^2 + m_\phi^2)\phi &= -g_{\phi K}\rho_{K^-} + g_{\phi Y}\rho_Y \\
-\nabla^2 A &= e\,\rho_p - e\,\rho_{K^-} + e\,\rho_{cY}
\end{aligned}$$

where $\rho_{K^-} = 2(E_{K^-} + g_{\omega K}\,\omega + g_{\rho K}\,\rho + g_{\phi K}\,\phi + e\,A)K^* K$

+ **antikaons**:

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

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

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

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

W_0 constrained by kaonic atom data

Absorption through:

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

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

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

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

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Results

Calculations of ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr, ^{208}Pb

$\mathscr{L}_N \leftarrow$ NL-SH, NL-TM1(2), L-HS

$\mathscr{L}_Y \leftarrow g_{vY} \leftarrow$ SU(6)
$g_{\sigma\Lambda}, g_{\sigma^*\Lambda} \leftarrow$ fitted to single and double Λ hypernuclei
$g_{\sigma\Xi} \leftarrow$ fitted to $V_\Xi \approx -18$ MeV

$\mathscr{L}_K \leftarrow g_{vK} \leftarrow$ SU(3):
$2g_{\omega K} = \sqrt{2}g_{\phi K} = 2g_{\rho K} = g_{\rho\pi} = 6.04$
$g_{\sigma^* K} = 2.65$ ($f_0(980) \rightarrow K^+K^-$)
$g_{\sigma K}$ coupling scaled $\leftarrow$ cover wide range of $B_{\bar{K}}$

Multi-$\bar{K}$ nuclei

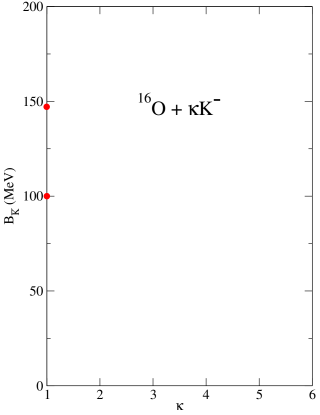
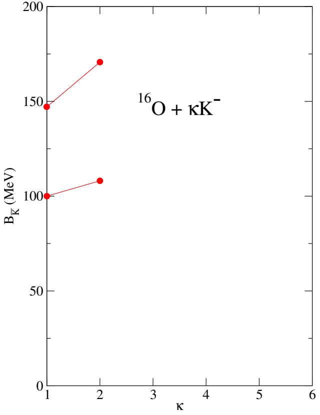


Fig. 1 K^- binding energy B_{K^-} in ^{16}O as a function of the number κ of antikaons.

Multi-$\bar{K}$ nuclei



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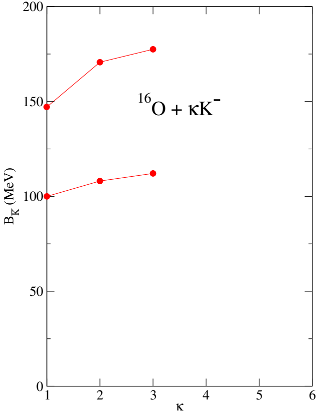

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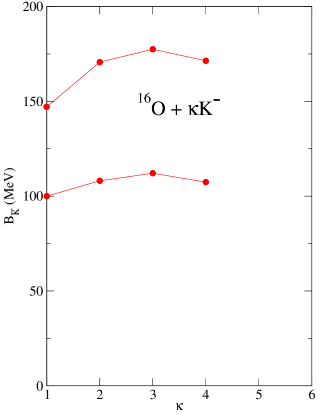

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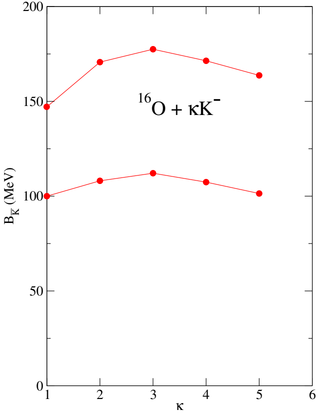

Fig. 1 K^- binding energy B_{K-} in ^{16}O as a function of the number κ of antikaons.

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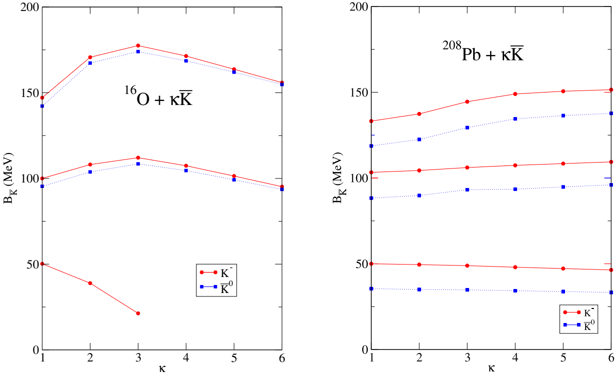

Fig. 2 The $\bar{K}$ binding energies as functions of the number κ of antikaons.

- saturation pattern observed across the periodic table

Multi-$\bar{K}$ nuclei

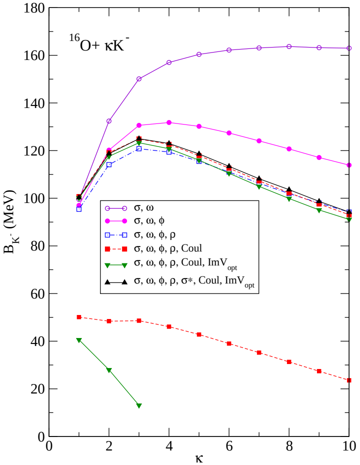

Fig. 3 The K^- binding energies as a function of the number κ of K^- mesons for different mean field compositions.

- saturation observed for any field composition containing ω-meson
- no saturation for purely scalar interaction
- substantial effect of $\mathrm{Im}\Pi_{K-}$ for $B_{K-} \lesssim 100$ MeV

Multi-$\bar{K}$ nuclei

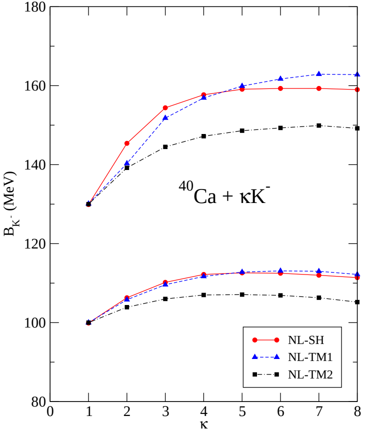

Fig. 4 The K^- binding energies as a function of the number κ of K^- mesons for different RMF models.

- saturation pattern qualitatively independent of RMF model used

Multi-$\bar{K}$ nuclei

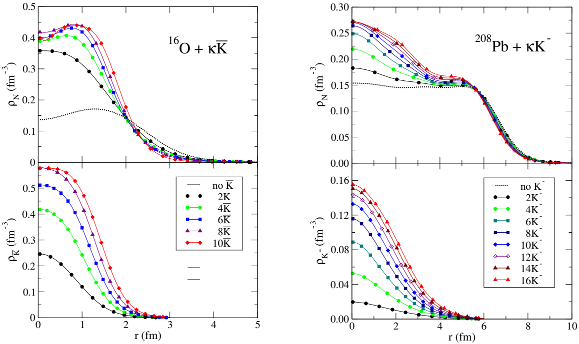

Fig. 5 Nuclear (ρ_N) and $\bar{K}$ ($\rho_{\bar{K}}$) density distributions for various numbers κ of antiakons.

- saturation of central nuclear and $\bar{K}$ densities

Multi-$\bar{K}$ nuclei

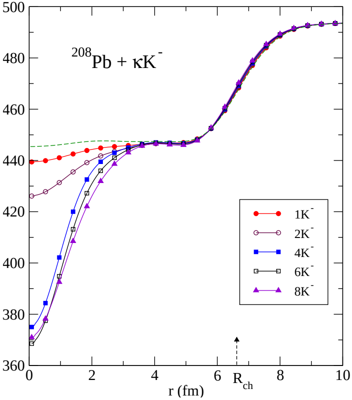

Fig. 6 $\bar{K}$ effective mass in ^{208}Pb+κK^-.

- $\bar{K}$ effective mass $m_K^* = \sqrt{m_K - g_{\sigma K} m_K \sigma}$ affected only in the region $r \approx$2-3 fm
- concept of nuclear matter far from being realized even in ^{208}Pb

Multi-$\bar{K}$ "exotic" configurations

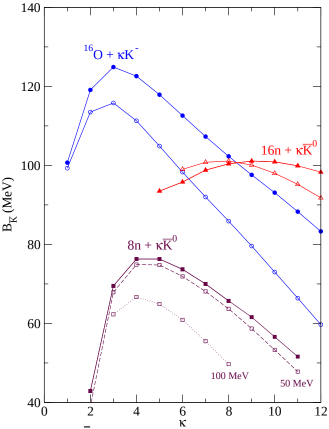

Fig. 7 $\bar{K}$ separation energy as a function of the number κ of antikaons.

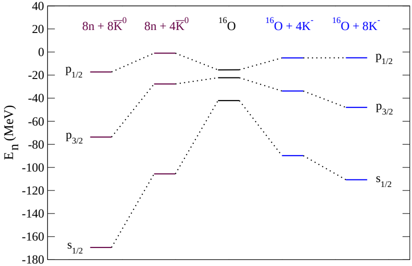

Fig. 8 Neutron single-particle spetra.

- systems of a finite number of neutrons bound by adding few $\bar{K}^0$'s

Multi-$\bar{K}$ "exotic" configurations

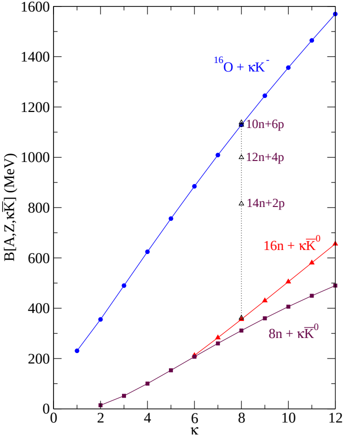

Fig. 9 Total binding energy of multistrange systems.

- configurations unstable against charge-exchange reactions, e.g. $16n + 8\bar{K}^0 \rightarrow {}^{16}\text{O} + 8K^-$

Multi-$\bar{K}$ hypernuclei

We condidered self-bound systems consisting of SU(3) octet baryons $\{N, \Lambda, \Sigma, \Xi\}$.
Only $\Xi^- p \rightarrow \Lambda\Lambda$ and $\Xi^0 n \rightarrow \Lambda\Lambda$ ($Q \approx 26$ MeV) can be overcome by binding effects $\rightarrow \{N, \Lambda, \Xi\}$ configurations.

- filling up Λ single-particle states up to the Λ Fermi level
- adding Ξ hyperons (Ξ^0, Ξ^-) as long as both reactions:
  $[AN, \eta\Lambda, \mu\Xi] \rightarrow [(A-1)N, \eta\Lambda, (\mu-1)\Xi] + 2\Lambda$
  $[AN, \eta\Lambda, \mu\Xi] \rightarrow [(A+1)N, (\eta-2)\Lambda, (\mu+1)\Xi]$
  are kinematically blocked

$\rightarrow$ particle-stable configurations with highest $|S|/B$ ratio for given core nucleus

Multi-$\bar{K}$ hypernuclei

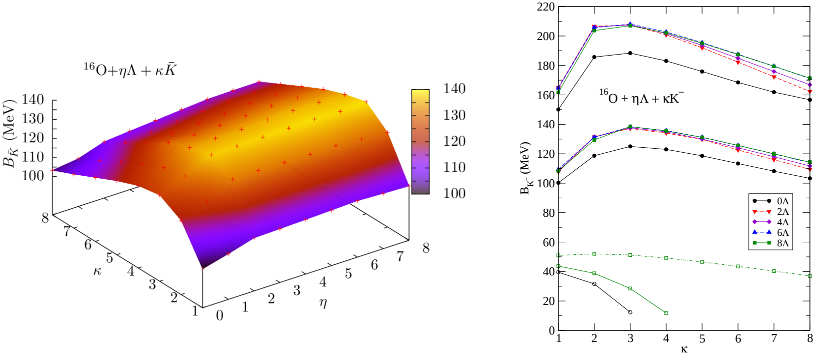

Fig. 10 The $\bar{K}$ binding energy $B_{\bar{K}}$ in ^{16}O as a function of the number κ of antikaons and η of Λ hyperons.

Multi-$\bar{K}$ hypernuclei

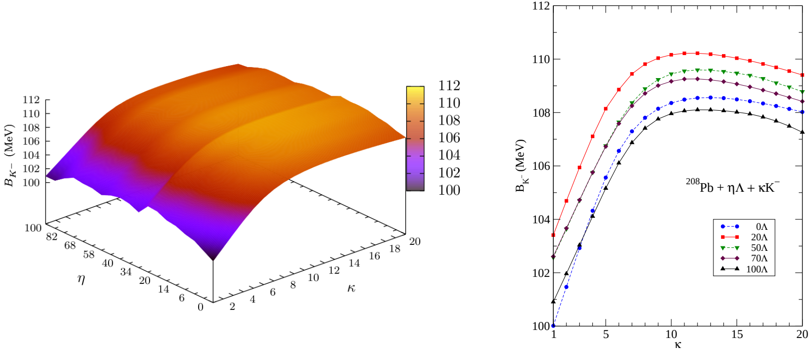

Fig. 11 The $\bar{K}$ binding energy $B_{\bar{K}}$ in ^{208}Pb as a function of the number κ of antikaons and η of Λ hyperons.

Multi-$\bar{K}$ hypernuclei

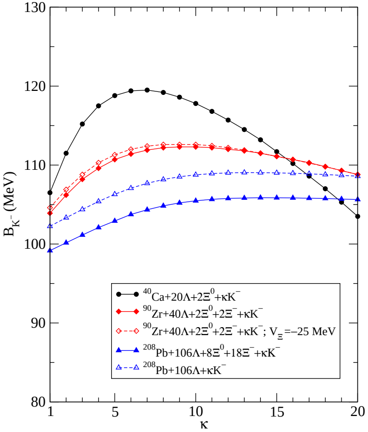

Fig. 12 K^- binding energies in hypernuclear configurations.

Multi-$\bar{K}$ hypernuclei

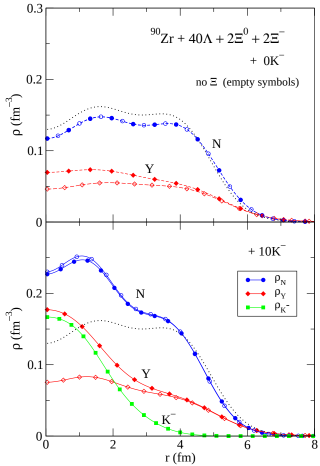

Fig. 13 Density distributions in multi-K^- hypernuclear configurations.

K^+ mesons in (hyper)nuclear medium

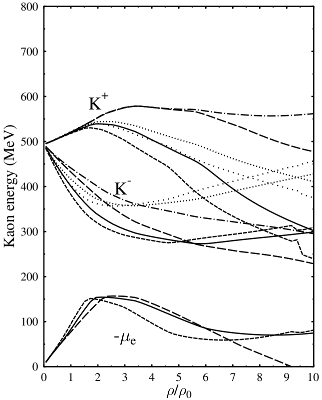

Fig. 14 The effective energy of kaons as well as electrochemical potential vs. the baryon densityfor neutron star matter.

(J. Schaffner, I.N. Mishustin Phys. Rev. C 53 (1996) 1416).

K^+ mesons in (hyper)nuclear medium

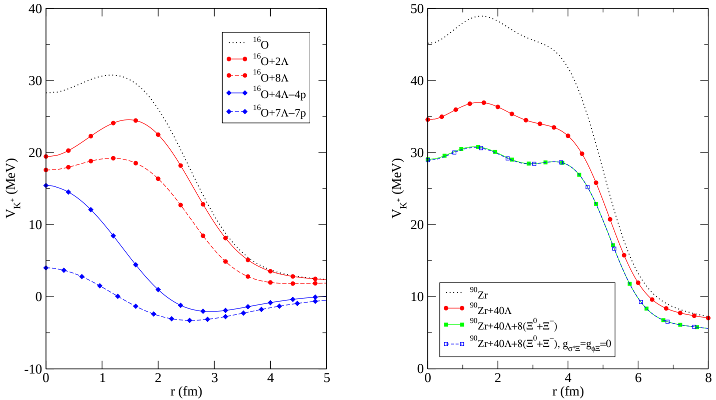

Fig. 14 The K^+ static potential in hypernuclear systems connected with ^{16}O and ^{90}Zr.

- presence of hyperons decreases K^+ repulsion

K^+ mesons in (hyper)nuclear medium

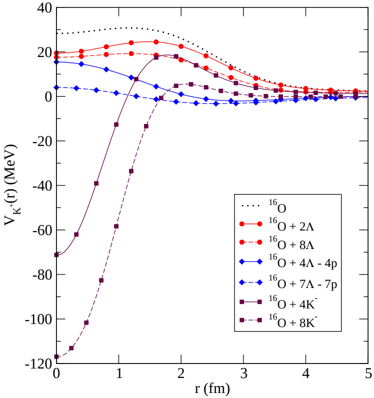

Fig. 15 The K^+ static potential in hypernuclear systems connected with ^{16}O.

- nuclei sustained by K^- mesons - immensely deep but short range K^+ potential $\rightarrow$ only weakly bound K^+ states found for large number of K^- mesons

Summary

- calculations of nuclear systems containing several antikaons:
  - $\bar{K}$ binding energies + nuclear densities saturate with number of $\bar{K}$ mesons
  - saturation occurs also in the presence of hyperons
  - $\rightarrow$ no kaon condensation precursor phenomena observed
- finite number of neutrons (protons) can be made self-bound by adding few $\bar{K}^0$ (K^-); the resulting configurations are more tightly bound than ordinary nuclear configurations but unstable against charge exchange reactions
- hyperons reduce K^+-nucleus repulsion, K^+ mesons remain unbound even for high $|S|/B$ ratio

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