Strange hadronic matter and kaon condensation

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D.Gazda, E.Friedman, A.Gal, J.Mareš:
Phys. Rev. C 80, 035205 (2009), Phys. Rev. C 77, 045206 (2008), Phys. Rev. C 76, 055204 (2007).

Motivation

$\bar{K}N$ interaction

strongly attractive, highly non-perturbative - $\Lambda(1405)$

$\Downarrow$

$\bar{K}$-nucleus interaction

strongly attractive and absorptive $\leftarrow$ 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

$\Downarrow$

kaon propagation in nuclear matter

heavy ion collisions

neutron star structure, **?** kaon **condensation**

Model

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

$$\begin{aligned}\mathcal{L} = & \bar{B}\,[\mathrm{i}\gamma^{\mu} D_{\mu} - (M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*)]\, B \\ & + (D_{\mu} K)^{\dagger}\,(D^{\mu} K) - (m_K^2 - g_{\sigma K}\, m_K \sigma - g_{\sigma^* K}\, m_K \sigma^*) K^{\dagger} K \\ & + (\sigma, \sigma^*, \omega_{\mu}, \vec{\rho}_{\mu}, \phi_{\mu}, A_{\mu} \text{ free-field terms}) - U(\sigma) - V(\omega),\end{aligned}$$

where

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

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:

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

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

$+$ **antikaons**:

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

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

K^- **absorption** in the nuclear medium introduced through the optical model phenomenology:

$$E_{K^-} \rightarrow E_{K^-} - \mathrm{i}\,\Gamma/2$$

$$\mathrm{Im}\,\Pi_{K^-} = 2E_{K^-} V_{\mathrm{opt}}$$

$$V_{\mathrm{opt}} \propto t \cdot \rho$$

density $\rho \leftarrow$ RMF

$\bar{K}N$ aplitude $t \leftarrow$

- **phenomenological** (constarined by K^- atom data)
  (Mareš, Friedman, Gal, NPA 770, 84, 2006)
- **chiral model**
  (Cieplý, Smejkal, EPJA 43, 191, 2010)

Results

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

$\mathcal{L}_N \leftarrow$ NL-SH, NL-TM1(2), L-HS, DD-TW, DD-PKDD, DD-ME1

$\mathcal{L}_Y \leftarrow g_{vY} \leftarrow$ 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

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

Single-K^- nuclei

$$\mathrm{Im}\Pi_{K^-} = \underbrace{(0.7\, f_{1\Sigma} + 0.1\, f_{1\Lambda}) W_0\, \rho_N(r)}_{\bar{K}N \to \pi\Sigma\,(70\%),\ \pi\Lambda\,(10\%)} + \underbrace{0.2\, f_{2\Sigma}\, W_0\, \rho_N^2(r)/\tilde{\rho}_0}_{\bar{K}NN \to \Sigma N\,(20\%)}$$

f_{iY} ... suppression factors (phase space considerations), W_0 ... fitted to kaonic atom data

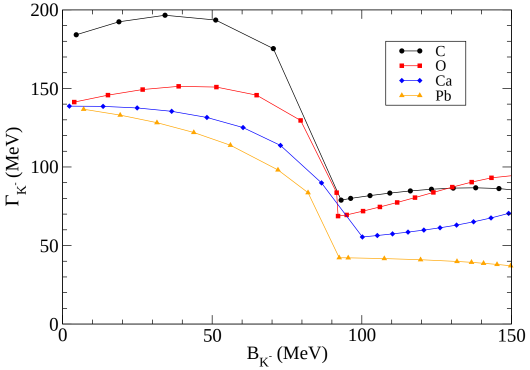

Fig. 1 The K^- decay width Γ_{K^-} in ^{16}O as a function of the K^- binding energy B_{K^-}.

Single-K^- nuclei

$$\text{Im}\Pi_{K^-} = -2\ \text{Im}\ E_K \frac{4\pi}{2\mu_{MB}}(t_{K^-p}\,\rho_p + t_{K^-n}\,\rho_n)$$

t_{K^-p}, t_{K^-n} from chiral model (only $\bar{K}N \to \pi\Sigma, \pi\Lambda$ considered!)

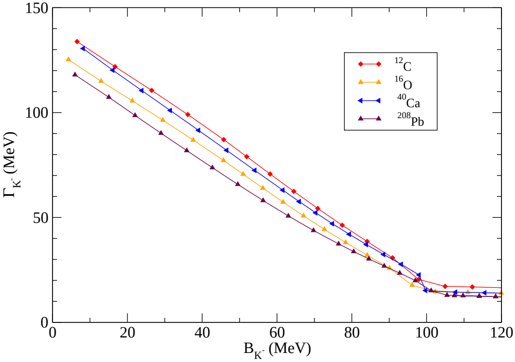

Fig. 2 The K^- decay width Γ_{K^-} in ^{16}O and ^{208}Pb as a function of the K^- binding energy B_{K^-}.

Single-K^- nuclei

$$[E_K^2 + \nabla^2 - m_K^2 - 2E_K V_{\rm opt}]K^- = 0$$

$$E_K \rightarrow E_K + V_C - {\rm i}\Gamma/2$$

$$V_{\rm opt} = -\frac{4\pi}{2\mu_{MB}}(t_{K^-p}\,\rho_p + t_{K^-n}\,\rho_n)$$

$$t_{K^-N} \leftarrow \text{chiral model}, \quad \rho_N \leftarrow \text{RMF}$$

A	B_{K^-} (MeV)	Γ_{K^-} (MeV)
^{12}C	81.7	28.5
^{16}O	76.3	29.6
^{40}Ca	96.5	16.6
^{90}Zr	104.3	10.2
^{208}Pb	109.0	9.9

Multi-$\bar{K}$ nuclei

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
  $B_{\bar{K}} \gtrsim 320$ MeV $\approx m_K + m_N - m_\Lambda \Rightarrow \bar{K}$'s relevant degrees of freedom for self-bound systems
  $B_{\bar{K}} \gtrsim 240$ MeV $\approx m_K + m_N - m_\Sigma \Rightarrow$ precursor phenomena to kaon condensation

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

Multi-$\bar{K}$ nuclei

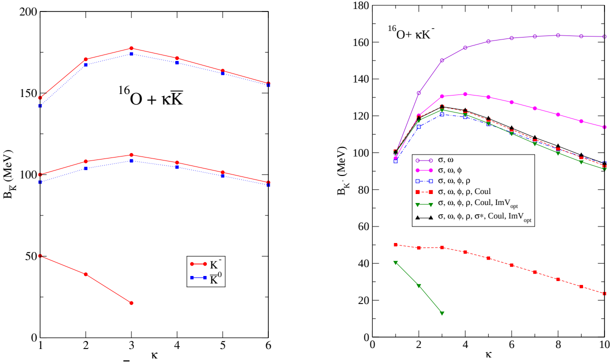

Fig. 3 The $\bar{K}$ binding energies as a functions of the number κ of antikaons.

- saturation of central nuclear densities
- saturation pattern observed across the periodic table
- saturation observed for any field composition containing ω-meson
- saturation pattern qualitatively independent of RMF model used

Multi-$\bar{K}$ nuclei

Dirac-Brueckner calculations of nuclear matter suggest $\mathbf{g_\phi = g_\phi(\rho)}$

$$[-i\alpha_j\nabla_j + \beta(M - S) + V - \frac{\partial S}{\partial \rho}\bar{\psi}\psi + \frac{\partial V}{\partial \rho}\psi^\dagger\psi]\psi = \varepsilon\psi$$

$$S = g_\sigma(\rho)\,\sigma$$

$$V = g_\omega(\rho)\,\omega + g_\rho(\rho)\,I_3\,\rho + e(I_3 + \tfrac{1}{2}Y)A$$

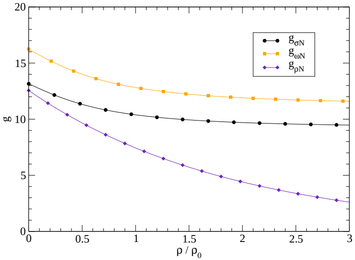

Fig. 4 Density dependence of the meson-nucleon coupling constants.

Multi-$\bar{K}$ nuclei

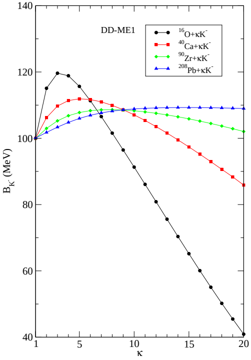

Fig. 5 The K^- binding energies as a function of the number κ of K^- mesons for density dependent RMF model.

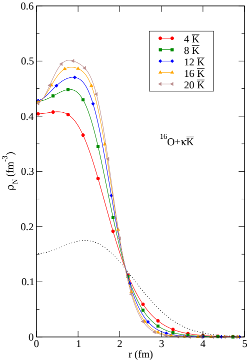

Fig. 6 Nuclear (ρ_N) and $\bar{K}$ ($\rho_{\bar{K}}$) density distributions for various numbers κ of antiakons.

Multi-$\bar{K}$ hypernuclei

We considered 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.

$$\Downarrow$$

$\{N, \Lambda, \Xi\}$ particle-stable configurations of highest $|S|/B$ ratio for given core nucleus.

Multi-$\bar{K}$ hypernuclei

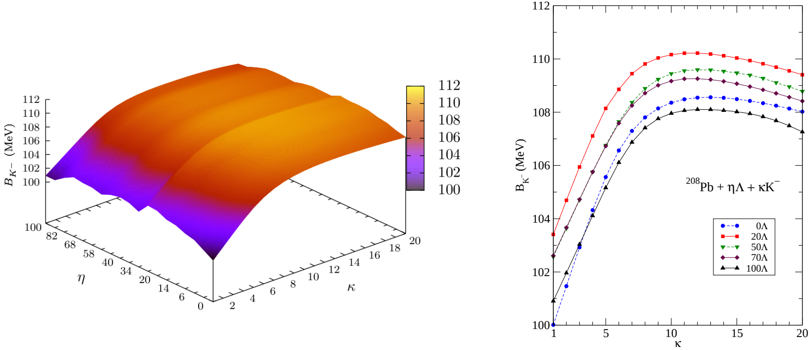

Fig. 7 The $\bar{K}$ binding energy $B_{\bar{K}}$ in ^{208}Pb as a function of the number κ of antikaons and η of Λ hyperons.

Multi-$\bar{K}$ hypernuclei

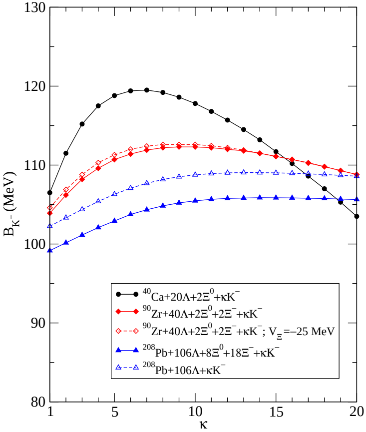

Fig. 8 K^- binding energies in hypernuclear configurations.

Summary

- **dynamical** calculations of single-K^- nuclei across the periodic table:
  - $\Gamma_{K^-} \gtrsim 40 \pm 10$ MeV for $B_{K^-} \sim (100, 200)$ MeV

- 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

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