Dynamics of $\bar{K}$ and multi-$\bar{K}$ nuclei

D. Gazda*, E. Friedman♯, A. Gal♯, J. Mareš*

*Nuclear Physics Institute, Řež, Czech Republic
♯Racah Institute of Physics, The Hebrew University, Jerusalem, Israel

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D.Gazda, E.Friedman, A.Gal, J.Mareš:
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Motivation

- $\bar{K}N$ interaction

  strongly attractive $\Leftarrow \exists\ \Lambda(1405)$ 27 MeV below $K^- p$ threshold

- $\bar{K}$-nucleus interaction

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

  ? optical potential depth - $\mathrm{Re}V_{opt} \simeq (150-200)$ MeV phenomenological models

  - $\mathrm{Re}V_{opt} \simeq (50-60)$ MeV chiral models

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

  ? sufficiently narrow to allow identification by experiment

- kaon propagation in nuclear matter (condensation)
  - heavy ion collisions
  - neutron star structure

Current status

- $(2N)\bar{K}$, $(3N)\bar{K}$, $(4N)\bar{K}$, $(8N)\bar{K}$ (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
- $^4\mathrm{He}(K^-_{stop}, p/n)$ (KEK-PS, E471), $^{16}\mathrm{O}(K^-, n)$ (BNL-AGS, parasite E930)
- K^- capture in Li and ^{12} (FINUDA, PRL (2005))

vs.

- $K^- pn \rightarrow \Lambda N + FSI$ (Magas *et al.*, PRC (2006))
  K^-+quasi-d cluster in ^{6}Li$\rightarrow \Sigma^- p$ (FINUDA, NPA (2006))
- K^-pp Faddeev calculations: $B = (50-70)$ MeV, $\Gamma = (60-100)$ MeV
  Schevchenko *et al.*; Ikeda and Sato

vs.

- K^- stopped in 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))

Methodology

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

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

where

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

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

with covariant derivative:

$$\mathcal{D}_\mu = \partial_\mu + \mathrm{i}\, g_{\omega K}\, \omega_\mu + \mathrm{i}\, g_{\rho K}\, \vec{\tau} \cdot \vec{\rho}_\mu + \mathrm{i}\, g_{\phi K}\, \phi_\mu + \mathrm{i}\, e\, \tfrac{1}{2} (\mathbb{1} + \tau_3)\, A_\mu .$$

nucleons:

$$[-\mathrm{i}\alpha_j\nabla_j + (m_N - g_{\sigma N}\,\sigma)\beta + g_{\omega N}\,\omega + g_{\rho N}\,\tau_3\,\rho + e\tfrac{1}{2}(\mathbb{1} + \tau_3)A]\psi_i = \varepsilon_i\psi_i$$

mesons:

$$(-\nabla^2 + m_\sigma^2)\sigma = g_{\sigma N}\rho_s + g_2\sigma^2 - g_3\sigma^3 + g_{\sigma K}\, m_K\, K^* K$$

$$(-\nabla^2 + m_\sigma^2)\sigma^* = g_{\sigma K}\, m_K\, K^* K$$

$$(-\nabla^2 + m_\omega^2)\omega = g_{\omega N}\rho_v - g_{\omega K}\,\rho_{K^-}$$

$$(-\nabla^2 + m_\rho^2)\rho = g_{\rho N}\rho_3 - g_{\rho K}\,\rho_{K^-}$$

$$(-\nabla^2 + m_\phi^2)\phi = g_{\phi K}\,\rho_{K^-}$$

$$-\nabla^2 A = e\,\rho_p - e\,\rho_{K^-}$$

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

$+$ **antikaons**:

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

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

$$\mathrm{Im}\,\Pi_{K^-} = (0.7\, f_{1\Sigma} + 0.1\, f_{1\Lambda}) W_0\, \rho_N(r) + 0.2\, f_{2\Sigma}\, W_0\, \rho_N^2(r)/\rho_0$$

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%)

Results

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

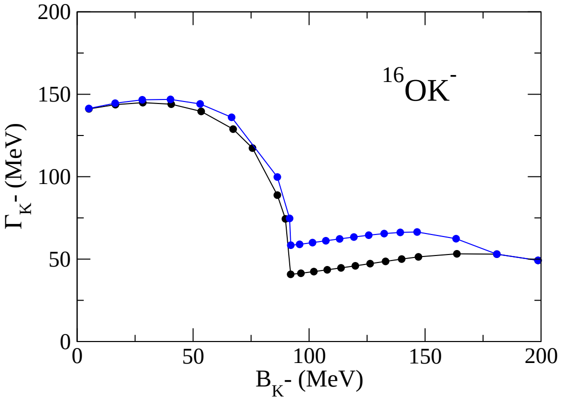
$g_{\sigma K}$, $g_{\omega K}$ couplings scaled $\longrightarrow$ wide range of $B_{\bar{K}}$ covered

Aims:

- dynamical polarization effects in nuclei due to $\bar{K}$
- correlations between $\bar{K}$ binding energies, widths and nuclear properties (density distribution, rms radius, ...)
- nuclear systems containing several $\bar{K}$'s

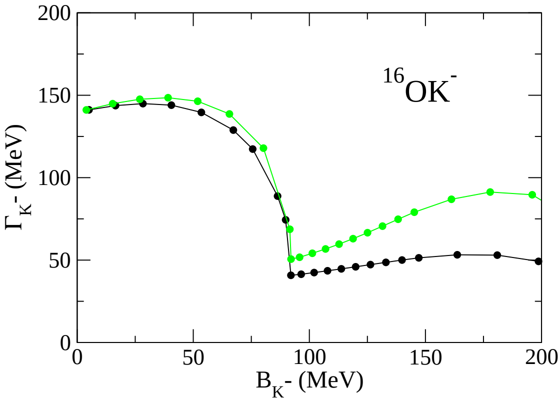
  possible formation of "exotic" configurations made of $p + K^-$ $(n + \bar{K}^0)$

$\bar{K}N \rightarrow \pi\Sigma$ (80%) vs. $\bar{K}N \rightarrow \pi\Sigma, \pi\Lambda$ (70%,10%)

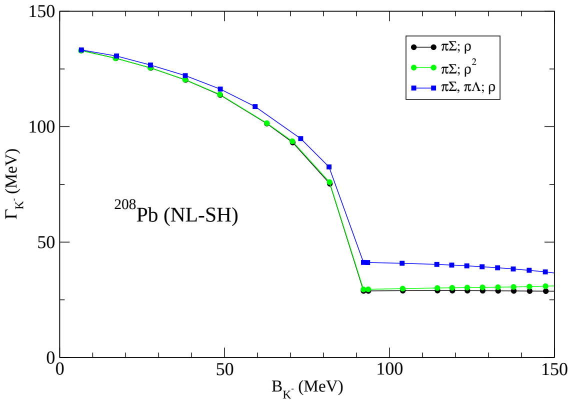


The K^- decay width Γ_{K^-} as a function of the K^- binding energy B_{K^-}.

$\bar{K}NN \rightarrow YN \propto \rho(r)$ vs. $\bar{K}NN \rightarrow YN \propto \rho^2(r)$

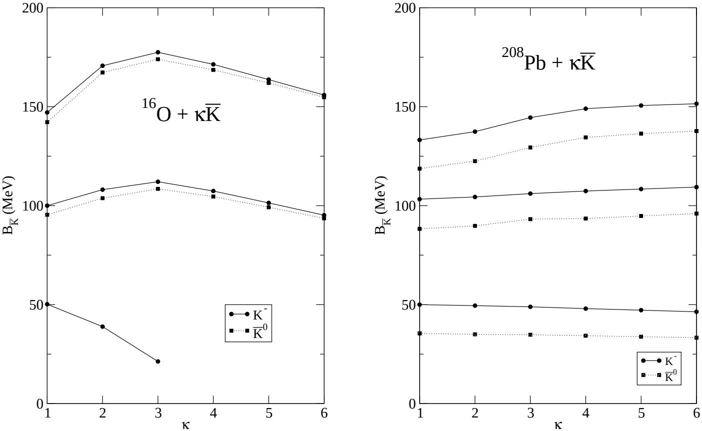


The K^- decay width Γ_{K^-} as a function of the K^- binding energy B_{K^-}.



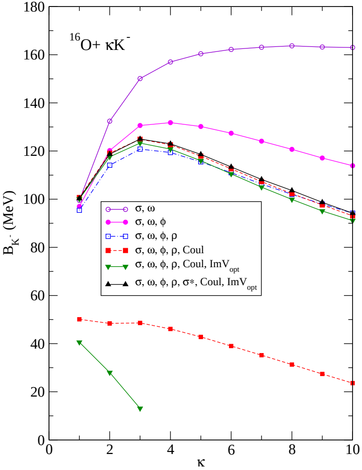
The K^- decay width Γ_{K^-} as a function of the K^- binding energy B_{K^-}.

- $1N$ absorption $\pi\Sigma$ vs. $\pi\Sigma + \pi\Lambda$ – difference independent of atomic number
- $2N$ absorption ρ vs. ρ^2 – difference $\propto$ core polarization



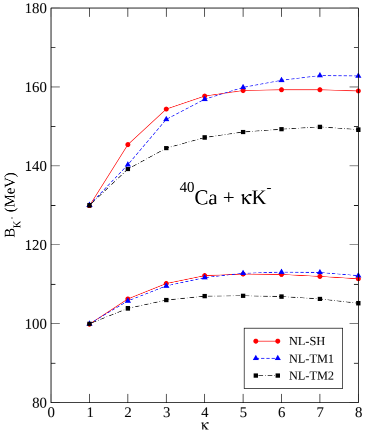
The $\bar{K}$ binding energies as functions of the number κ of antikaons.

- saturation pattern observed across the periodic table



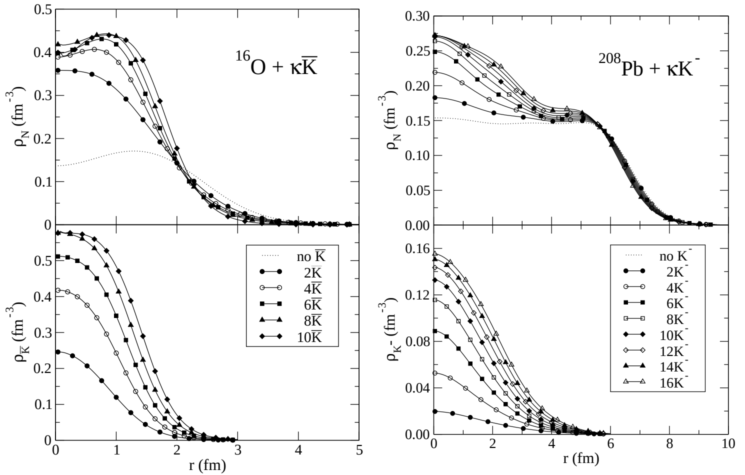
The K^- binding energy as a function of the number κ of antikaons.

- saturation pattern independent of mean-field composition
  (when ω-field present)
- no saturation of $B_{\bar{K}}$ for purely scalar interaction

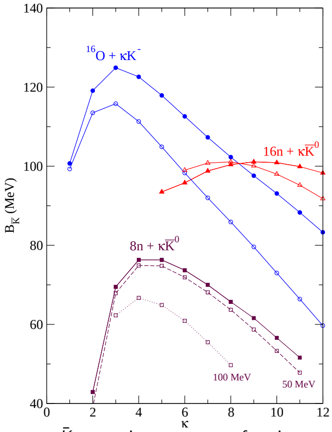


The K^- binding energy as a function of the number κ of antikaons.

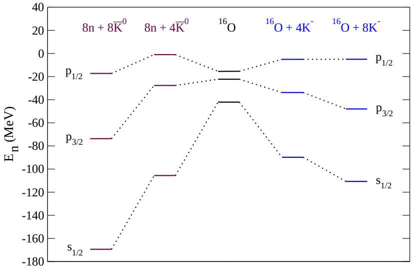
- saturation pattern independent of RMF parametrization



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



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



Neutron single-particle spetra.

- systems of a finite number of neutrons bound by adding few $\bar{K}^0$'s
- unstable configurations, e.g. $16n + 8\bar{K}^0 \rightarrow {}^{16}\mathrm{O} + 8K^-$

Summary

- $\bar{K}N \to \pi\Lambda$ decay channel enhances the K^- conversion width
- ρ^2 density dependence of the $\bar{K}NN \to YN$ absorption mode adds further conversion width (especially to the deeply bound K^--nuclear states)
- calculations of nuclear systems containing several antikaons: $\bar{K}$ binding energies + nuclear densities saturate with number of $\bar{K}$ mesons $\to$ 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