Widths of $\bar{K}$-nuclear deeply bound states in a dynamical model

J. Mareš [a], E. Friedman [b], A. Gal [b]

[a] *Nuclear Physics Institute, 25068 Řež, Czech Republic*

[b] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

Abstract

The relativistic mean field (RMF) model is applied to a system of nucleons and a $\bar{K}$ meson, interacting via scalar and vector boson fields. The model incorporates the standard RMF phenomenology for bound nucleons and, for the $\bar{K}$ meson, it relates to low-energy $\bar{K}N$ and K^- atom phenomenology. Deeply bound $\bar{K}$ nuclear states are generated dynamically across the periodic table and are exhibited for ^{12}C and ^{16}O over a wide range of binding energies. Substantial polarization of the core nucleus is found for these light nuclei. Absorption modes are also included dynamically, considering explicitly the reduced phase space for $\bar{K}$ absorption from deeply bound states. The behavior of the calculated width as function of the $\bar{K}$ binding energy is studied in order to explore limits on the possible existence of narrow $\bar{K}$ nuclear states.

PACS: 13.75.Jz, 25.80.Nv, 36.10.Gv

Keywords: $\bar{K}$ nuclear interaction, $\bar{K}$ nuclear deeply bound states

Corresponding author: Avraham Gal, avragal@vms.huji.ac.il

tel: +972 2 658 4930, fax: +972 2 561 1519

July 21, 2004

Phys. Lett. B 606 (2005) 295.

1. MOTIVATION

- strongly attractive $\bar{K}N$ interaction
  ($\Lambda(1405)$ - 27 MeV below K^-p threshold)
- strongly attractive $\bar{K}$-nucleus interaction
  (strong interaction shifts & widths in kaonic atoms)

$\mathrm{Re}\, V_{opt}^{K^-} \approx 150-200$ MeV
phenomenology
RMF

$\mathrm{Re}\, V_{opt}^{K^-} \approx 50-60$ MeV
chiral $\bar{K}N$ amplitude
+ coupled channel approach

$\Downarrow$

? $\exists$ $\bar{K}$ - nuclear deeply bound states
(width ? - are the possible states sufficiently narrow to allow detection and identification ?)

- Theory: few body systems - $pp\bar{K}$, $^3He\bar{K}$, $ppp\bar{K}$, $^8Be\bar{K}$ ...
  - Large polarization effects ($\rho \approx 4-8 \times \rho_0$, reduced rms radii)
  - $B_{\bar{K}} \geq 100$ MeV, $\Gamma_{\bar{K}} \approx 20-25$ MeV

- Experiment:
  - $^4He(K^-_{stop}, p/n)$ (KEK-PS, E471)
  - $^{16}O(K^-, n)$ (BNL-AGS, parasite E930)
  - $^{12}C(K^-, p)$ (KEK-PS, parasite E522)
  - FINUDA (PRL 94 (2005) 212303)

- OUR AIM: To study dynamical effects for the deeply bound $\bar{K}$ states - the anticipated widths of such states in particular.

II. MODEL

Relativistic Mean Field model for a system of nucleons + $\bar{K}$ interacting through the $\sigma, \omega, \ldots$ boson fields:

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_K$$

- RMF Lagrangian $\mathcal{L}_N$, linear (L) and nonlinear (NL) parametrization $\Rightarrow$ <u>different compressibility</u> of the nuclear core)

- (ANTI)KAON incorporated by $\mathcal{L}_K$:

$$\mathcal{L}_K = \mathcal{D}^*_\mu \bar{K} \mathcal{D}^\mu K - m_K^2 \bar{K} K - g_{\sigma K} m_K \sigma \bar{K} K$$

- NUCLEONS: the original (nuclear case) form of the Dirac eq. is not affected by $\mathcal{L}_K$

- MESONS ($\sigma, \omega, \ldots$):

$$(-\Delta + m_\sigma^2)\sigma = -g_{\sigma N}\rho_S \underline{- g_{\sigma K} m_K \bar{K} K} + \underbrace{(-g_2\sigma^2 - g_3\sigma^3)}_{NL}$$

$$(-\Delta + m_\omega^2)\omega_0 = g_{\omega N}\rho_V \underline{- 2 g_{\omega K}(\omega_K + g_{\omega K}\omega_0)\bar{K} K},$$

where $\omega_K = \sqrt{m_K^2 + g_{\sigma K} m_K \sigma + p_K^2} - g_{\omega K}\omega_0$

$$(-\Delta + m_\rho^2)\rho_0 = g_{\rho N}\rho_3$$

$$-\Delta A_0 = e\rho_P$$

- + K.G. eq. for $\bar{K}$

$$[\Delta - 2\mu(B + V_{opt} + V_c) + (V_c + B)^2]\bar{K} = 0$$

V_c = Coulomb potential, μ = $\bar{K}$-nucleus reduced mass,
B = complex binding energy

- $\mathrm{Re}\, V_{opt} = \frac{m_K}{\mu}\left(\frac{1}{2}S - V - \frac{V^2}{2m_K}\right)$

  $(S = g_{\sigma K}\sigma,\ V = g_{\omega K}\omega_0)$

- $\mathrm{Im}\, V_{opt} = sf\, t\rho$

  phenomenological, t fitted to $\bar{K}$ atomic data

  ρ is a **DYNAMICAL** quantity affected by the $\bar{K}$ interaction with nucleons

- The system of coupled eqs. was solved selfconsistently → iterations

  $\Downarrow$

  Crucial for the proper evaluation of the dynamical effects of $\bar{K}$ on the nuclear core and vice versa.

NOTE: the coupling of $\bar{K}$ to ρ neglected
(N=Z nuclei studied: ^{12}C, ^{16}O, ^{40}Ca, ^{208}Pb)

- **sf** = suppression factor

from phase-space considerations
(assuming 2 body kinematics + taking into account $B_{\bar{K}}$)

1) π conversion ($\approx 80\%$)

$\bar{K}N \to \pi\Sigma$ (≈ 100 MeV), $\pi\Lambda$ (≈ 180 MeV)

$$sf_1 = \frac{M_{01}^3}{M_1^3}\sqrt{\frac{[M_1^2-(m_\pi+m_Y)^2][M_1^2-(m_Y-m_\pi)^2]}{[M_{01}^2-(m_\pi+m_Y)^2][M_{01}^2-(m_Y-m_\pi)^2]}}\cdot\Theta(M_1-m_\pi-m_Y)$$

$M_{01} = m_{\bar{K}} + m_N$, $M_1 = M_{01} - B_K$

2) nonpionic mode ($\approx 20\%$)

$\bar{K}NN \to YN$ ($Y = \Lambda, \Sigma$)

$$sf_2 = \frac{M_{02}^3}{M_2^2}\sqrt{\frac{[M_2^2-(m_N+m_Y)^2][M_2^2-(m_Y-m_N)^2]}{[M_{02}^2-(m_N+m_Y)^2][M_{02}^2-(m_Y-m_N)^2]}}\cdot\Theta(M_2-m_Y-m_N)$$

$M_{02} = m_{\bar{K}} + 2m_N$, $M_2 = M_{02} - B_K$

- 1) + 2) $\Rightarrow$ $sf = 0.8\, sf_1 + 0.2\, sf_2$ (branching ratios from CERN bubble chamber exp.)

III. RESULTS

Calculations of ^{12}C, ^{16}O, (^{40}Ca, ^{208}Pb)
(mostly $\bar{K}$ in 1s state)

AIM = establish correlations between $\bar{K}$ binding energy, width, nuclear properties (average density $\bar{\rho} = \int \frac{\rho^2 dr}{A}$, rms radius, s.p. energies ...)

$\Downarrow$

wide range of $B_{\bar{K}}$ covered

- $\alpha_\sigma, \alpha_\omega$ $\left(\alpha_i = \frac{g_{iK}}{g_{iN}}\right)$, t from RMF fits to kaonic atom data ($\mathrm{Re}\, V^{K}_{atom} \approx$ 150 – 200 MeV)

dynamical calcul. $\Rightarrow$ $\mathrm{Re}\, V^{K}_{nucl} \approx 2\, \mathrm{Re}\, V^{K}_{atom}$

$\downarrow$

α_σ scaled down to $\alpha_\sigma = 0$, then α_ω scaled until $\bar{K}$ unbound

- $\alpha_\sigma, \alpha_\omega, t$ from fits to kaonic atom data using RMF (L) + (at large radii) $+\rho$, where t from chiral $\bar{K}N$ amplitudes ($\mathrm{Re}\, V^{K}_{atom} \approx$ 50 – 60 MeV)

$\downarrow$

α_ω fixed, α_σ scaled up

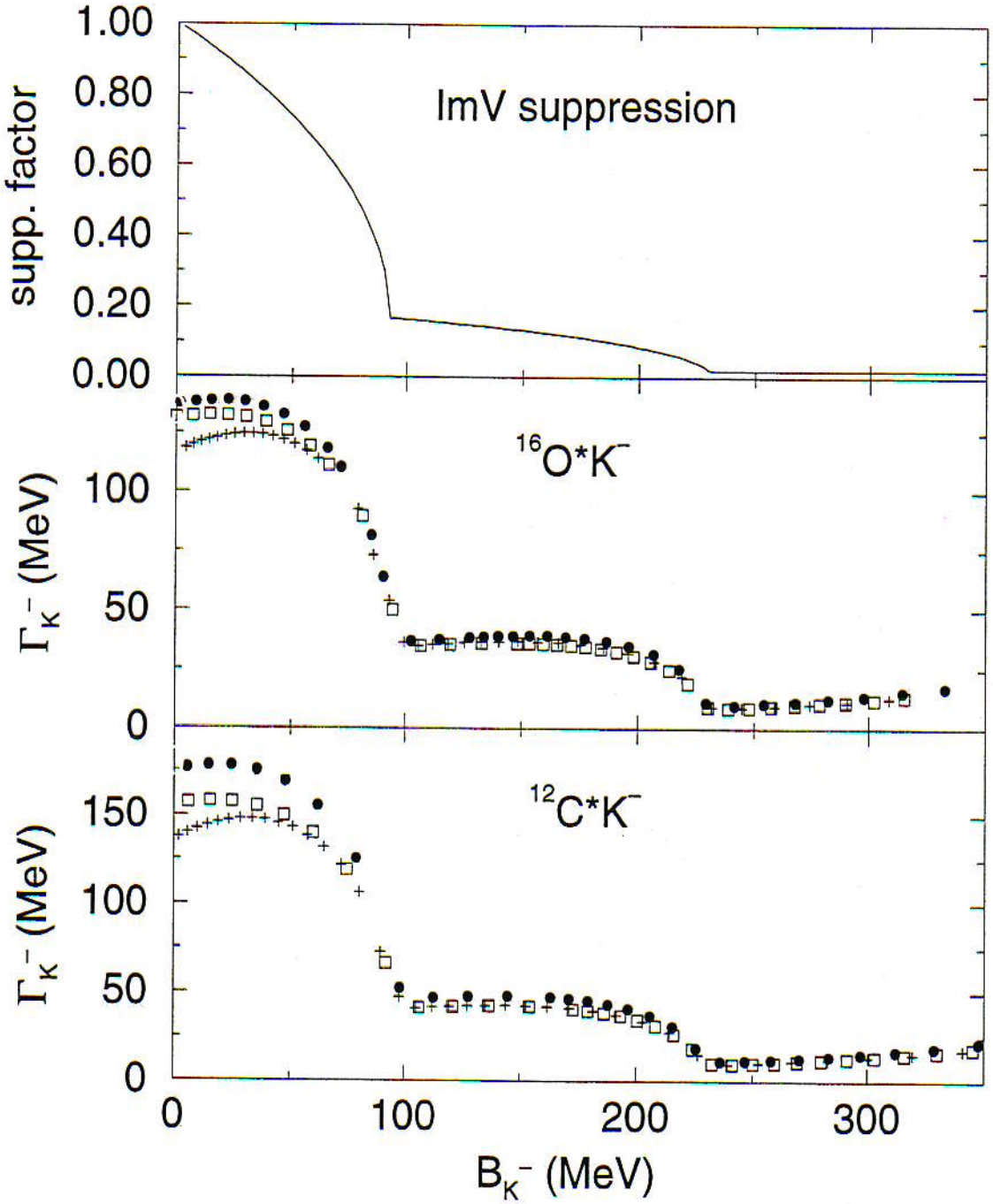

FIG. 1. Phase-space suppression factor for the imaginary potential (top), and widths of the 1s K^--nuclear state (middle: in ^{16}O, bottom: in ^{12}C) as function of the K^- binding energy (see text for symbols).

□ = linear model L (Horowitz, Serot)

● = nonlinear model NL (Shorma et al.)

+ = linear + "chiral tail" method for scanning $B_{\bar{K}}$

=> • The widths $\Gamma_{\bar{K}}$ follow closely the dependence $sf(B_{\bar{K}})$

• $B_{\bar{K}} > 50$ MeV – the dependence $\Gamma_{\bar{K}}(B_{\bar{K}})$ is almost universal for a given nucleus.

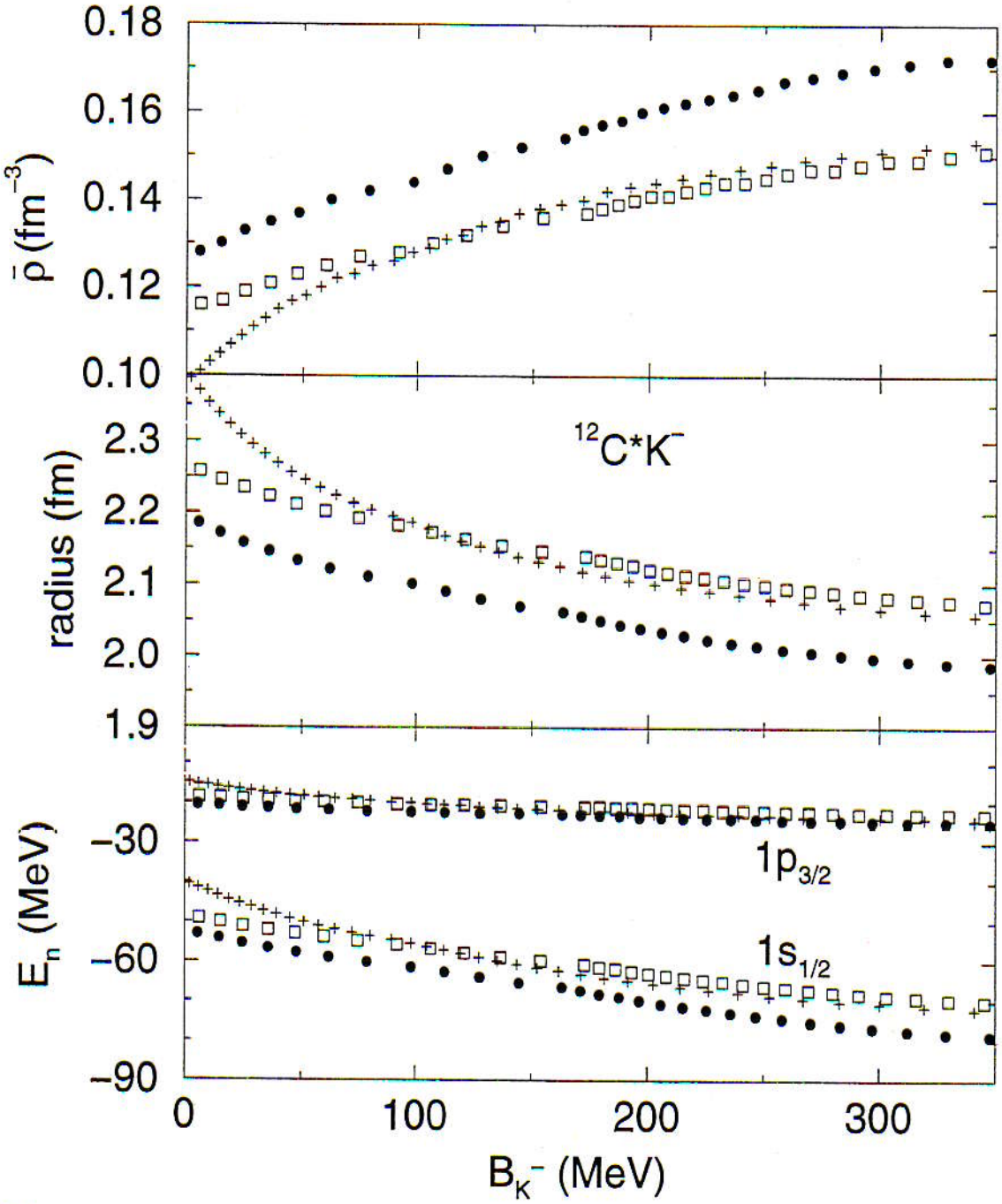

FIG. 2. Average nuclear density, nuclear rms radius and neutron single-particle energies for $_{K^-}{}^{12}$C. Symbols are as in Fig. 1.

$\bar{\rho} = \int \frac{\rho^2 dr}{A}$, rms radius, neutron s.p. energies in $^{12}CK^-$.

□ = linear model L

• = nonlinear model NL

+ = linear + "chiral tail" model

TABLES

TABLE I. K^- bound-state spectra in ${}_{K^-}^{16}\mathrm{O}$ calculated for several RMF (NL) Lagrangians specified by different coupling-constant ratios $\alpha_\sigma = g_{\sigma K}/g_{\sigma K}^{(1)}$ and $\alpha_\omega = g_{\omega K}/g_{\omega K}^{(1)}$. The static average density for $^{16}\mathrm{O}$ is $\bar{\rho} = 0.100\ \mathrm{fm}^{-3}$.

α_σ	α_ω	nl	B_{K^-} (MeV)	Γ_{K^-} (MeV)	$\bar{\rho}$ (fm^{-3})
0.45	1	$1s$	196.1	35.0	0.133
		$1p$	82.2	83.0	0.127
		$2s$	3.7	89.9	0.111
0.05	1	$1s$	133.9	38.7	0.127
		$1p$	50.6	119.0	0.120
0	0.85	$1s$	90.2	64.2	0.121
		$1p$	23.8	124.5	0.115

'$\hbar\omega$' spacings are bigger than in static calculations

REMARKS:

- Differences between L and NL models reflect different compressibilities and also diff. predictions for the studied quantities in L and NL models.

- $B_{\bar{K}} > 50$ MeV $\rightarrow$ the dependence $\Gamma_{\bar{K}}(B_{\bar{K}})$ is almost universal for a given nucleus. Results are independent of the way how $B_{\bar{K}}$ is being scanned.

- Increase of the rms radius in ^{16}O for large $B_{\bar{K}}$
  $\Uparrow$
  reduced nucleon $1p\,1/2$ state energy due to the increased SO term

- $B_{\bar{K}} = 0 \rightarrow$ plotted values of rms radii, s.p. energies... do not reach the values in ordinary nuclei
  $\Uparrow$
  $\alpha_s, \alpha_w \neq 0$, $\mathrm{Im}\, V_{opt} \neq 0$

- Similar calculations for ^{40}Ca, ^{208}Pb:
  The dependence $\Gamma_{\bar{K}}(B_{\bar{K}})$ is similar in shape to the results for ^{12}C, ^{16}O.
  The effects on $\bar{\rho}$, rms radii ... are negligibly small (as expected for heavier nuclei).

IV. CONCLUSIONS

- RMF model applied to a system of nucleons + $\bar{K}$.
  The model incorporated:
  Nucleons: standard RMF phenomenology
  $\bar{K}$: + extension of low energy $\bar{K}N$ + $\bar{K}$atom phenomenology

- 1N + 2N absorption modes included within an optical model approach, explicitely considering the phase-space available for absorption from deeply bound states.

- Deeply bound states generated dynamically - (accross the periodic table, here ^{12}C & ^{16}O, over a wide range of $B_{\bar{K}}$)
  Substantial polarization of the core nucleus found

- The behaviour $\Gamma_{\bar{K}}(B_{\bar{K}})$ studied in order to place limits on the possible $\exists$ of narrow deeply bound $\bar{K}$ nuclear states
  (placing a lower limit $\Gamma_{\bar{K}} \sim 35-40$ MeV on $\bar{K}$ states in ^{16}O bound in the range $B_{\bar{K}} \sim 100-200$ MeV)