Calculations of kaonic nuclei based on chiral meson-baryon coupled channel interaction models

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Introduction

- Self-consistent calculations of K^--nuclear quasi-bound states using the following chiral meson-baryon interaction models:
  - Prague (P NLO)
    (A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115)
  - Kyoto-Munich (KM NLO)
    (Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A 881 (2012) 98)
  - Murcia (M1 and M2)
    (Z. H. Guo and J. A. Oller, Phys. Rev. C 87,(2013) 035202)
  - Bonn (B2 and B4)
    (M. Mai and U.-G. Meißner, Nucl. Phys. A 900, (2013) 51)

Free-space $K^- p$ amplitudes

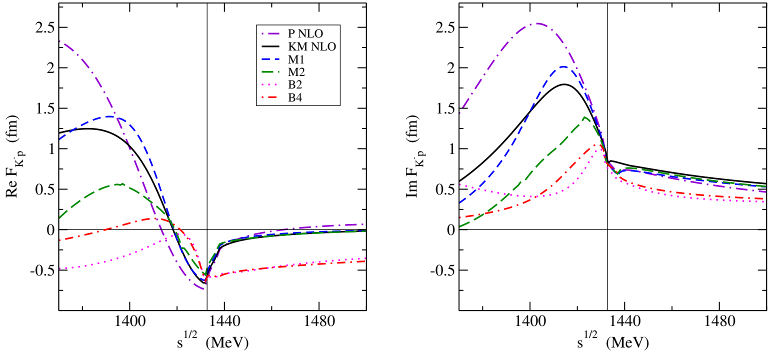

Fig.1: Energy dependence of real (left) and imaginary (right) parts of free-space $K^- p$ amplitudes in considered models.

Free-space $K^- n$ amplitudes

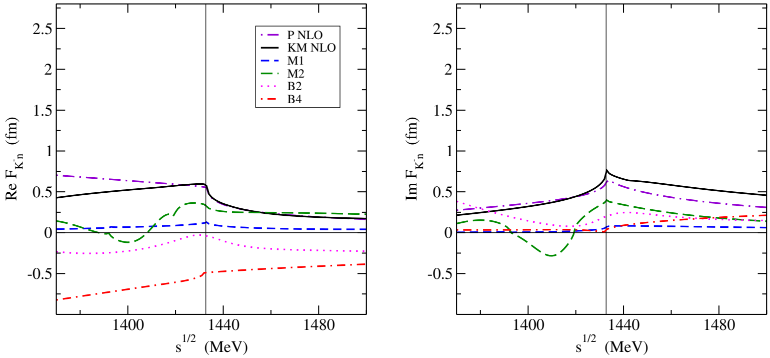

Fig.2:Energy dependence of real (left) and imaginary (right) parts of free-space $K^- n$ amplitudes in considered models.

Model

- Klein-Gordon equation for K^-

  $$\left[\omega_K^2 + \vec{\nabla}^2 - m_K^2 - \Pi_K(\vec{p}_K, \omega_K, \rho)\right] \phi_K = 0$$

  complex energy $\omega_K = m_K - B_K - \mathrm{i}\Gamma_K/2 - V_C = \tilde{\omega}_K - V_C$

- self-energy operator

  $$\Pi_K = 2\mathrm{Re}(\tilde{\omega}_{K^-}) V_{K^-} = -4\pi \frac{\sqrt{s}}{m_N} \left(F_0 \tfrac{1}{2}\rho_p + F_1 \left(\tfrac{1}{2}\rho_p + \rho_n\right)\right),$$

  F_0 and F_1 – isospin 0 and 1 scattering amplitudes

- Nucleus described within the RMF model

Model

- Free space amplitudes → in-medium amplitudes - WRW method
  (T. Wass, M. Rho, W. Weise, Nucl. Phys. A 617 (1997) 449)

$$F_1 = \frac{F_{K^-n}(\sqrt{s})}{1 + \frac{1}{4}\xi_k \frac{\sqrt{s}}{m_N} F_{K^-n}(\sqrt{s})\rho} , \quad F_0 = \frac{[2F_{K^-p}(\sqrt{s}) - F_{K^-n}(\sqrt{s})]}{1 + \frac{1}{4}\xi_k \frac{\sqrt{s}}{m_N} [2F_{K^-p}(\sqrt{s}) - F_{K^-n}(\sqrt{s})]\rho}$$

where

$$\xi_k = \frac{9\pi}{p_f^2} 4 \int_0^\infty \frac{dt}{t} \exp(iqt) j_1^2(t), \qquad q = \frac{1}{p_f}\sqrt{\tilde{\omega}_{K^-}^2 - m_{K^-}^2} .$$

- P NLO + Pauli + SE model
  (A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115)

$$F_{ij}(p, p'; \sqrt{s}) = -\frac{g_i(p) g_j(p')}{4\pi f_i f_j} \sqrt{\frac{M_i M_j}{s}} \left[(1 - C(\sqrt{s}) \cdot G(\sqrt{s})^{-1}) \cdot C(\sqrt{s})\right]_{ij} ,$$

$$G_i(\sqrt{s}; \rho) = \frac{1}{f_i^2} \frac{M_i}{\sqrt{s}} \int_{\Omega_i(\rho)} \frac{d^3\vec{p}}{(2\pi)^3} \frac{g_i^2(p)}{p_i^2 - p^2 - \Pi_i(\sqrt{s}, \vec{p}; \rho) + i0} .$$

In-medium modified $\bar{K}N$ amplitudes

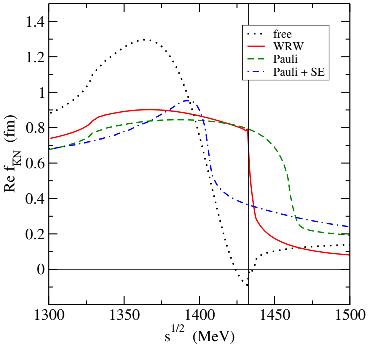

Fig.3: Energy dependence of reduced free-space (dotted line) $f_{\bar{K}N} = \frac{1}{2}(f_{K^-p} + f_{K^-n})$ amplitude compared with WRW modified amplitude (solid line), Pauli (dashed line), and Pauli + SE (dot-dashed line) modified amplitude for $\rho_0 = 0.17$ fm^{-3} in the P NLO model.

Energy dependence

- Amplitudes as a function of available energy $\sqrt{s}$
  $(s = (E_N + E_{K^-})^2 - (\vec{p}_N + \vec{p}_{K^-})^2)$
- $\bar{K}N$ cms frame $\rightarrow$ K^--nucleus frame $\vec{p}_N + \vec{p}_{K^-} \neq 0$
  (A. Cieplý, E. Friedman, A. Gal, D. Gazda, J. Mareš, PLB 702, 402 (2011))

$$\sqrt{s} = m_N + m_{K^-} - 8.5 - \xi_N B_{K^-} + \xi_{K^-} \mathrm{Re}\mathcal{V}_{K^-}(r) - \xi_N T_N (\frac{\rho}{\rho_0})^{2/3} ,$$

where $\mathcal{V}_{K^-} = V_{K^-} + V_{\mathrm{C}}$, $T_N = 23$ MeV, and $\xi_{N(K^-)} = m_{N(K^-)}/(m_N + m_{K^-})$.

K^- optical potential

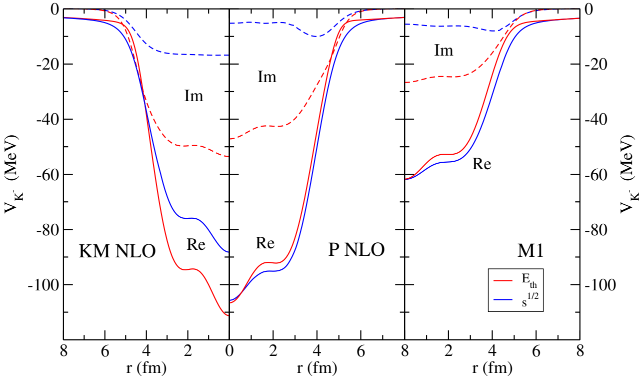

Fig.4: K^- optical potential in ^{40}Ca calculated for self-consistent $\sqrt{s}$ and at threshold $E_{\rm th}$ in the KM NLO, P NLO, and M1 models.

K^- optical potential

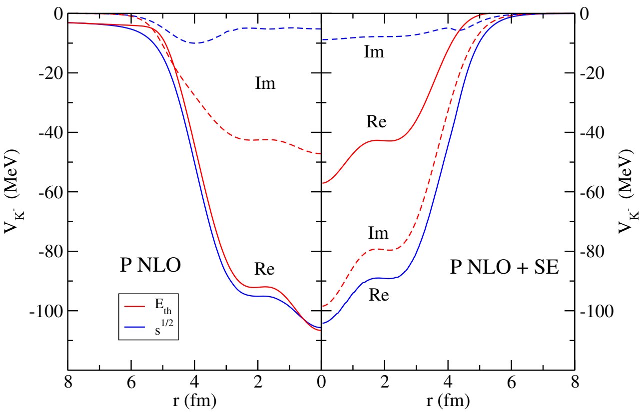

Fig.5: K^- optical potential in ^{40}Ca calculated self-consistently for in-medium $\sqrt{s}$ and at threshold E_{th} using WRW modified amplitudes in the P NLO model compared with P NLO + Pauli + SE model.

K^- 1s binding energies and widths

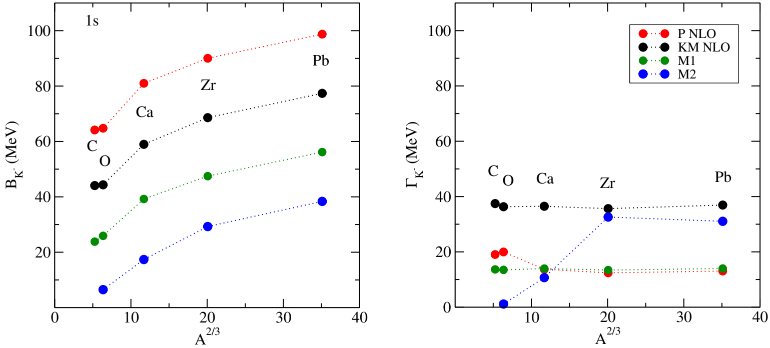

Fig.6: 1s K^- binding energies (left) and corresponding widths (right) in various nuclei calculated self-consistently in the P NLO, KM NLO, M1, and M2 models.

K^- 1s binding energies and widths

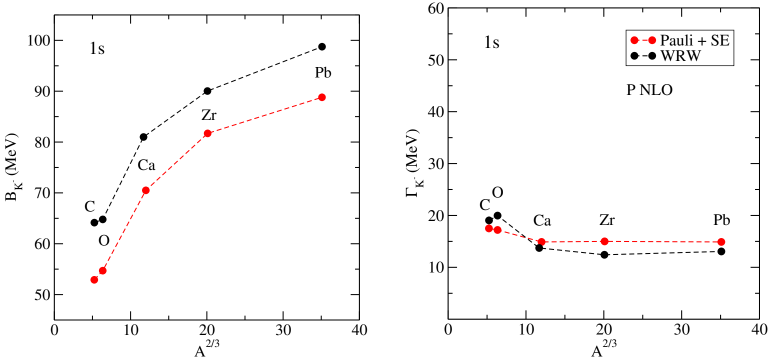

Fig.7: K^- binding energies (left) and widths (right) calculated using the WRW method in the P NLO model compared with P NLO + Pauli + SE model.

K^- spectrum in ^{40}Ca

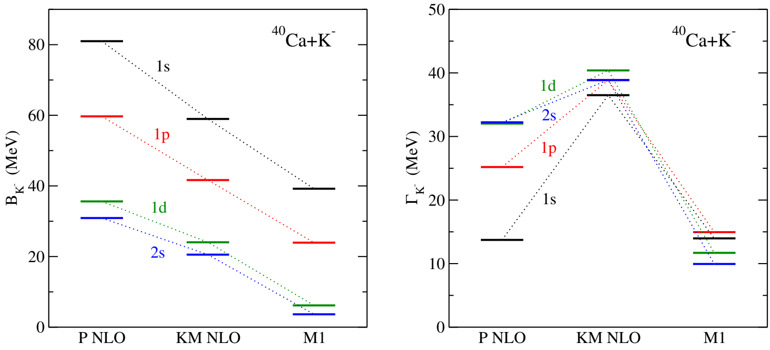

Fig.8: K^- binding energies (left) and widths (right) in s, p and d levels in ^{40}Ca calculated self-consistently in the P NLO, KM NLO, and M1 models.

Effects not included in the present calculations

- dynamic approach — core polarization effect up to $\simeq 5$ MeV in K^- binding energies
- P-wave interaction — weakly attractive $\simeq +5$ MeV in binding energy, $\simeq -1$ MeV in width
- 2N absorption $\bar{K}NN \to YN$

The effect of 2N absorption (CS30 model):

		C	O	Ca	Zr	Pb
$\sqrt{s}$+SE+dyn.	B_K	55.7	56.0	70.2	80.5	87.0
	Γ_K	12.3	12.1	10.8	10.9	10.8
$\sqrt{s}$+SE+dyn.+2N	B_K	54.0	55.1	67.6	79.6	86.3
	Γ_K	44.9	53.3	65.3	48.7	47.3

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

Conclusions

- Calculations of K^--nuclear quasi-bound states based on chiral meson-baryon interaction models:
  - large model dependence of K^- binding energies
  - small K^- widths (10 - 20 MeV) in P NLO and M1 models, twice larger widths ($\simeq$ 40 MeV) in KM NLO model
  - 2N absorption important — adds up to 50 MeV to the widths
  - no bound states found for B2 and B4 models