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Calculations of $\bar{K}$-nuclear quasi-bound states using chiral $\bar{K}N$ amplitudes

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Abstract. We review our recent calculations of K^- quasi-bound states in nuclear systems using subthreshold energy dependent chiral $\bar{K}N$ amplitudes. Strong energy dependence of the scattering amplitudes requires self-consistent evaluation of the involved $\bar{K}N$ interactions. In view of sizable widths predicted by our calculations, an unambiguous identification of K^--nuclear quasi-bound states in ongoing experimental searches would be difficult.

1 Introduction

Most of the current calculations of K^--nuclear quasi-bound states are based on the $\bar{K}N$ interactions derived within an SU(3) chiral approach combined with coupled channel T-matrix resummation techniques [1–3]. In such an approach, constrained by fitting to K^-p threshold and low-energy data, the $\Lambda(1405)$ resonance is generated dynamically. Its presence induces strong energy dependence in the scattering amplitudes $f_{\bar{K}N}(\sqrt{s})$ which has to be treated self-consistently, as shown in refs. [4–6]. The key issue is that in the nuclear medium (for $A \gg 1$ approximated by the lab system)

$$\sqrt{s} = \sqrt{(\sqrt{s_{\rm th}} - B_K - B_N)^2 - (\vec{p}_K + \vec{p}_N)^2} \leq \sqrt{s_{\rm th}}, \tag{1}$$

where $\sqrt{s_{\rm th}} \equiv m_K + m_N$ and B_K (B_N) is the antikaon (nucleon) binding energy and the momentum dependent term generates additional substantial downward energy shift, since $(\vec{p}_K + \vec{p}_N)^2 \neq 0$, unlike the case of the two-body cm system.

Main results of our recent calculations of K^- quasi-bound states in nuclear few-body [6] and many-body [4, 5] systems are summarized in the following sections.

2 Few-body kaonic nuclear clusters

We performed calculations of three-body $(\bar{K}NN)_{I=0}$ and four-body $(\bar{K}NNN)_{I=0,1}$ and $(\bar{K}\bar{K}NN)_{I=0}$ nuclear quasi-bound states. The $\bar{K}$-nuclear cluster wavefunctions were expanded in a hyperspherical

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basis and the ground-state binding energies were calculated variationally. The corresponding $\bar{K}N \to \pi Y$ widths were evaluated using the expression:

$$\frac{\Gamma}{2} \approx \langle \Psi_{g.s.} | - ImV_{\bar{K}N} | \Psi_{g.s.} \rangle \,, \tag{2}$$

where $V_{\bar{K}N}$ sums overall pairwise $\bar{K}N$ interactions. For two-body interactions involved, we used the AV4' V_{NN} [7], an effective energy-dependent $V_{\bar{K}N}$ [8] and a weakly repulsive $V_{\bar{K}\bar{K}}$ [9]. In $\bar{K}$-nuclear clusters, the energy dependent $V_{\bar{K}N}(\sqrt{s})$ was evaluated self-consistently for $\sqrt{s}$, expressed near threshold in the form:

$$\sqrt{s} = \sqrt{s_{\rm th}} - \frac{B}{A} - \frac{A-1}{A} B_K - \xi_N \frac{A-1}{A} \langle T_{NN} \rangle - \xi_K \left(\frac{A-1}{A} \right)^2 \langle T_K \rangle \,, \tag{3}$$

where $\xi_{N(K)} = m_N(K)/(m_N + m_K)$, B is the total binding energy of the system, T_K is the kaon kinetic energy operator in the total cm frame and T_{NN} is the pairwise NN kinetic energy operator in the NN pair cm system. A similar procedure was used for the $\bar{K}\bar{K}NN$ cluster (see [6] for details).

Results of our self-consistent calculations are summarized in Fig. 1. Since $\bar{K}N$ amplitudes (and consequently potentials) decrease upon going subthreshold, self-consistent calculations yield binding energies and widths of the calculated nuclear clusters lower than calculations performed at threshold, typically $\Delta B \sim 10$ MeV and $\Delta\Gamma \sim 10 - 40$ MeV. We reproduced results of previous $\bar{K}NN_{I=0}$ calculations using chiral energy-dependent $\bar{K}N$ amplitudes [10]. In view of the low $\bar{K}NN_{I=0}$ binding energy $B(\bar{K}NN) \approx 16$ MeV and relatively large absorption width $\Gamma(\bar{K}NN) \approx 40$ MeV, it might be difficult to identify the $K^- pp$ quasi-bound state unambiguously in ongoing experiments.

We found relatively modest binding of the four-body $\bar{K}$ nuclear clusters, about 30 MeV in the lowest $I = 0$ systems, with absorption widths ranging from 30 MeV for $\bar{K}NNN$ to about 80 MeV for the $\bar{K}\bar{K}NN$ quasi-bound state.

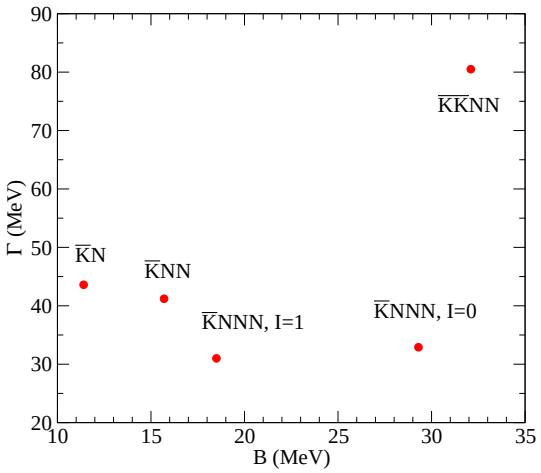

Figure 1. Calculated binding energies and $\bar{K}N \to \pi Y$ widths of few-body $\bar{K}$-nuclear clusters [6].

It is to be noted that the widths shown in Fig. 1 are due to $\bar{K}N \to \pi Y$. Two-nucleon $K^-NN \to YN$ absorption widths are expected to add $\Delta\Gamma \lesssim 10$ MeV in $\bar{K}NN_{I=0}$ system [10] and ~ 20 MeV in the 4-body clusters [6]. The binding energies of K^- nuclear clusters could also be enhanced by dispersive contributions. Our recent fits to kaonic atoms [4, 11] suggest that $\Delta B_{\rm disp} \sim \Delta\Gamma_{\rm abs}$, and the binding energies could reach values $B(K^-pp) \sim 25$ MeV and $B(\bar{K}NNN,\ \bar{K}\bar{K}NN) \sim 50$ MeV.

3 Many-body K^--nuclear systems

The K^--nuclear quasi-bound states were calculated within the RMF formalism (see Refs. [4, 5] for details). The interaction of a K^- meson with a nucleus is described by the Klein–Gordon (KG) equation of the form

$$\left[\nabla^2 + \tilde{\omega}_K^2 - m_K^2 - \Pi_K(\omega_K, \vec{p}_K, \rho)\right]\phi = 0, \tag{4}$$

where $\tilde{\omega}_K = \omega_K - {\rm i}\Gamma_K/2 - V_C$ is complex energy of antikaon containing the Coulomb interaction V_C, with Γ_K being the width of K^- nuclear state of energy $\omega_K = m_K - B_K$. The self-energy operator $\Pi_K = 2({\rm Re}\,\omega_K)V_K$ reads:

$$\Pi_K(\omega_K, \vec{p}_K, \rho) = -4\pi\frac{\sqrt{s}}{m_N}\left[F_{K^-p}(\sqrt{s}, \vec{p}, \rho)\rho_p + F_{K^-n}(\sqrt{s}, \vec{p}, \rho)\rho_n\right], \tag{5}$$

where $F_{K^-p(n)}$ is the K^-–proton (neutron) in-medium scattering amplitude constructed within a chirally motivated coupled-channel model and ρ_p (ρ_n) is the proton (neutron) RMF density distribution in a core nucleus. The scattering amplitudes in Eq. (5) are a function of $\bar{K}N$ c.m. energy $\sqrt{s}$ and relative momentum $\vec{p}$. The transformation of the two-body $\bar{K}N$ arguments into the $\bar{K}$–nuclear c.m. frame (for $A \gg 1$) leads to:

$$p^2 \approx \xi_N\xi_K\left[2m_K\,23\,(\rho/\rho_0)^{2/3} - 2m_N(B_K + {\rm Re}\,\mathcal{V}_K(\rho))\right] \quad \text{(in MeV)}, \tag{6}$$

$$\sqrt{s} \approx \sqrt{s_{\rm th}} - B_N - \xi_N B_K - 15.1\left(\frac{\rho}{\rho_0}\right)^{2/3} + \xi_K {\rm Re}\mathcal{V}_K(\rho) \qquad \text{(in MeV)}, \tag{7}$$

where $\mathcal{V}_K = V_K + V_C$.

We note that the K^- potential V_K and the K^- binding energy B_K appear as arguments in the expression for $\sqrt{s}$, which in turn serves as an argument for the self energy Π_K, and thus for V_K. Therefore, a self-consistency scheme in terms of both V_K and B_K is required for solving the KG equation (4).

We considered two in-medium versions of the scattering amplitudes: the version which takes into account only Pauli blocking in the intermediate states, and the version (+SE) which adds self-consistently hadron in-medium self-energies [4, 5]. The $\bar{K}N$ amplitudes were constructed using the in-medium coupled-channel separable interaction model NLO30 [3] that reproduces all available low energy $\bar{K}N$ observables, including the latest $1s$ level shift and width in the K^- hydrogen atom from the SIDDHARTA experiment [12]. While the two in-medium versions of the $\bar{K}N$ scattering amplitudes yield by factor 2 different potential depths ${\rm Re}V_K$ at threshold, they give similar depths in the self-consistent calculations with the subthreshold extrapolation, ${\rm Re}V_K \sim 80 - 120$ MeV, depending on a particular nucleus.

Figure 2 shows binding energies and widths of K^- quasi-bound states – including excited states – in selected nuclei calculated self-consistently for $\sqrt{s}$ of Eq. (7), using the '+SE' amplitudes. The widths of low-lying K^- states due to $K^-N \to \pi Y$ conversions are substantially reduced in the self-consistent calculations, thus reflecting the proximity of the $\pi\Sigma$ threshold. On the contrary, the widths of higher excited K^- states are quite large even if only the pion conversion modes on a single nucleon are considered. After including 2 body $K^-NN \to YN$ absorption modes, the total decay widths Γ_K are

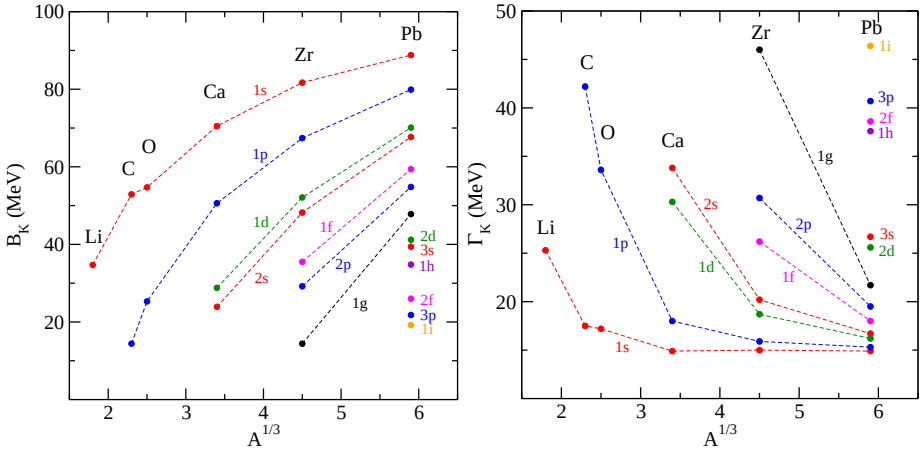

Figure 2. Binding energies B_K (left panel) and widths Γ_K (right panel) of K^- quasi-bound states in selected nuclei, calculated self-consistently with the '+SE' NLO30 scattering amplitudes [3]. $K^-NN \to YN$ absorption modes are not included.

comparable or even larger than the corresponding binding energies B_K for *all* K^- nuclear quasi-bound states, exceeding considerably the level spacing. Our results should thus discourage attempts to search for isolated peaks corresponding to K^- nuclear quasi-bound states in many-body nuclear systems.

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References

[1] A. Ramos, E. Oset, Nucl. Phys. A **671**, 481 (2000)
[2] B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A **25**, 79 (2005); Phys. Rev. Lett. **94**, 213401 (2005)
[3] A. Cieplý, J. Smejkal, Nucl. Phys. A **881**, 115 (2012)
[4] A. Cieplý, E. Friedman, A. Gal, D. Gazda, J. Mareš, Phys. Lett. B **702**, 402 (2011); Phys. Rev. C **84**, 045206 (2011)
[5] D. Gazda, J. Mareš, Nucl. Phys. A **881**, 159 (2012)
[6] N. Barnea, A. Gal, E. Z. Liverts, Phys. Lett. B **712**, 132 (2012)
[7] R. B. Wiringa, S. C. Pieper, Phys. Rev. Lett. **89**, 182501 (2002)
[8] T. Hyodo, W. Weise, Phys. Rev. C **77**, 035204 (2008)
[9] Y. Kanada-En'yo, D. Jido, Phys. Rev. C **78**, 025212 (2008)
[10] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A **804**, 197 (2008); Phys. Rev. C **79**, 014003 (2009)
[11] E. Friedman, A. Gal, Nucl. Phys. A **881**, 150 (2012); Nucl. Phys. A **899**, 60 (2013)
[12] M. Bazzi *et al.* (SIDDHARTA Collaboration), Phys. Lett. B **704**, 113 (2011); Nucl. Phys. A **881**, 88 (2012)