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Recent studies of kaonic atoms and nuclear clusters

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Abstract

Recent studies of kaonic atoms, few-body kaonic quasibound states and kaonic nuclei are reviewed, with emphasis on implementing the subthreshold energy dependence of the $\bar{K}N$ interaction in chiral interaction models that are consistent with the SIDDHARTA K^- hydrogen data. Remarks are made on the possible role of the p-wave $\Sigma(1385)$ resonance with respect to that of the s-wave $\Lambda(1405)$ resonance in searches for strangeness $\mathcal{S}=-1$ dibaryons.

Keywords: Kaon–baryon interactions; Few-body systems; Mesic nuclei; Mesonic atoms

1. Introduction

Recent NLO chiral model calculations of near-threshold $\bar{K}N$ dynamics, reproducing the SIDDHARTA measurement of atomic K^- hydrogen 1s level shift and width [1], have been discussed by Hyodo [2]. The $\Lambda(1405)$-induced strong energy dependence of the scattering amplitudes $f_{\bar{K}N}(\sqrt{s})$ arising in these calculations introduces a new feature into the analysis of K^- atomic and nuclear systems as realized for K^- atoms in the early 1970s [3,4]. Thus, in nuclear matter, approximated for $A \gg 1$ by the lab system,

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

where $\sqrt{s_{\rm th}} \equiv m_K + m_N$, B_K and B_N are appropriate binding energies, and where additional downward energy shift is generated by the momentum dependent term. Unlike in the free-space $\bar{K}N$ cm system where $(\vec{p}_K + \vec{p}_N)_{\rm cm} = 0$, this term is found to contribute substantially in the lab

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Table 1
Calculated $K^- pp$ binding energies B and widths Γ (in MeV).

	Chiral, energy dependent			Non-chiral, static calculations			
	var. [7]	var. [8]	Fad. [9]	var. [10]	Fad [11]	Fad [12]	var. [13]
B	16	17–23	9–16	48	50–70	60–95	40–80
Γ	41	40–70	34–46	61	90–110	45–80	40–85

system in realistic applications. Therefore, a reliable model extrapolation of $\bar{K}N$ amplitudes into subthreshold energies is mandatory in K^- atom and nuclear applications.

Below I give a brief overview of works on kaonic quasibound systems and kaonic atoms where subthreshold $\bar{K}N$ amplitudes were used in a physically correct way during the last two years. It is shown how the energy dependence of these amplitudes, when translated into density dependence, leads to special patterns in kaonic systems. Finally, I focus attention to the recently proposed $I = 3/2$, $J^\pi = 2^+$ $\Sigma(1385)N$ dibaryon around the $\pi\Sigma N$ threshold [5] and suggest how to search for it in experiments that look for the $I = 1/2$, $J^\pi = 0^-$ $\Lambda(1405)N$ dibaryon, better known as $K^- pp$. In lieu of a concluding section, conclusions are marked in boldface throughout this review.

2. Few-body kaonic quasibound states

A prototype of such states is $K^- pp$ which stands for $\bar{K}NN$ with isospin $I = 1/2$ and spin-parity $J^\pi = 0^-$, dominated by $I_{NN} = 1$ and s waves. A summary of few-body calculations of this system is given in Table 1 updating older versions in recent international conferences [6].

The listed calculations are $\bar{K}NN$ variational (var.) where the complex $\bar{K}N$ interaction accounts for the $\bar{K}N$–$\pi\Sigma$ two-body coupled channels but disregards $\bar{K}NN$–$\pi\Sigma N$ coupling, or fully coupled channels three-body Faddeev (Fad.). A more revealing classification of these calculations is according to whether or not the input two-body interactions are energy dependent. The table makes it clear that the binding energies calculated by using chiral, energy dependent interactions are considerably lower than those calculated using energy independent interactions, the reason for which is the marked difference between the $(\bar{K}N)_{I=0}$ interaction strengths which yield a quasibound state at ≈ 1420 MeV in the former case and at ≈ 1405 MeV in the latter case.

The recent calculations by Barnea et al. [7] include on top of $K^- pp$ also the four-body $\bar{K}NNN$ quasibound states with $I = 0, 1$ and the $I = 0$ lowest $\bar{K}\bar{K}NN$ quasibound state. The calculations were done extending a nuclear hyperspherical basis to include $\bar{K}$ mesons. The A-body wavefunctions were expanded in this complete basis and (real) ground-state binding energies were computed variationally. Convergence was assessed by increasing systematically the size of the basis used. For input two-body interactions, the AV4' V_{NN} was used together with an effective energy-dependent complex $V_{\bar{K}N}$ [14] and a weakly repulsive $V_{\bar{K}\bar{K}}$ [15]. In single-$\bar{K}$ configurations, $V_{\bar{K}N}$ was evaluated at subthreshold energies obtained by expanding Eq. (1) nonrelativistically near $\sqrt{s_{\rm th}}$:

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

where B is the total binding energy of the system and $B_K = -E_K$, $\xi_{N(K)} \equiv m_{N(K)}/(m_N + m_K)$, T_K is the kaon kinetic energy operator in the total cm frame and $T_{N:N}$ is the pairwise NN kinetic energy operator in the NN pair cm system. This expression provides a self-consistency