Overview of $\bar{K}N$ and $\bar{K}$-nucleus dynamics

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Abstract The main features of coupled-channel $\bar{K}N$ dynamics near threshold and its repercussions in few-body $\bar{K}$-nuclear systems are briefly reviewed highlighting the $I = 1/2$ $\bar{K}NN$ system. For heavier nuclei, the extension of mean-field calculations to multi-$\bar{K}$ nuclear quasibound states is discussed focusing on kaon condensation.

Keywords $\bar{K}N$ dynamics · $\bar{K}$-nuclear quasibound states

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1 Introduction

The $\bar{K}$-nucleus interaction near threshold is strongly attractive and absorptive as suggested by fits to the strong-interaction shifts and widths of $K^-$-atom levels [1][2]. Global fits yield extremely deep density dependent optical potentials with nuclear-matter depth $\text{Re}V_{\bar{K}}(\rho_0) \sim -(150-200)$ MeV at threshold. Chirally based coupled-channel models that fit the low-energy $K^-p$ reaction data, and the $\pi\Sigma$ spectral shape of the $\Lambda(1405)$ resonance, yield moderate depths $\text{Re}V_{\bar{K}}(\rho_0) \sim -100$ MeV, as summarized recently in Ref. [3]. A major uncertainty in these chirally based studies arises from fitting the $\Lambda(1405)$ resonance by the imaginary part of the $\pi\Sigma(I = 0)$ amplitude calculated within the same coupled channels chiral scheme. A third class, of shallower potentials with $\text{Re}V_{\bar{K}}(\rho_0) \sim -(40-60)$ MeV, was obtained by imposing a Watson-like self-consistency requirement [4]. However, one needs then to worry about higher orders in the chiral expansion which are not yet in.

I start by making introductory remarks on the $\bar{K}N - \pi\Sigma$ system, followed by reviewing two topics related to $\bar{K}$ nuclear quasibound states: (i) the $K^-pp$ system as a prototype of few-nucleon quasibound states of $\bar{K}$ mesons; and (ii) multi-$\bar{K}$ nucleus quasibound states. In reviewing the latter topic I will discuss the phenomenological evidence for the ‘extremely deep’ $\bar{K}$-nucleus potentials used in nuclear and nuclear-matter calculations.

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2 Polology of $\bar{K}N - \pi \Sigma$ coupled channels

Modern chirally motivated $\bar{K}N - \pi \Sigma$ coupled-channel models give rise to two Gamow poles that dominate low-energy $\bar{K}N$ dynamics. Representative pole positions are shown on the left-hand side of Fig. 1 for the coupled channels model of Ref. [7], together with the trajectories followed by these poles upon scaling the $\bar{K}N$ interactions. This model fits well all the low-energy $K^{-}p$ scattering and reaction data. It reproduces reasonably well the $\pi \Sigma$ spectrum shape, identified with the $\Lambda(1405)\pi \Sigma$ resonance, which is determined primarily by the lower pole at $(1391, -i51)$ MeV. This identification is further supported by the trajectory of the lower pole which merges into an $I = 0$ genuinely bound state below the $\pi^{0}\Sigma^{0}$ threshold when the $\bar{K}N$ interactions are sufficiently increased. The upper pole, in this model, is located above the $K^{-}p$ threshold. However, its position and the trajectory it follows away from the real energy axis are model dependent and sensitive to off-shell effects.\footnote{For example, the pole positions in Ref. [8] are $z_\geq = 1428 - i17$, $z_\leq = 1400 - i76$ MeV.} As discussed below in Sect. 3, the upper pole affects significantly the three-body $[\bar{K}(NN)_{I=1} - \pi \Sigma N]_{I=1/2}$ dynamics of the $K^{-}pp$ system. The energy and width of the ($\bar{K}NN$ quasibound - $\pi \Sigma N$ resonance) state are determined by a Gamow pole whose trajectory, from Ref. [8], is depicted in circles on the right-hand side of Fig. 1. Similarly to the lower-pole $\Lambda(1405)$ trajectory in the two-body case, this three-body pole also merges below the $\pi \Sigma N$ threshold into a genuinely bound state which, upon extending the model space, becomes a quasibound $\pi \Sigma N$ state decaying to lower channels ignored here.\footnote{The other trajectory, depicted in squares, is relevant only to the discussion in Sect. 3.}
The lightest $\bar{K}$ nuclear configuration maximizing the strongly attractive $I = 0$ $\bar{K}N$ interaction is $[\bar{K}(NN)_{I=1}]_{I=1/2, J^P=0^-}$, loosely denoted as $K^{-}pp$. The FINUDA collaboration presented evidence in $K^{-}$ stopped reactions on several nuclear targets for the process $K^{-}pp \rightarrow \Lambda p$, interpreting the observed signal as due to a $K^{-}pp$ deeply bound state with $(B, \Gamma_m) \approx (115, 67)$ MeV [9]. However, this interpretation has been challenged in Refs. [10, 11]. A preliminary new analysis of DISTO $pp \rightarrow K^{+} \Lambda p$ data was presented in EXA08 suggesting a $K^{-}pp$ signal with $(B, \Gamma_m) \approx (105, 118)$ MeV [12].

The location practically on top of the $\pi\Sigma N$ threshold, and particularly the large width, are at odds with any of the few-body calculations listed below, posing a problem for a $K^{-}pp$ quasibound state interpretation.

Results of few-body calculations for the $K^{-}pp$ system are displayed in Table 1. The marked difference between the $\bar{K}NN$ single channel binding energies $B_{K^{-}pp}$ reflects the difference between the input $\bar{K}N$ amplitudes shown in Fig. 2: the Yamazaki-Akaishi $I = 0$ single-pole amplitude [13] resonates at 1405 MeV, whereas the Dote-Hyodo-Weise $I = 0$ amplitude [15] resonates at 1420 MeV (close to the upper of two poles). This dependence on the input amplitudes has been verified in coupled-channel Faddeev calculations [6,19] and in variational calculations [18].

A notable feature of the $K^{-}pp$ coupled-channel calculations [16,17,18] in Table 1 is that the explicit use of the $\pi\Sigma N$ channel adds about $20 \pm 5$ MeV to the binding energy calculated using effective $\bar{K}N$ potential within a single-channel calculation. This is
Fig. 3 Comparisons between density dependent potentials (DD, FB, F) and a $t\rho$ potential fitted to kaonic-atom data [2]. Left: the real part of the $K^-\,^{58}\text{Ni}$ potential. Right: functional derivatives of kaonic atoms $\chi^2$ with respect to the fully complex (Comp, dashed) and real (Re, solid) potential as a function of $\eta = (r - R_c)/a_c$ using $2pF$ charge density distributions.

demonstrated on the right-hand side of Fig. 1 by comparing corresponding points on the two trajectories shown there.

4 $K$-nucleus potentials from kaonic atoms and from nuclear reactions

Figure 3 (left) illustrates the real part of the best-fit $K$-nucleus potential for $^{58}\text{Ni}$ as obtained for several models. The corresponding values of $\chi^2$ for 65 $K^-\text{-atom}$ data points are given in parentheses. A Fourier-Bessel (FB) fit [20] is also shown, within an error band. Just three terms in the FB series, added to a $t\rho$ potential, suffice to achieve a $\chi^2$ as low as 84 and to make the potential extremely deep, in agreement with the density-dependent best-fit potentials DD and F. In particular, the density dependence of potential F provides by far the best fit ever reported for any global $K^-\text{-atom}$ data fit, and the lowest $\chi^2$ value as reached by the model-independent FB method.

The functional derivative (FD) method for identifying the radial regions to which exotic atom data are sensitive is demonstrated in Fig. 3 (right) for the F and $t\rho$ best-fit potentials [20]. It is clear that whereas within the $t\rho$ potential there is no sensitivity to the interior of the nucleus, the opposite holds for the density dependent F potential which accesses regions of full nuclear density. This owes partly to the smaller imaginary part of F, which also explains why the FD for the complex F potential is well approximated by that for its real part.

A fairly new and independent evidence in favor of extremely deep $K$-nucleus potentials is provided by $(K^-, n)$ and $(K^-, p)$ spectra taken at KEK on $^{12}\text{C}$ [21] and very recently also on $^{16}\text{O}$ (presented in PANIC08) at $p_{K^-} = 1$ GeV/c. The $^{12}\text{C}$ spectra are shown in Fig. 4 where the solid lines on the left-hand side represent calculations (outlined in Ref. [22]) using potential depths in the range 160-190 MeV. The dashed lines correspond to using relatively shallow potentials of depth about 60 MeV which I consider therefore excluded by these data.
In conclusion, optical potentials derived from the observed strong-interaction effects in kaonic atoms and from $(K^-, N)$ nuclear spectra are sufficiently deep to support strongly-bound antikaon states. However, a fairly sizable extrapolation is required to argue for $\bar{K}$-nuclear quasibound states at energies of order 100 MeV below threshold, using a potential determined largely near threshold.

5 Multi-$\bar{K}$ nucleus quasibound states from RMF calculations

Relativistic mean field (RMF) calculations of single- and of multi-$\bar{K}$ nuclei are reported in these Proceedings by J. Mareš. Dynamical calculations of single-$\bar{K}$ medium and heavy nuclei produce quasibound states bound by 100-150 MeV for potentials compatible with $K^-$ atom data. These calculations also provide a quantitative estimate of the expected widths, which are larger than 100 MeV near threshold and remain of order 50 MeV or more, even as the primary $\bar{K}N \to \pi\Sigma$ decay mode shuts off at about 100 MeV below threshold. Highlights of multi-$\bar{K}$ nuclear calculations are demonstrated here in Fig 5. On the left-hand side, results of RMF calculations are shown for $2n + \kappa\bar{K}^0$ systems, where all decay channels are suppressed. For $\kappa = 1$, the $\bar{K}^0_{nn}$ system which is charge symmetric to $K^-_{pp}$ was found to be unbound, apparently because RMF calculations do not allow for a $\bar{K}N \to \pi\Sigma$ channel coupling. Binding within these schematic calculations starts at $\kappa = 2$ if isovector degrees of freedom are treated properly (say, using SU(3)) and for $\kappa = 3$ if they are suppressed. The $\bar{K}^0$ separation energy, denoted $B_{\bar{K}^-}$, is found to decrease with $\kappa$ which is a special case of the saturation property established in heavier system, as discussed below.

$K^-$ separation energies $B_{K^-}$ in multi-$K^-$ nuclei $^{40}\text{Ca} + \kappa K^-$ are shown on the right-hand side of Fig. 6 for two choices of $g_{\sigma K}$, designed within each RMF model to produce $B_{K^-} = 100$ and 130 MeV for $\kappa = 1$. A robust saturation of $B_{K^-}$ with $\kappa$, independently of the applied RMF model, emerges from these calculations. The saturation values of $B_{K^-}$ do not allow conversion of $\Lambda$ hyperons to $\bar{K}$ mesons through strong decays $\Lambda \to p + K^-$ or $\Xi^- \to \Lambda + K^-$ in multi-strange hypernuclei, which there-
Fig. 5 RMF calculations of multi-$\bar{K}$ nucleus quasibound states as function of the number $\kappa$ of $\bar{K}$ mesons. Left: for two neutrons, demonstrating the isovector effect. Right: for $^{40}$Ca core, for several nuclear RMF models, with two choices of parameters fixed for $\kappa = 1$ [24].

Therefore remain the lowest-energy configuration for multi-strange systems. This provides a powerful argument against $\bar{K}$ condensation in the laboratory, under strong-interaction equilibrium conditions [24, 25]. It does not apply to kaon condensation in neutron stars, where equilibrium configurations are determined by weak-interaction conditions.

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