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

Avraham Gal

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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.

Avraham Gal
Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
E-mail: avragal@vms.huji.ac.il

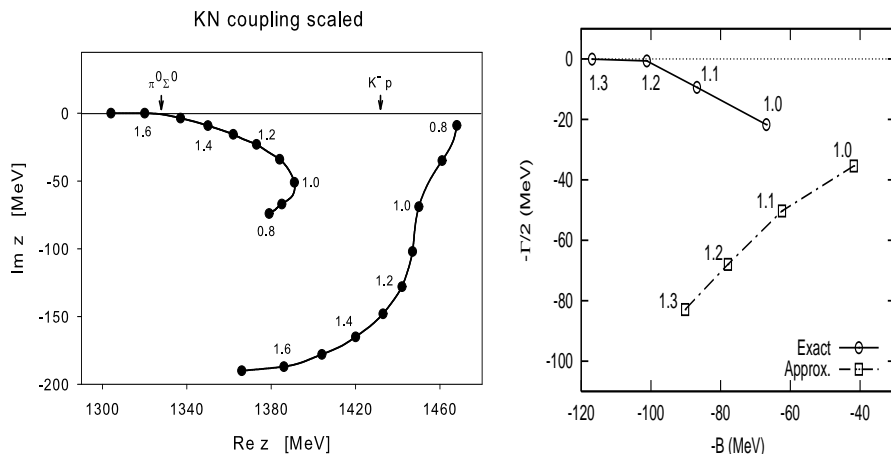


Fig. 1 Left: trajectories of Gamow poles in the complex energy (z) plane, on the Riemann sheet $[\Im k_{\bar{K}N}, \Im k_{\pi\Sigma}] = [+,-]$, upon scaling the $\bar{K}N$ interaction strengths (taken from Ref. [5]). The $\pi^0\Sigma^0$ and K^-p thresholds are marked by arrows. Right: $\bar{K}NN(I=1/2)$ quasibound state energy from Ref. [6] as a function of the $\bar{K}N$ interaction strength within a three-body coupled channel calculation (circles) and within a single channel approximate calculation (squares).

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.¹ 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. [6], 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.²

¹ For example, the pole positions in Ref. [8] are $z_> = 1428 - i17$, $z_< = 1400 - i76$ MeV.

² The other trajectory, depicted in squares, is relevant only to the discussion in Sect. 3.

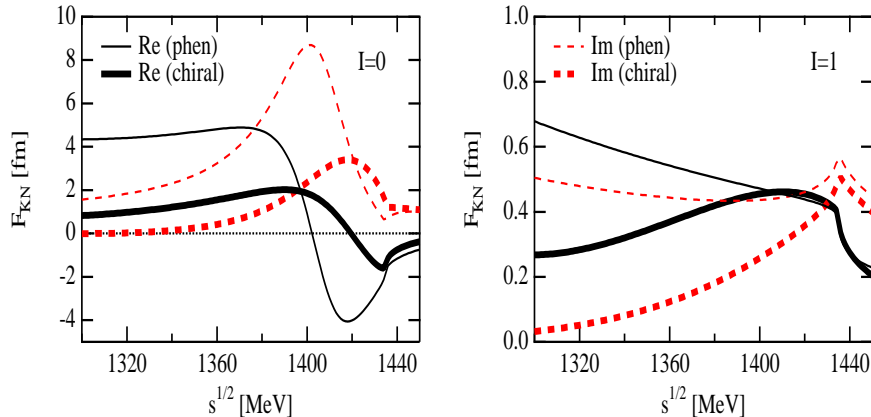


Fig. 2 Comparison of the Yamazaki-Akaishi phenomenological $\bar{K}N$ amplitudes [14] with the Hyodo-Weise chirally based $\bar{K}N$ amplitudes [8]. Figure taken from Ref. [8].

Table 1 Calculated B_{K^-pp} , mesonic (Γ_m) & nonmesonic (Γ_{nm}) widths (in MeV) of K^-pp .

	$\bar{K}NN$ single channel		$\bar{K}NN - \pi\Sigma N$ coupled channels		
	ATMS [13,14]	AMD [15]	Faddeev [16]	Faddeev [17]	variational [18]
B_{K^-pp}	48	17–23	50–70	60–95	40–80
Γ_m	61	40–70	90–110	45–80	40–85
Γ_{nm}	12	4–12			~ 20

3 Few-nucleon \bar{K} systems

The lightest \bar{K} nuclear configuration maximizing the strongly attractive $I = 0$ $\bar{K}N$ interaction is $[\bar{K}(NN)_{I=1}]_{I=1/2, J^\pi=0^-}$, 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 $(B, \Gamma) \approx (115, 67)$ 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 $(B, \Gamma) \approx (105, 118)$ 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 ± 5 MeV to the binding energy calculated using effective $\bar{K}N$ potential within a single-channel calculation. This is

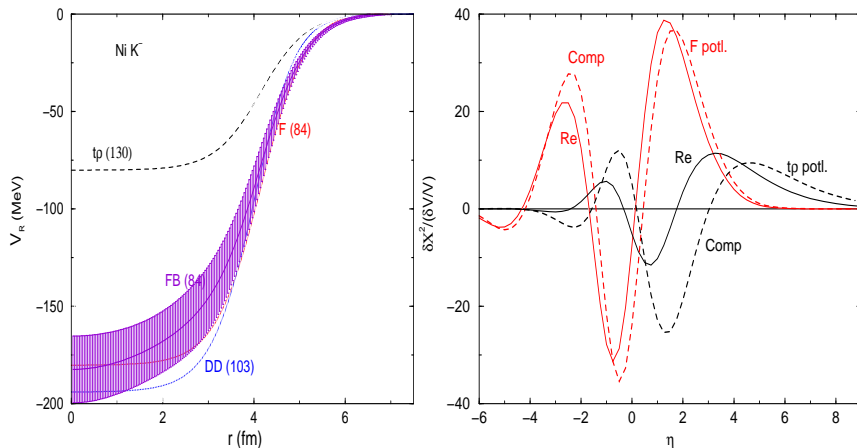


Fig. 3 Comparisons between density dependent potentials (DD, FB, F) and a $t\rho$ potential fitted to kaonic-atom data [2]. Left: the real part of the $\bar{K} - {}^{58}\text{Ni}$ potential. Right: functional derivatives of kaonic atoms χ^2 with respect to the fully complex (Comp, dashed) and real (Re, 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 \bar{K} -nucleus potentials from kaonic atoms and from nuclear reactions

Figure 3 (left) illustrates the real part of the best-fit \bar{K} -nucleus potential for ${}^{58}\text{Ni}$ as obtained for several models. The corresponding values of χ^2 for 65 K^- -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 χ^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^- -atom data fit, and the lowest χ^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 \bar{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 $p_{K^-} = 1 \text{ GeV}/c$. 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.

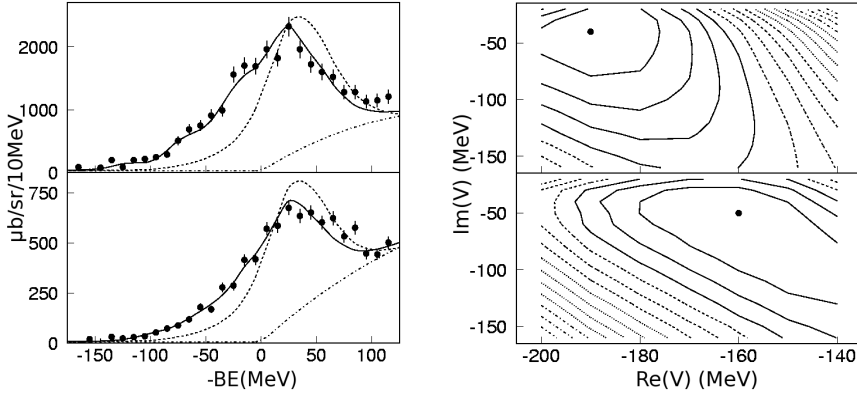


Fig. 4 KEK-PS E548 missing mass spectra (left) and χ^2 contour plots (right) for (K^-, n) (upper) & (K^-, p) (lower) at $p_{K^-} = 1$ GeV/c on ^{12}C [21].

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 $\bar{K}N \rightarrow \pi\Sigma$ decay mode shuts off at about 100 MeV below threshold [10, 23]. 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 $\bar{K}N - \pi\Sigma$ 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 κ 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. 5 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 κ , independently of the applied RMF model, emerges from these calculations. The saturation values of B_{K^-} do not allow conversion of Λ hyperons to \bar{K} mesons through strong decays $\Lambda \rightarrow p + K^-$ or $\Xi^- \rightarrow \Lambda + K^-$ in multi-strange hypernuclei, which there-

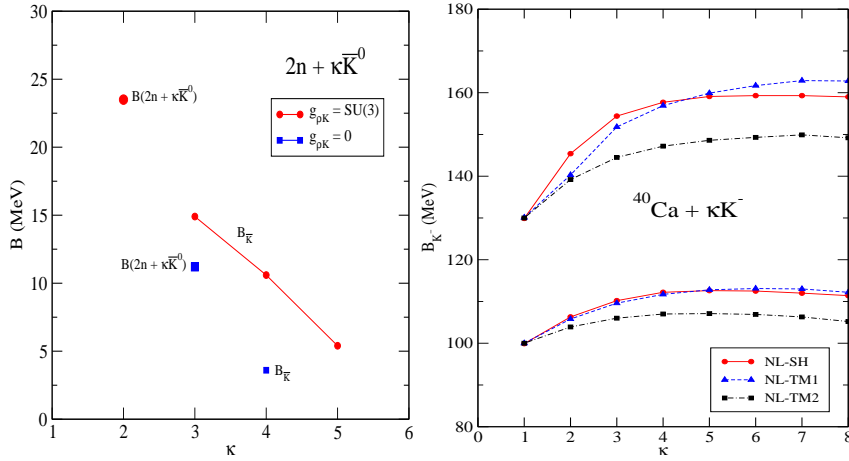


Fig. 5 RMF calculations of multi- \bar{K} nucleus quasibound states as function of the number κ of \bar{K} mesons. Left: for two neutrons, demonstrating the isovector effect. Right: for ^{40}Ca core, for several nuclear RMF models, with two choices of parameters fixed for $\kappa = 1$ [24].

fore 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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