On a quasi-bound state in the K^-np system caused by strong interactions

Nina V. Shevchenko

Nuclear Physics Institute, Řež, Czech Republic

STRANU workshop, 24.05.2021

Interest to antikaon-nucleon systems: quasi-bound state in the K^-pp system
[*Y.Akaishi,T.Yamazaki, Phys.Rev.C65, 044005 (2002)*]
$\rightarrow$ experimental and theoretical efforts with different results

Our contribution: series of dynamically exact calculations of three-body antikaon-nucleon systems

- Quasi-bound states in $\bar{K}NN$, spin 0 ($K^-pp/\bar{K}^0np$) and $\bar{K}\bar{K}N$ systems - binding energy and width
- No quasi-bound state in $\bar{K}NN$, spin 1 ($K^-np/\bar{K}^0nn$) - proven
- Near-threshold scattering in $\bar{K}NN$, spin 1 (K^-d)
(Faddeev-type AGS equations with coupled $\bar{K}NN - \pi\Sigma N$ channels)
- $1s$ level shift and width of kaoninc deuterium (Faddeev-type equations with directly included Coulomb interaction)

[N.V. S., Three-Body Antikaon–Nucleon Systems, Few Body Syst. 58, 6 (2017)]

No quasi-bound state in $\bar{K}NN$, spin 1 ($K^- np$) - proven

$K^- np$ quasi-bound state caused by strong interactions: $\leftrightarrow$ kaonic deuterium (an atom, Coulomb is the main interaction, is known)

Evidence

Faddeev calculations of the $K^- d$ scattering length $a_{K^- d}$ – evidence that a "strong" quasi-bound state in $K^- np$ could exists:

- Analytical continuation of the effective range formula below the $K^- d$ threshold $\to$ $K^- np$ quasi-bound state with binding energy 14.6 – 19.6 MeV, width 15.6 – 22.0 MeV should exist
- Systematic search for these states using three-body coupled-channel AGS equations $\to$ no (corresponding) poles in the complex energy plane

The reason of discrepancy: effective range formula is valid in the vicinity of the corresponding threshold (*expected large binding energy and width - out of the validity region*)

Strength constant of $V_{\bar{K}N-\pi\Sigma}$ changed by hands:

$$\lambda_{I=0}^{\bar{K}N,\bar{K}N} \to c\,\lambda_{I=0}^{\bar{K}N,\bar{K}N},\ c = 1.25..1$$

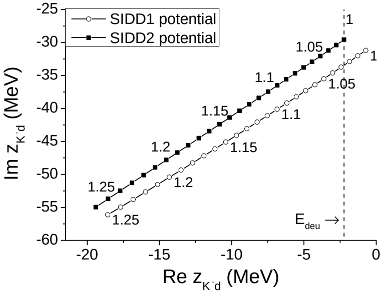


Fig: Pole trajectories in the $K^- np$ system for increasing absolute value of the $\lambda_{I=0}^{\bar{K}\bar{K}}$ strength constant of the phenomenological $V_{\bar{K}N-\pi\Sigma}^{1,SIDD}$ and $V_{\bar{K}N-\pi\Sigma}^{2,SIDD}$ potentials. The numbers along the trajectories indicate the multiplication factors. Quasi-bound states are the poles to the left of the $K^- d$ threshold.

Next step – four-body calculations of the $\bar{K}NNN$ system using Faddeev-type equations. New NN potential constructed and used (V_{NN} by *P. Doleschall* was used before) → quasi-bound state in the $K^- np$ subsystem caused by strong interactions was found

Two-term Separable New potential (TSN) of nucleon-nucleon interaction

$$V_{NN}^{\rm TSN}(k,k') = \sum_{m=1}^{2} g_m(k)\,\lambda_m\;g_m(k')\,,$$

$$g_m(k) = \sum_{n=1}^{3} \frac{\gamma_{mn}}{(\beta_{mn})^2+k^2}, \quad \text{for } m=1,2$$

fitted to Argonne $V18$ potential *[R.B. Wiringa, V.G.J. Stoks, R. Schiavilla, Phys. Rev. C 51, 38 (1995)]* phase shifts

Triplet and singlet scattering lengths a and effective ranges $r_{\rm eff}$

$$a_{np}^{\rm TSN} = -5.400\,{\rm fm}, \qquad r_{{\rm eff},np}^{\rm TSN} = 1.744\,{\rm fm}$$
$$a_{pp}^{\rm TSN} = 16.325\,{\rm fm}, \qquad r_{{\rm eff},pp}^{\rm TSN} = 2.792\,{\rm fm},$$

deuteron binding energy $E_{\rm deu} = 2.2246$ MeV.

New NN potential

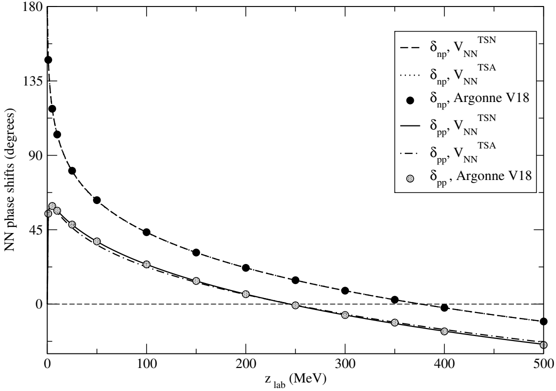


Fig: Phase shifts of *np* and *pp* scattering calculated using the new V_{NN}^{TSN} and $V_{NN}^{\mathrm{TSA-B}}$ potentials plus phase shifts of Argonne $V18$

Antikaon-nucleon interaction

Three potentials

- phenomenological $\bar{K}N - \pi\Sigma$ with one-pole $\Lambda(1405)$ resonance
- phenomenological $\bar{K}N - \pi\Sigma$ with two-pole $\Lambda(1405)$ resonance
- chirally motivated $\bar{K}N - \pi\Sigma - \pi\Lambda$ potential, two-pole $\Lambda(1405)$

reproduce (with the same level of accuracy):

- $1s$ level shift and width of kaonic hydrogen *(SIDDHARTA)*
  direct inclusion of Coulomb interaction, no Deser-type formula used
- Cross-sections of $K^- p \to K^- p$ and $K^- p \to MB$ reactions
- Threshold branching ratios γ, R_c and R_n
- ◦ $\Lambda(1405)$ resonance (*one- or two-pole structure*)
  $M^{PDG}_{\Lambda(1405)} = 1405.1^{+1.3}_{-1.0}$ MeV, $\Gamma^{PDG}_{\Lambda(1405)} = 50.5 \pm 2.0$ MeV [*PDG (2016)*]

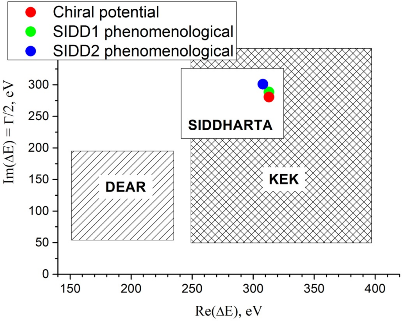


Fig: Experimental and theoretical $1s$ level shift and width of kaonic hydrogen given by the three $\bar{K}N$ potentials

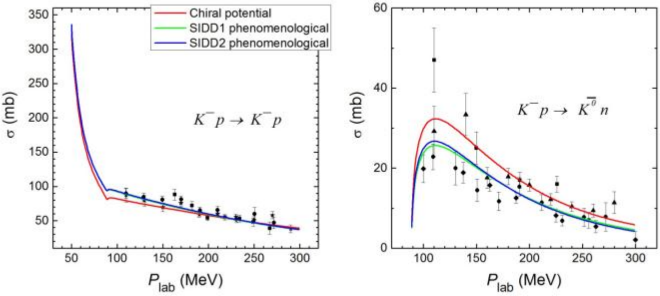
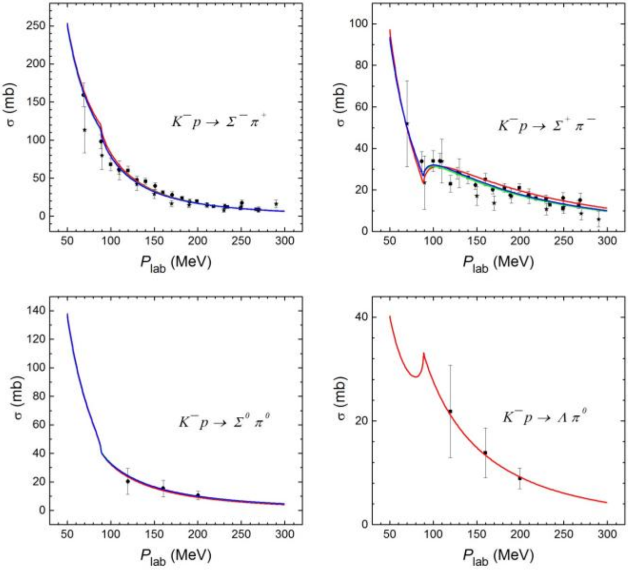


Fig: Comparison with the experimental data on $K^- p$ cross-sections (phenomenological and chirally motivated potentials)

K^-p cross-sections: theory vs. experiment



Antikaon-nucleon potentials: strong pole(s)

Table: Strong poles ($\Lambda(1405)$) given by the three antikaon-nucleon potentials (MeV)

	z_{pole1}	z_{pole2}
$V^{1,\text{SIDD}}_{\bar{K}N}$	$1426 - i\,48$	–
$V^{2,\text{SIDD}}_{\bar{K}N}$	$1414 - i\,58$	$1386 - i\,104$
$V^{\text{Chiral}}_{\bar{K}N}$	$1417 - i\,33$	$1406 - i\,89$

"Experimental" value:

$M^{PDG}_{\Lambda(1405)} = 1405.1^{+1.3}_{-1.0}$ MeV, $\Gamma^{PDG}_{\Lambda(1405)} = 50.5 \pm 2.0$ MeV

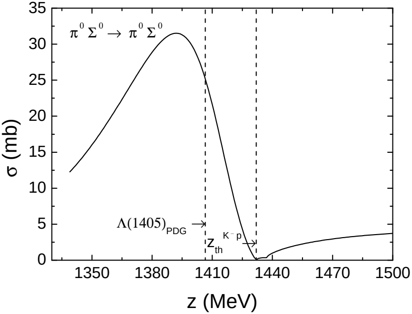


Fig: Elastic $\pi^0\Sigma^0$ cross-sections of the chirally motivated potential $V^{\rm Chiral}_{\bar{K}N}$ – $\Lambda(1405)$ resonance.

Three-body Faddeev-type Alt-Grassberger-Sandhas equations,
solved separtely

$$U_{ij}^{\alpha\beta} = \delta_{\alpha\beta}\,(1-\delta_{ij})\,(G_0^{\alpha})^{-1} + \sum_{k,\gamma=1}^{3} (1-\delta_{ik})\,T_k^{\alpha\gamma}\,G_0^{\gamma}\,U_{kj}^{\gamma\beta}, \quad i,j = 1,2,3,$$

particle channels:

$$\alpha = 1 : |\bar{K}_1 N_2 N_3\rangle,\ \alpha = 2 : |\pi_1 \Sigma_2 N_3\rangle,\ \alpha = 3 : |\pi_1 N_2 \Sigma_3\rangle$$

Input: two-body T-matrices, corresponding to $V_{\bar{K}N-\pi\Sigma(-\pi\Lambda)}$ (three versions), V_{NN}^{TSN} (new), $V_{\Sigma N(-\Lambda N)}$ (isospin-dependent and spin-independent, parameters fitted to experimental cross-sections)

Quantum numbers:

spin $S = 1$, orbital momentum $L = 0$, isospin $I = 1/2$:

- $\bar{K}NN$ system with $J^{\pi} = 1^{-}$ (isospin representation)
- $K^{-}np/\bar{K}^{0}nn$ system (particle representation)

Table: Binding energy B_{K^-np} (MeV) and width Γ_{K^-np} (MeV) of the quasi-bound state in the $K^- pn$ system: coupled-channel $\bar{K}NN - \pi\Sigma N$ calculation and one-channel $\bar{K}NN$ with exact optical $V^{\text{Opt}}_{\bar{K}N}$; $z_{th,\text{K}^-\text{d}} = m_{\bar{K}} + 2\, m_N + E_{\text{deu}}$.

	Coupled-channels calculation		With exact optical $\bar{K}N$ potential	
	B_{K^-np}	Γ_{K^-np}	B_{K^-np}	Γ_{K^-np}
$V^{1,\text{SIDD}}_{\bar{K}N}$	–	–	0.8	68.3
$V^{2,\text{SIDD}}_{\bar{K}N}$	0.9	59.4	3.8	63.2
$V^{\text{Chiral}}_{\bar{K}N}$	1.3	41.8	0.9	43.6

[N.V. S., Few Body Syst. 61, 27 (2020)]

Table: Binding energy B_{K^-pp} (MeV) and width Γ_{K^-pp} (MeV) of the quasi-bound state in the $K^- pp$ system: coupled-channel $\bar{K}NN - \pi\Sigma N$ calculation and one-channel $\bar{K}NN$ with exact optical $V^{\rm Opt}_{\bar{K}N}$; $z_{th,\mathrm{K^-pp}} = m_{\bar{K}} + 2\,m_N$.

	Coupled channels calculation		With exact optical $\bar{K}N$ potential		Our previous coupled-channel results	
	B_{K^-pp}	Γ_{K^-pp}	B_{K^-pp}	Γ_{K^-pp}	B_{K^-pp}	Γ_{K^-pp}
$V^{1,\rm SIDD}_{\bar{K}N}$	52.18	67.1	53.29	63.3	53.29	64.9
$V^{2,\rm SIDD}_{\bar{K}N}$	46.56	51.2	46.65	47.4	47.45	49.8
$V^{\rm Chiral}_{\bar{K}N}$	29.43	46.4	30.01	46.6	32.24	48.6

Summary

- quasi-bound K^-np state caused by strong interactions was predicted, its binding energy is small ($1-2$ MeV), while the width ($40-60$ MeV) is comparable with the width of the K^-pp quasi-bound state
- the particular model of V_{NN} plays a minor role in the K^-pp system
- the same is true for the K^-np system, but since the quasi-bound state there is situated so close to the threshold, V_{NN} can resolve the question of the K^-np quasi-bound state existence
- the quasi-bound K^-np state caused by strong interactions is stronger bound and is much broader than kaonic deuterium, therefore, the atomic and the strong quasi-bound states cannot be misidentified