On K^--nuclear interaction, K^--nuclear quasibound states and K^- atoms

Jaroslava Óbertová

Nuclear Physics Institute of CAS, Řež
Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University in Prague

Àngels Ramos
University of Barcelona

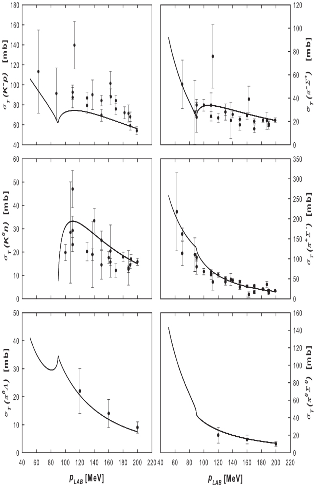
Eliahu Friedman
Hebrew University, Jerusalem

Jiří Mareš
NPI, Řež

HYP2022, June 27 - July 1, 2022, Prague, Czech Republic

$K^- N$ interactions

$K^- p$ scattering:



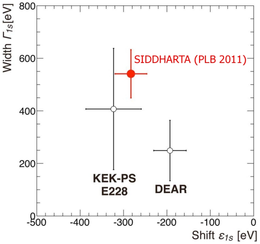
Threshold branching ratios:

$$\gamma = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \frac{\Gamma(K^- p \to \text{charged})}{\Gamma(K^- p \to \text{all})} = 0.664 \pm 0.011$$

$$R_n = \frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutral})} = 0.189 \pm 0.015$$

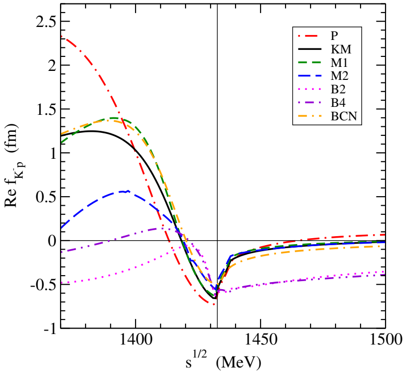
Kaonic hydrogen:

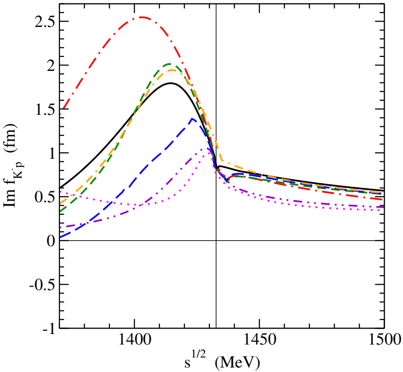


- $K^- p$ data well described by several chiral models

  A. Cieplý, M. Mai, U.-G. Meissner, J. Smejkal, NPA 945 (2016) 17

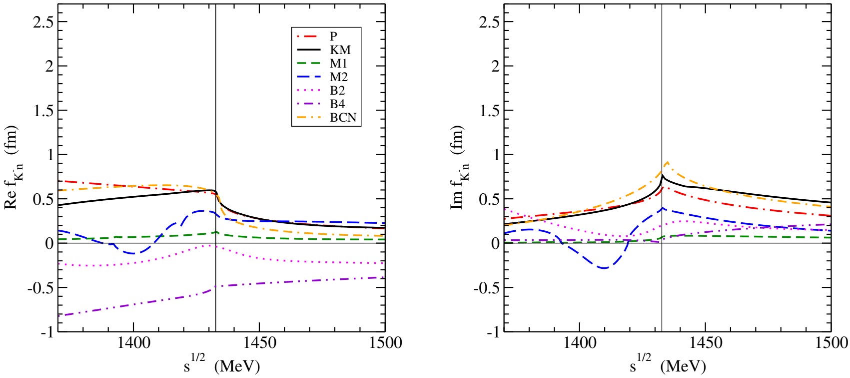
Free-space $K^- p$ amplitudes in various chiral models





Prague (P)	*A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115*
Kyoto-Munich (KM)	*Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98*
Murcia (M1 and M2)	*Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202*
Bonn (B2 and B4)	*M. Mai, U.-G. Meißner, Nucl. Phys. A 900 (2013) 51*
Barcelona (BCN)	*A. Feijoo, V. Magas, A. Ramos, Phys. Rev. C 99 (2019) 035211*

Free-space $K^- n$ amplitudes



Kaonic atoms

- Info about K^-N interaction below threshold provided by kaonic atoms

  65 data points (energy shifts, widths, yields=upper level widths) from CERN, Argonne, RAL, BNL

- Chirally motivated models fail to describe kaonic atom data

  E. Friedman, A. Gal, NPA 959 (2017) 66

model	B2	B4	M1	M2	P	KM
$\chi^2(65)$	1174	2358	2544	3548	2300	1806

Multinucleon processes

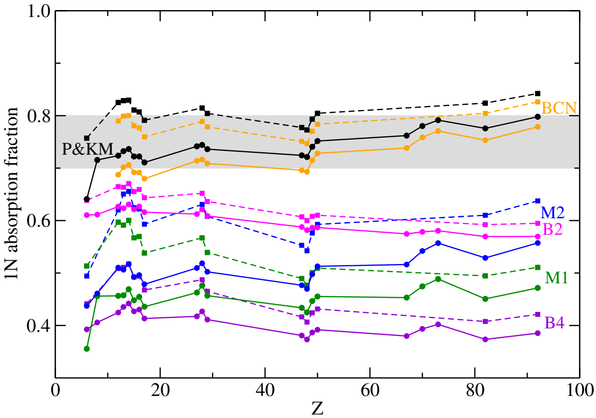
- Chiral models include only $K^- N \rightarrow \pi Y$ $(Y = \Lambda, \Sigma)$ decay channel
- K^- interactions with two and more nucleons should be included, (e.g., $K^- + N + N \rightarrow Y + N$) $\leftarrow$ analysis of kaonic atom data
  E. Friedman, A. Gal, NPA 959 (2017) 66

$$V^{\mathrm{phen}}_{K^-\mathrm{multiN}} = -4\pi B(\frac{\rho}{\rho_0})^{\alpha}\rho \ ,$$

where B is a complex amplitude, ρ is nuclear density distribution, ρ_0 is saturation density and α is positive

- $\chi^2(65)$ goes down to 105 - 125

Single- vs. multi-nucleon processes



- Fraction of *single-nucleon* absorption 0.75 ± 0.05 (average value) used as an additional constraint.

$\rightarrow$ Only P, KM and BCN models found acceptable in kaonic atom analysis

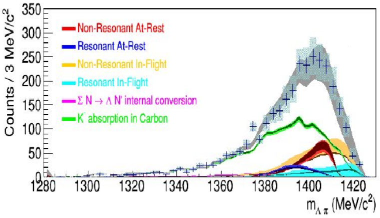
E. Friedman, A. Gal, NPA 959 (2017) 66

AMADEUS@DAΦNE

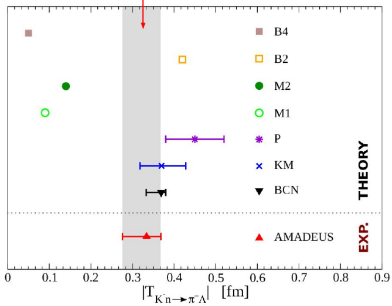
K. Piscicchia, talk at THEIA-STRONG2020 Web-Seminar,20 December 2020

Outcome of the measurement

Investigated using: **K⁻ "n"** ^{3}He → **Λπ⁻** ^{3}He



$|f^s_{ar}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\ \mathrm{fm}$.



[K. Piscicchia, S. Wycech, L. Fabbietti et al. Phys.Lett. B782 (2018) 339-345]
[K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954 (2016) 75-93]

K^- in many-body systems

- free chiral $K^- N$ amplitudes

  $\Downarrow$

  in-medium $K^- N$ amplitudes $\rightarrow$ accounting for Pauli principle (WRW method *T. Wass, M. Rho, W. Weise, NPA 617 (1997) 449*)

  $\Downarrow$

  K^- optical potential $V_{K^-} = V_{K^- N} + V^{\mathrm{phen}}_{K^- \mathrm{multiN}}$

  $\Downarrow$

  self-consistent solution of Klein-Gordon equation

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

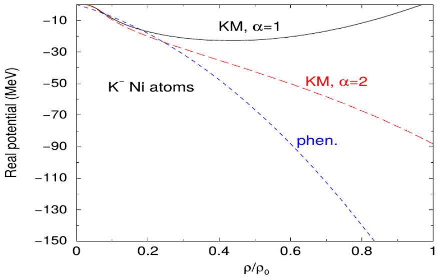
$\Pi_K(\vec{p}_K, \omega_K, \rho) = 2\mathrm{Re}(\omega_K) V_{K^-}$,

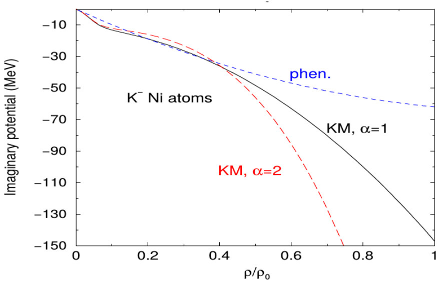
complex energy $\tilde{\omega_K} = m_K - B_K - \mathrm{i}\Gamma_K/2 - V_C = \omega_K - V_C$

- nucleus described within the Relativistic Mean-Field model

K^- in many-body systems

- K^- bound inside a nucles probes densities around saturation density ρ_0
- Experiments with kaonic atoms probe the K^- optical potential (mainly its imaginary part) up to $\sim 50\%$ of ρ_0





Multinucleon processes

- Two limiting cases for $V^{\mathrm{phen}}_{K^-\mathrm{multiN}}$ considered in calculations of kaonic nuclei:

  J. Hrtánková, J. Mareš, PLB 770 (2017) 342; PRC 96 (2017) 015205

  - full density option (FD) – $B(\rho/\rho_0)^\alpha\rho$ form in the entire nucleus
  - half density limit (HD) – fix $V^{phen}_{K^-\mathrm{multiN}}$ at constant value $V^{\mathrm{phen}}_{K^-\mathrm{multiN}}(0.5\rho_0)$ for $\rho(r) \geq 0.5\rho_0$

- self-consistent calculations performed using P and KM models for $\alpha = 1$ and $\alpha = 2$
- ImB multiplied by a kinematical suppression factor to account for phase space reduction

K^- 1s binding energies and widths in various nuclei

Table 1: 1s K^- binding energies B_{K^-} and widths Γ_{K^-} (in MeV) in various nuclei calculated using the single nucleon K^-N amplitudes (denoted KN); plus K^- multinucleon amplitude $B(\rho/\rho_0)^\alpha$, where $\alpha = 1$ and 2, for the HD and FD options.

KM model			$\alpha = 1$		$\alpha = 2$	
		KN	HD	FD	HD	FD
^{16}O	B_{K^-}	45	34	not	48	not
	Γ_{K^-}	40	109	bound	121	bound
^{40}Ca	B_{K^-}	59	50	not	64	not
	Γ_{K^-}	37	113	bound	126	bound
^{208}Pb	B_{K^-}	78	64	33	80	53
	Γ_{K^-}	38	108	273	122	429
P model			$\alpha = 1$		$\alpha = 2$	
^{16}O	B_{K^-}	64	49	not	63	not
	Γ_{K^-}	25	94	bound	117	bound
^{40}Ca	B_{K^-}	81	67	not	82	not
	Γ_{K^-}	14	95	bound	120	bound
^{208}Pb	B_{K^-}	99	82	36	96	47
	Γ_{K^-}	14	92	302	117	412

Microscopic model for $K^- NN$ absorption in nuclear matter

- K^- multi-nucleon absorption fraction in the surface region of atomic nuclei represents about 20%

  NC 53 (1968) 313 (Berkeley), *NPB 35 (1971) 332 (BNL)*, *NC 39A (1977) 538 (CERN)*

- K^- multi-nucleon absorption in atoms described by phenomenological optical potential

  E. Friedman, A. Gal, NPA 959 (2017) 66

- Model for $K^- NN$ absorption in nuclear matter using free-space chiral amplitudes

  T. Sekihara et al., PRC 86 (2012) 065205

- Solid microscopic model for $K^- NN$ absorption needed!

Microscopic model for $K^- NN$ absorption in nuclear matter

Microscopic model for K^- two-nucleon absorption in symmetric nuclear matter *J. Hrtánková, À. Ramos, PRC 101 (2020) 035204*

- based on a meson-exchange approach
  H. Nagahiro et al., PLB 709 (2012) 87
- P and BCN chiral $K^- N$ amplitudes employed
- Pauli correlations in the medium for $K^- N$ amplitudes considered
- real part of the $K^- NN$ optical potential evaluated as well
- $K^- N$ optical potential derived within the same approach

$K^- N$ absorption in nuclear matter

$$K^- N \to \pi Y \quad (Y = \Lambda, \Sigma)$$

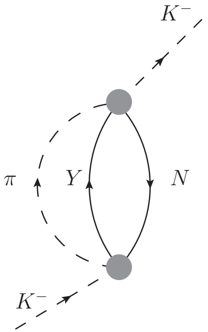


Fig.1: Feynman diagram for K^- absorption on a single nucleon in nuclear matter. The shaded circles denote the $K^- N$ t-matrices derived from a chiral model.

K^-NN absorption in nuclear matter

$$K^- + N + N \to Y + N \quad (Y = \Lambda, \Sigma)$$

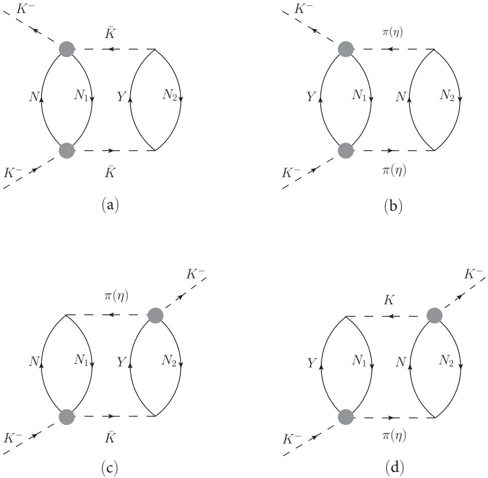


Fig.2: Two-fermion-loop (2FL) Feynman diagrams for non-mesonic K^- absorption on two nucleons N_1, N_2 in nuclear matter. The shaded circles denote the K^-N t-matrices derived from a chiral model.

$K^- NN$ absorption in nuclear matter

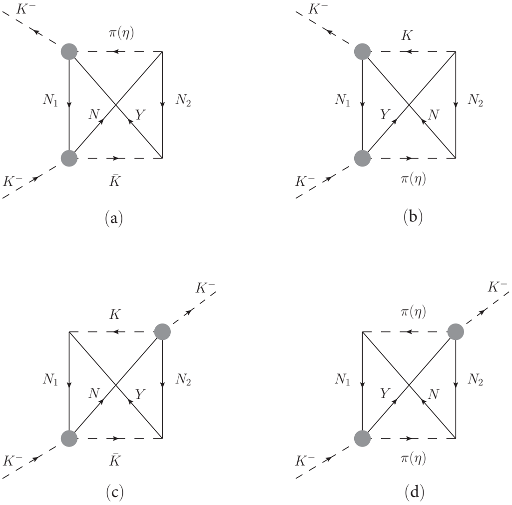


Fig.3: One-fermion-loop (1FL) Feynman diagrams for non-mesonic K^- absorption on two nucleons N_1, N_2 in nuclear matter. The shaded circles denote the $K^- N$ t-matrices derived from a chiral model.

$K^- NN$ absorption in nuclear matter

- $V_{K^-N} = \sum_{channels} V_{K^-N \to \pi Y}$ (Fig.1)
- $V_{K^-NN} = \sum_{\mathrm{channels}} V^{\mathrm{2FL}}_{K^-NN} + V^{\mathrm{1FL}}_{K^-NN}$ (Fig.2 and 3)

  $\to$ contributions from 37 2FL and 28+33 1FL diagrams

Table 2: All considered channels for mesonic and non-mesonic K^- absorption in matter.

K^-N	$\to \pi Y$	$K^-N_1N_2$	$\to YN$
K^-p	$\to \pi^0\Lambda$	K^-pp	$\to \Lambda p$
	$\to \pi^0\Sigma^0$		$\to \Sigma^0 p$
	$\to \pi^+\Sigma^-$		$\to \Sigma^+ n$
	$\to \pi^-\Sigma^+$	$K^-pn(np)$	$\to \Lambda n$
K^-n	$\to \pi^-\Lambda$		$\to \Sigma^0 n$
	$\to \pi^-\Sigma^0$		$\to \Sigma^- p$
	$\to \pi^0\Sigma^-$	K^-nn	$\to \Sigma^- n$

AMADEUS: Ratio for 2N absorption

Recently measured ratio *R. Del Grande et al., EPJ C79 (2019) 190*

$$R = \frac{\mathrm{BR}(K^- pp \to \Lambda p)}{\mathrm{BR}(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2(\mathrm{stat.})^{+0.2}_{-0.3}(\mathrm{syst.})$$

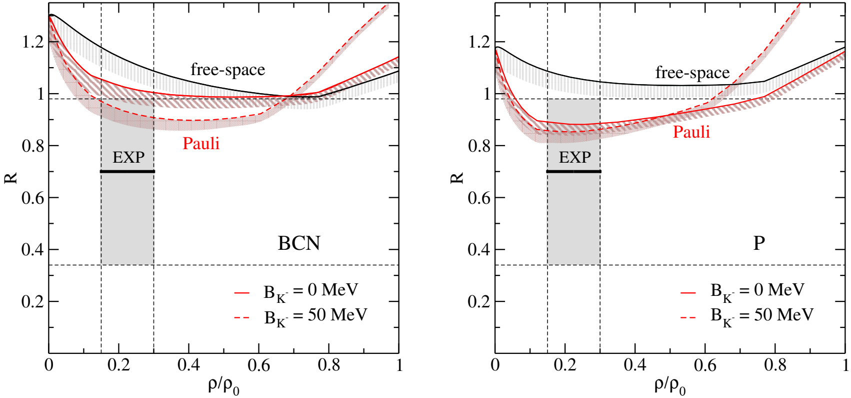


Fig.4: The ratio R as a function of relative density, calculated using the free-space and Pauli blocked amplitudes for $B_{K^-} = 0$ MeV and $B_{K^-} = 50$ MeV. Color bands denote the uncertainty due to different cut-off values $\Lambda_c = 800 - 1200$ MeV.

Application to kaonic atoms

- $K^- NN$ model applied in calculations of energy shifts and widths in kaonic atoms
- BCN amplitudes used $\rightarrow$ in-medium modifications included (Pauli or WRW *T. Wass, M. Rho, W. Weise, NPA 617 (1997) 449*)
- microscopic $K^- N + K^- NN$ potentials calculated for 23 targets and confronted with kaonic atom data
- $K^- N + K^- NN$ potentials then supplemented by a phenomenological term describing 3 and 4 nucleon processes $\sim -4\pi B(\frac{\rho}{\rho_0})^\alpha \rho$
- values of α and complex amplitude B fitted to data

Confrontation with kaonic atom data

Table 3: Values of $\chi^2(65)$ resulting from comparisons of predictions with kaonic atom data using K^-N, $K^-N + K^-NN$, and $K^-N + K^-NN$+phen. multiN potentials. Values of complex amplitude B and parameter α for potentials based on Pauli blocked and WRW modified BCN amplitudes.

	K^-N	$K^-N + K^-NN$	+ phen.	ReB (fm)	ImB (fm)	α
Pauli	825	565	105	-1.97(13)	-0.93(11)	1.4
WRW	2378	1123	116	-0.90(9)	0.72(10)	0.6

- best fit K^-N + phen. multiN potential based on BCN amplitudes
  ReB = -1.3 fm, ImB = 1.9 fm, $\alpha = 1$, $\chi^2 = 112.3$

Calculated branching ratios in ^{12}C+K^- atom

Table 4: Primary-interaction branching ratios (in %) for mesonic ($K^-N \rightarrow Y\pi$, $Y = \Lambda, \Sigma$) and non-mesonic absorption ($K^-NN \rightarrow YN$) of K^- in ^{12}C+K^- atom (l=2), calculated with $K^-N + K^-NN$ potentials based on WRW and Pauli blocked BCN and P amplitudes.The experimental data corrected for primary interaction are shown for comparison.

^{12}C + K^- (l=2)	BCN		P		Exp. [1]	
mesonic ratio	WRW	Pauli	WRW	Pauli	^{4}He	^{12}C
$\Sigma^+\pi^-$	26.9	22.4	28.1	22.1	31.2 ± 5.0	29.4 ± 1.0
$\Sigma^-\pi^0$	8.3	7.7	7.2	5.9	4.9 ± 1.3	2.6 ± 0.6
$\Sigma^-\pi^+$	15.5	17.5	17.1	17.6	9.1 ± 1.6	13.1 ± 0.4
$\Sigma^0\pi^-$	8.4	7.9	7.3	5.9	4.9 ± 1.3	2.6 ± 0.6
$\Sigma^0\pi^0$	17.2	16.4	19.3	17.3	17.7 ± 2.9	20.0 ± 0.7
$\Lambda\pi^0$	5.2	5.0	4.2	3.7	5.2 ± 1.6	3.4 ± 0.2
$\Lambda\pi^-$	10.4	9.9	8.3	7.2	10.5 ± 3.0	6.8 ± 0.3
total 1N ratio	91.9	87.0	90.7	82.0	83.5 ± 7.1	77.9 ± 1.6

non-mesonic ratio	WRW	Pauli	WRW	Pauli	76% CF_3Br + 24% C_3H_8 [2]
$\Lambda p + \Lambda n + \Sigma^0 p + \Sigma^0 n$	4.2	6.7	4.6	9.0	14.1 ± 2.5 [a]
$\Sigma^- p + \Sigma^- n$	1.7	3.1	2.1	4.2	7.3 ± 1.3 [a]
$\Sigma^+ n$	2.2	3.5	2.6	4.8	4.3 ± 1.2 [a]
$\Sigma^0 p + \Sigma^0 n$	1.9	3.1	2.2	4.2	-
total 2N ratio	8.1	13.0	9.3	18.0	$16 \pm 3(\text{stat.})^{+4}_{-5}(\text{syst.})$ [3]

[a] multinucleon capture rate

[1] *C. Vander Velde-Wilquet et al., NC 39 A (1977) 538*

[2] *H. Davis et al., NC 53 A (1968) 313*

[3] *R. Del Grande et al., EPJ C79 (2019) 190*

Summary

- K^-N interaction described by chiral meson-baryon coupled channel interaction models
- Interactions of K^- with two and more nucleons important for realistic description of the K^--nucleus interaction
  - only P, KM, and BCN models compatible with available data
- Calculations of K^--nuclear quasi-bound states in various nuclei
- K^- multinucleon interactions inside the nucleus included:
  - K^- nuclear quasi-bound states in many-body systems, if they ever exist, have huge widths, considerably exceeding their binding energies

Summary

- We have developed a microscopic model for $K^- NN$ absorption in nuclear matter using amplitudes derived from the P and BCN chiral meson-baryon interaction models

  J. Hrtánková, À. Ramos, PRC 101 (2020) 035204

  - Pauli blocked amplitudes included $\rightarrow$ medium effects non-negligible

- Microscopic $K^- N + K^- NN$ potentials confronted with kaonic atom data
  - the description of kaonic atoms improves considerably when microscopic $K^- NN$ potentials are included (χ^2 drops down twice)
  - microscopic $K^- N + K^- NN$ potentials still have to be supplemented by a phenomenological term to account for K^--3N (4N) processes and to get χ^2/d.p.≤ 2

- Further improvements of the $K^- NN$ model $\rightarrow$ inclusion of hadron self-energies in progress!