Overview of Strong Interaction from Kaonic Atoms

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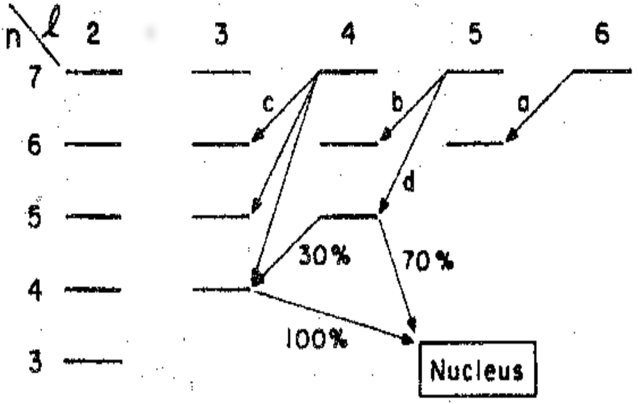
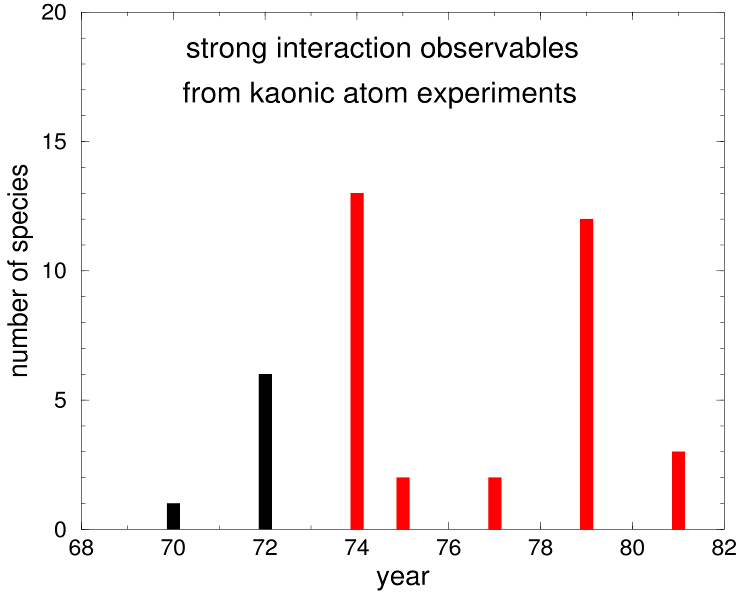
OUTLINE

- Experimental introduction.
- Early phenomenological analyses.
  Deep or shallow?
  Kaon condensation in neutron stars? (1995)
  Conflicts with more fundamental approaches (2000).
- Going sub-threshold *systematically.* (2011)
  Several models for chiral amplitudes.
  Mixed chiral and phenomenological approaches.
  Ambiguities.
- Additional data: single-nucleon absorption fractions.
  Ambiguities removed. (2017)
  Some consequences.
- Concluding remarks.

Schematics of exotic-atom energy levels



Following NPA231 (1974) 477



strong interaction observables
from kaonic atom experiments
number of species
year
0
5
10
15
20
68
70
72
74
76
78
80
82

Comments on experiments

- Results from CERN, Argonne, Rutherford Lab., BNL
- Use weighted averages
- Good accuracies for shifts and widths
- Reasonable accuracies for yields (= upper level widths)

Puzzles with early data for H and He removed by new precision experiments at KEK and Frascati between 1997 and 2007.

The simplest optical potential:

$$2\mu V_{\rm opt}(r) = -4\pi(1 + \frac{A-1}{A}\frac{\mu}{M})\{b_0[\rho_n(r) + \rho_p(r)] + b_1[\rho_n(r) - \rho_p(r)]\} .$$

ρ_n and ρ_p are the neutron and proton density distributions, M is the mass of the nucleon, μ is the reduced mass.

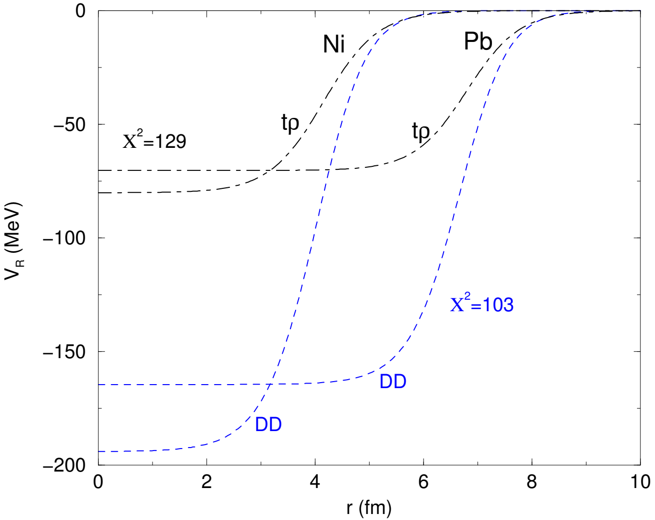
Global fits to kaonic atom data usually cannot determine b_1.
Good fits (χ^2=129 for 65 points) lead to

$$b_0 = 0.63 \pm 0.06 + \mathrm{i}\ (0.89 \pm 0.05)\ \mathrm{fm},$$

which in the impulse approximation is minus the scattering amplitude at threshold.
From phase-shifts $b_0 = -0.15 + \mathrm{i}\ 0.62$ fm.

The low-density limit is not respected.

Replace $b_0 \to b_0 + B_0[\rho(r)/\rho_0]^\alpha$ and vary B_0 and α.



Smaller changes in imaginary potentials.

Consequences of very deep real potential:

- Is it reliable?
- Possible kaon condensation at $\rho = 3\rho_0$ in neutron stars. Much interest in 1995; currently of not much interest.
- Possibility of strongly bound anti kaons in nuclei. Expect huge widths. Still somewhat controversial.

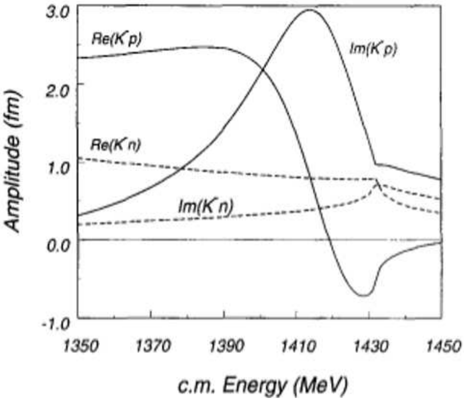
Early attempts to use 'chiral' amplitudes

Ramos & Oset, NPA 671 (2000) 481
Baca et al., NPA 673 (2000) 335
Cieply et al.,NPA 696 (2001) 173

- Poor agreement with data ($\chi^2(65)$=300)
- Reduced χ^2 to 200 with typical 50% rescaling
- χ^2=130 by adding a $t\rho$ term with NEGATIVE absorption

Something is missing!

Early example of chiral amplitutes
Kaiser, Siegel, Weise, NPA 594 (1995) 325



Reminder of 'in-medium kinematics'

Adopt the Mandelstam variable $s = (E_{K^-} + E_N)^2 - (\vec{p}_{K^-} + \vec{p}_N)^2$ as the argument transforming free-space to in-medium $K^- N$ amplitudes.

In the kaonic-atom c.m. frame the average of $(\vec{p}_{K^-} + \vec{p}_N)^2$ is

the average of $\vec{p}_N^{\,2} + \frac{A-2}{A}\vec{p}_{K^-}^{\,2}$

thus reducing further the relevant energy.

Reminder of 'in-medium kinematics'

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$\delta\sqrt{s} = \sqrt{s} - E_{\rm th}$, $E_{\rm th} = m_{K^-} + m_N$, then to first order in $B/E_{\rm th}$ one gets

$$\delta\sqrt{s} = -B_N \rho/\bar{\rho} - \beta_N [T_N (\rho/\bar{\rho})^{2/3} + B_{K^-} \rho/\rho_0] + \beta_{K^-} [{\rm Re}\ V_{K^-} + V_c (\rho/\rho_0)^{1/3}],$$

$\beta_N = m_N/(m_N + m_{K^-})$, $\beta_{K^-} = m_{K^-}/(m_N + m_{K^-})$, $\rho_0 = 0.17$ fm^{-3}.
Average binding energy $B_N = 8.5$ MeV, T_N=23 MeV (Fermi gas model).
The specific ρ/ρ_0 and $\rho/\bar{\rho}$ forms ensure that $\delta\sqrt{s} \to 0$ when $\rho \to 0$

Solving by iterations, $\sqrt{s}$ and hence amplitudes become functions of ρ, essentially *averaging over subthreshold energies.*

Accepting 'Minimal Substitution' (MS), $V_c(r)$ is subtracted from $\delta\sqrt{s}$, (as supported by analyses of pion-nucleus experiments).

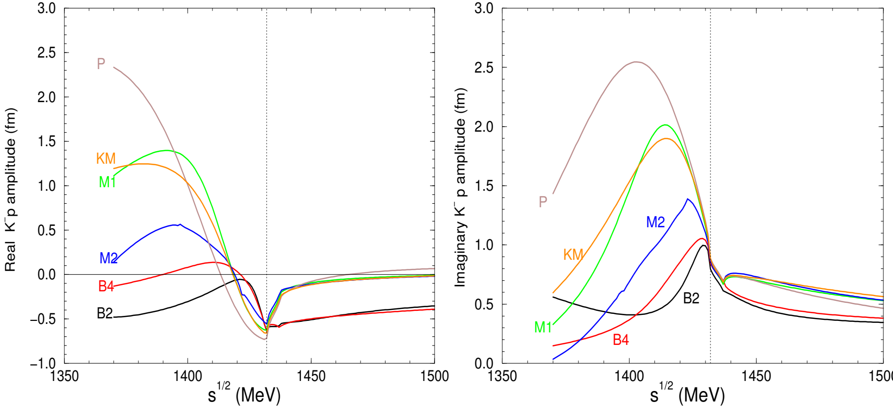
For attractive potentials the energy $\sqrt{s}$ is below threshold within the nuclear medium.

In addition there are corrections due to Pauli correlations.

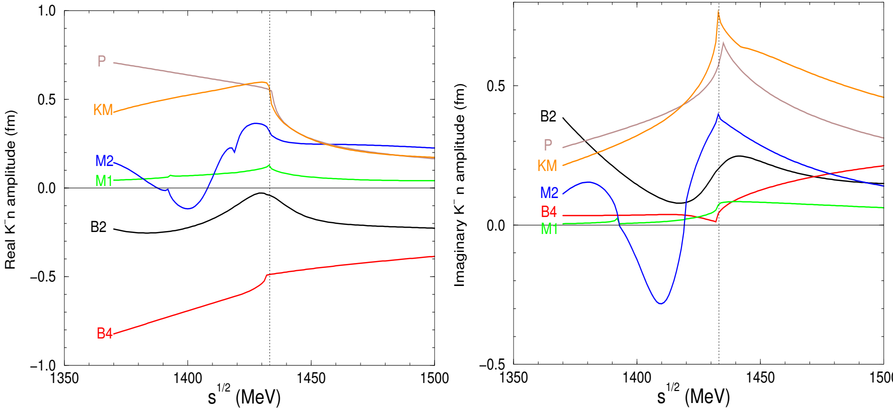
The algorithm performs averaging over subthreshold energies.

PLB 702 (2011) 402; PRC 84 (2011) 045206; NPA 899 (2013) 60; EPJ Web of Conferences 81 (2014) 01018; NPA 959 (2017); (partial list).

Six chiral $K^- N$ models constrained by fits to near-threshold data, including the SIDDHARTA result for K^-H at threshold



Six chiral $K^{-}N$ models constrained by fits to near-threshold data, including the SIDDHARTA result for K^{-}H at threshold



χ^2 for 65 kaonic atoms data points from optical potentials based only on single-nucleon amplitudes.

model	B2	B4	M1	M2	P	KM	YA
$\chi^2(65)$	1174	2358	2544	3548	2300	1806	2116

χ^2 for 18 high quality data points (P, S, Cl, Cu, Ag, Pb)

model	B2	B4	M1	M2	P	KM	YA
$\chi^2(18)$	364	733	949	1232	480	449	538

Not fits!

Fits to 65 kaonic atoms data points when single-nucleon amplitudes are supplemented by a $B(\rho/\rho_0)^\alpha$ term with fixed α compatible with its best-fit value. B in units of fm.

model	B2	B4	M1	M2	P	KM	YA
α	0.3	0.3	0.3	1.0	1.0	1.0	1.0
ReB	2.4±0.2	3.1±0.1	0.3±0.1	2.1±0.2	−1.3±0.2	−0.9±0.2	-2.0± 0.2
ImB	0.8±0.1	0.8±0.1	0.8±0.1	1.2±0.2	1.5±0.2	1.4±0.2	0.65 ±0.2
χ^2(65)	111	105	121	109	125	123	150

Is it necessary to go subthreshold?
Example for KM, when $\delta\sqrt{s}$=0:
$\alpha = 1.0$, Re$B = -1.8 \pm 0.1$, Im$B = -1.1 \pm 0.1$, $\chi^2(65)$ =139

Negative ImB and/or significantly larger χ^2 obtained for all seven models when taken on threshold.
Similar problems when ignoring Pauli correlations.

- Except for YA, all models lead to acceptable χ^2 values of 110 to 120 for 65 points.
- The additional potential has a $\rho^{1.3}$ to $\rho^{2.5}$ dependence. Could represent multi-nucleon processes.
- Unable to distinguish between the six models!

Ambiguities below threshold. Need additional information.

Fraction of multinucleon absorptions at rest from Bubble-Chamber experiments

$$K^- + N \to Y + \pi$$
$$K^- + N + N \to Y + N$$

0.26±0.03 on a mixture of C, F and Br (Berkeley, 1968)
0.28±0.03 on Ne (BNL, 1971)
0.19±0.03 on C (CERN, 1977)
Results from nuclear emulsions quote larger uncertainties.

We therefore adopt as a best estimate of experimental K^- multinucleon absorption-at-rest fraction an average value of 0.25±0.05 for C and heavier nuclei.

Apply fraction of *single*-nucleon absorptions 0.75±0.05 as an additional constraint.

The level width Γ is obtained from the eigenvalue $E_{K^-} - i\Gamma/2$ when solving the Klein-Gordon equation with an optical potential, ($E_{K^-} = m_{K^-} - B_{K^-}$). It is also related to the imaginary part of the potential by the overlap integral of $\mathrm{Im}\, V_{K^-}$ and $|\psi|^2$,

$$\Gamma \ = -2\ \frac{\int \mathrm{Im}\, V_{K^-}\ |\psi|^2\ d\vec{r}}{\int [1 - (B_{K^-} + V_{\mathrm{C}})/\mu_K]\ |\psi|^2\ d\vec{r}}$$

where B_{K^-}, V_{C} and μ_K are the K^- binding energy, Coulomb potential and reduced mass, respectively, and ψ is the K^- wave function of the particular state concerned.

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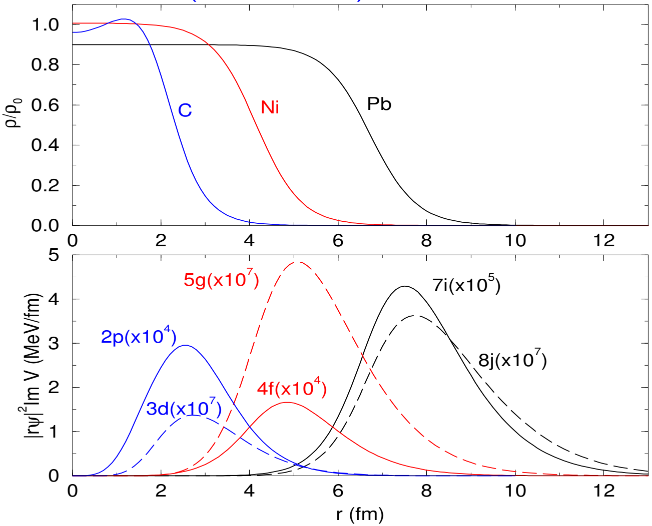
where B_{K^-}, V_{C} and μ_K are the K^- binding energy, Coulomb potential and reduced mass, respectively, and ψ is the K^- wave function of the particular state concerned.

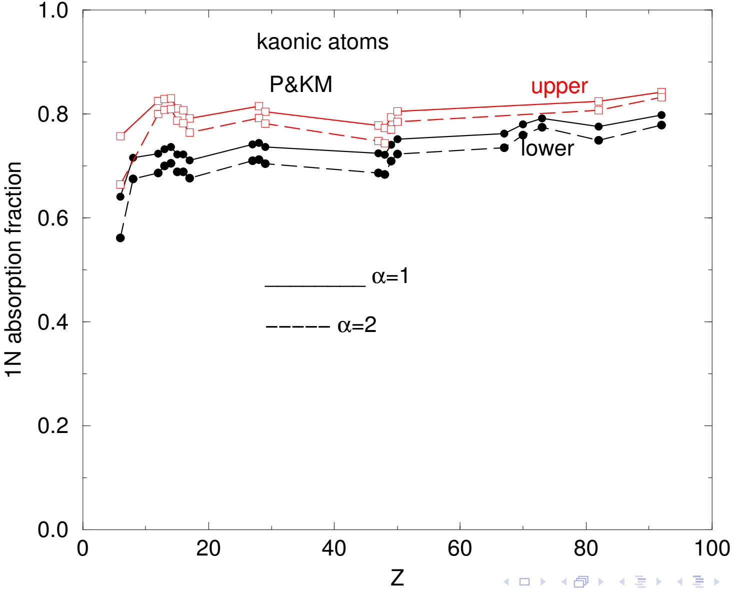
When the *best fit* optical potential is $V^{(1)}_{K^-}+V^{(2)}_{K^-}$, the sum of a single-nucleon part and a multinucleon part, it is straight forward to calculate the fraction of single-nucleon absorptions, separately for any nucleus and for any specific kaonic atom state.

Kaonic atoms overlaps for 'lower' (solid curves) and 'upper' (dashed curve) states.

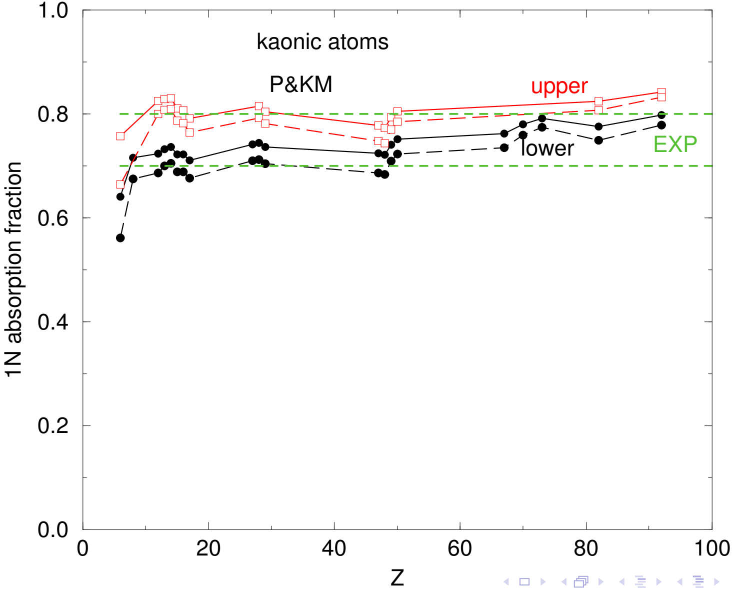


Very similar behavior along the Periodic Table.

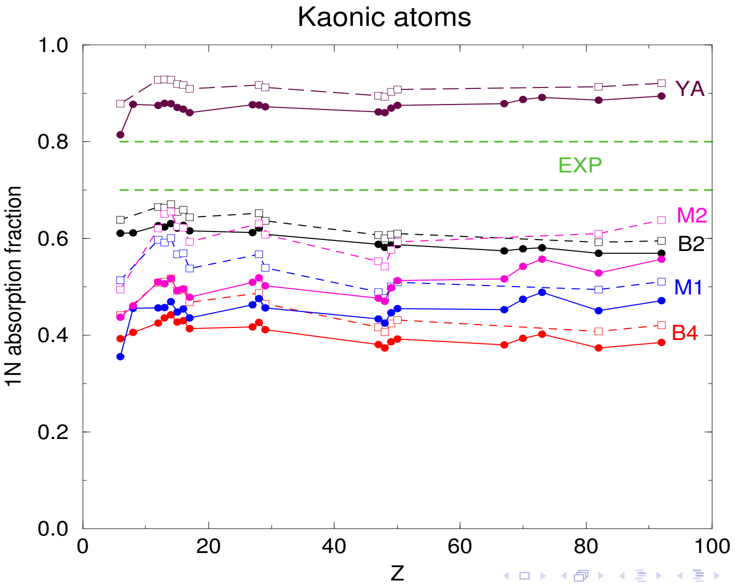
Fraction of single-nucleon absorption for amplitudes P and KM.
Solid circles for lower states, open squares for upper states.

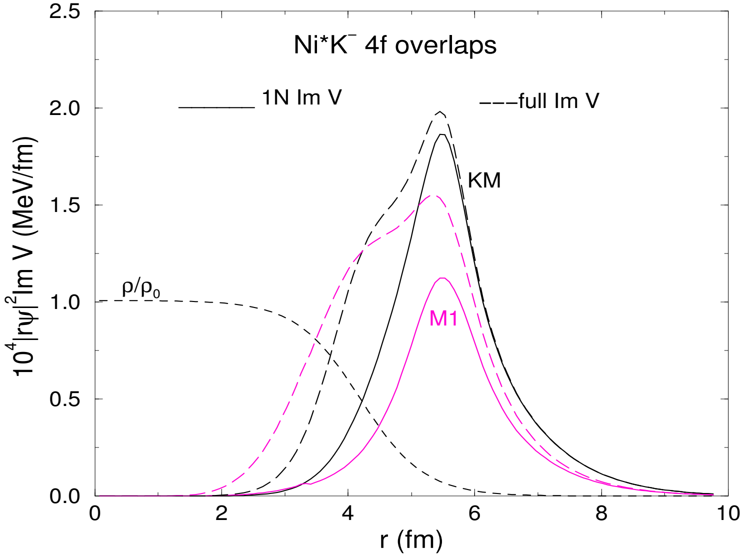


Fraction of single-nucleon absorption for amplitudes P and KM. Solid circles for lower states, open squares for upper states.

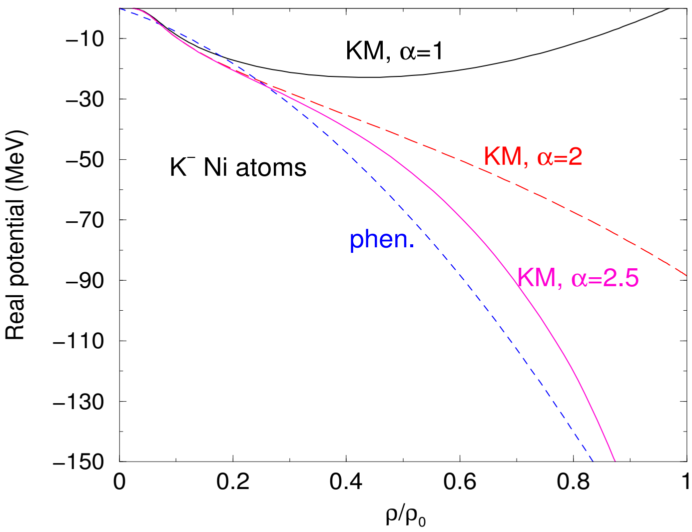


Fraction of single-nucleon absorption for the other 5 amplitudes.
Solid circles for lower states, open squares for upper states.

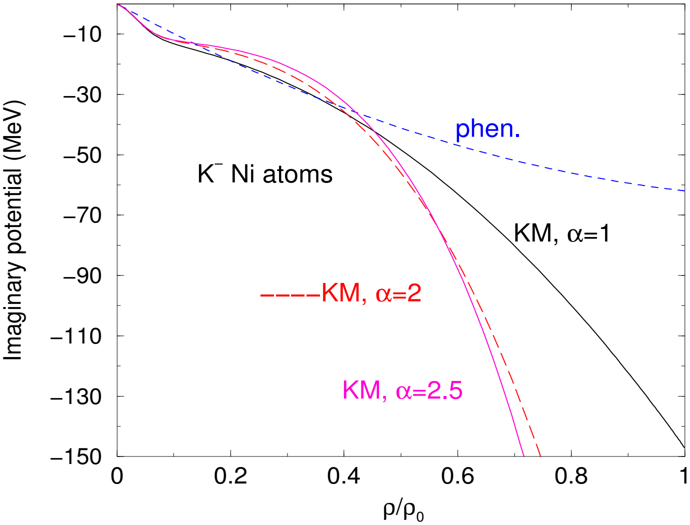




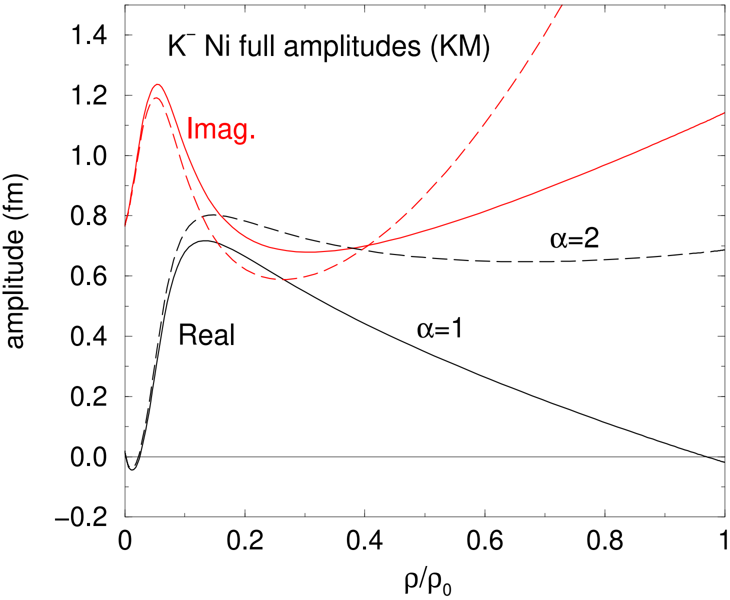
$\Gamma(\text{exp})=1.03\pm0.12$ keV, $\Gamma(\text{KM}+\text{m}N)=0.94$ keV, $\Gamma(\text{M1}+\text{m}N)=0.90$ keV



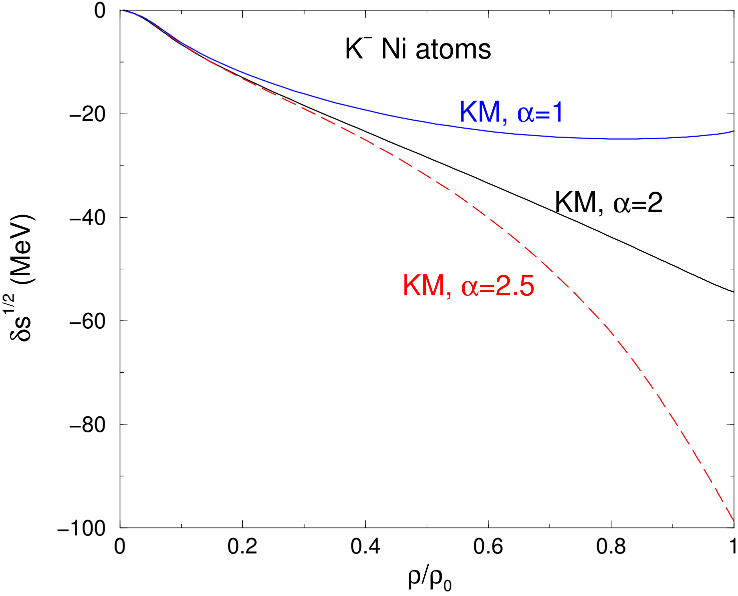
Arbitrary model-dependence above 25% of central density



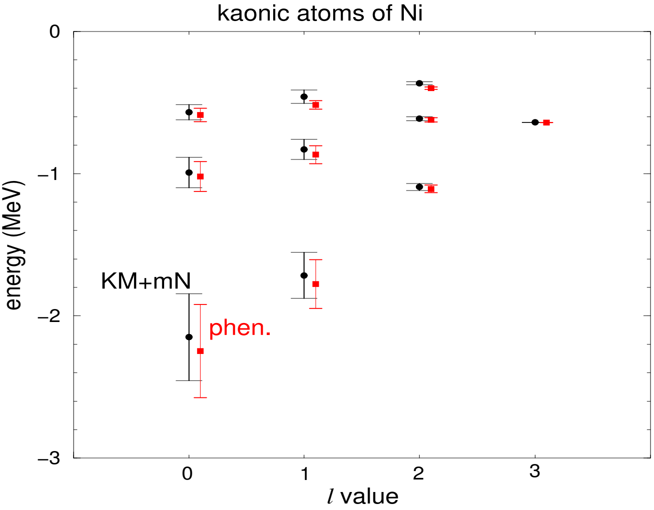
Arbitrary model-dependence above 50% of central density.
Well-defined below 50% of central density.



K⁻ Ni full amplitudes (KM)
Imag.
Real
α=1
α=2
amplitude (fm)
ρ/ρ0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
–0.2
0
0.2
0.4
0.6
0.8
1

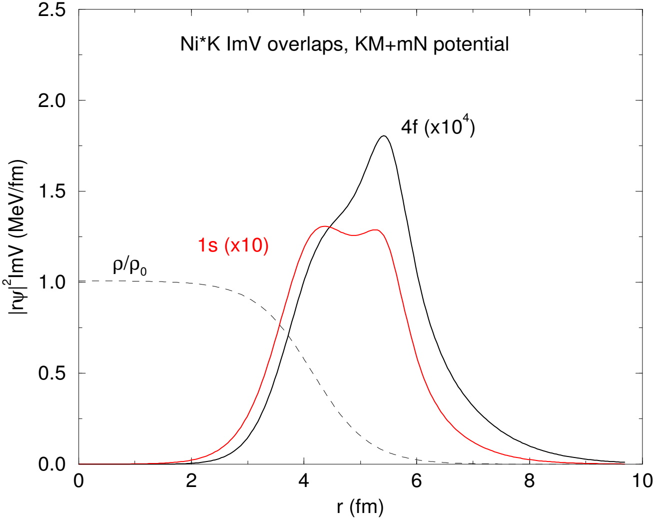


K⁻ Ni atoms
KM, α=1
KM, α=2
KM, α=2.5
0
−20
−40
−60
−80
−100
0
0.2
0.4
0.6
0.8
1
δs^1/2 (MeV)
ρ/ρ0



Could be observed by *l*-selective reactions.

Absorption causes repulsion of the atomic wave function.



Unlikely to provide information beyond ‘normal’ kaonic atoms.

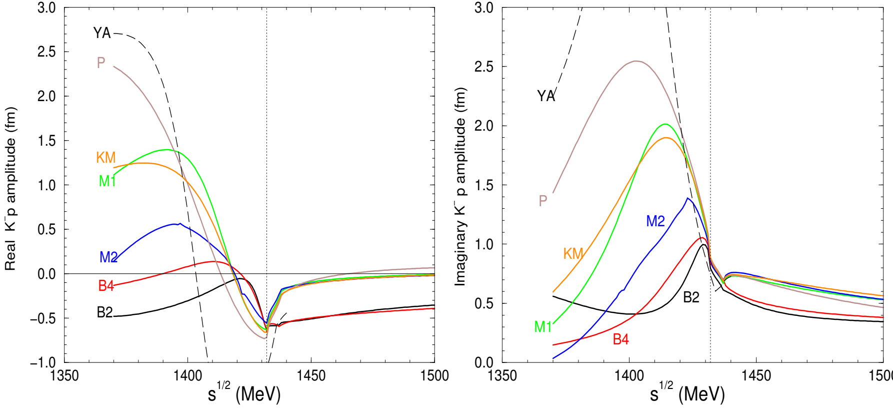
Summary

- Good global fits with mixed chiral (1N) + phenomenological multi-nucleon amplitudes within sub-threshold kinematics.
- Fractions of single-nucleon absorption favor the P and the KM models.
- All seven models predict these fractions to depend very little on nuclear species and atomic state.
- Real potential not known above 25% of central density. Unable to answer 'deep or shallow?'
- Imaginary potential known up to 50% of central density. Could constrain theories of multi-nucleon absorption.
- Deeply (Coulomb bound) kaonic atom states are well-defined but unlikely to provide new information.
- Deep strongly bound nuclear states are too broad to be well-defined.

Thank you for your attention!

Nucl. Phys. A 959 (2017) 66-82.

Six chiral K^-N models constrained by fits to near-threshold data, including the SIDDHARTA result for K^-H at threshold. The YA is a non-chiral energy-independent potential.



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