Future directions in kaonic atom physics

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OUTLINE

- Experimental comments
- Phenomenological comments
- Beyond the '$t\rho$' model
- Going sub-threshold
- Future directions

Experimental

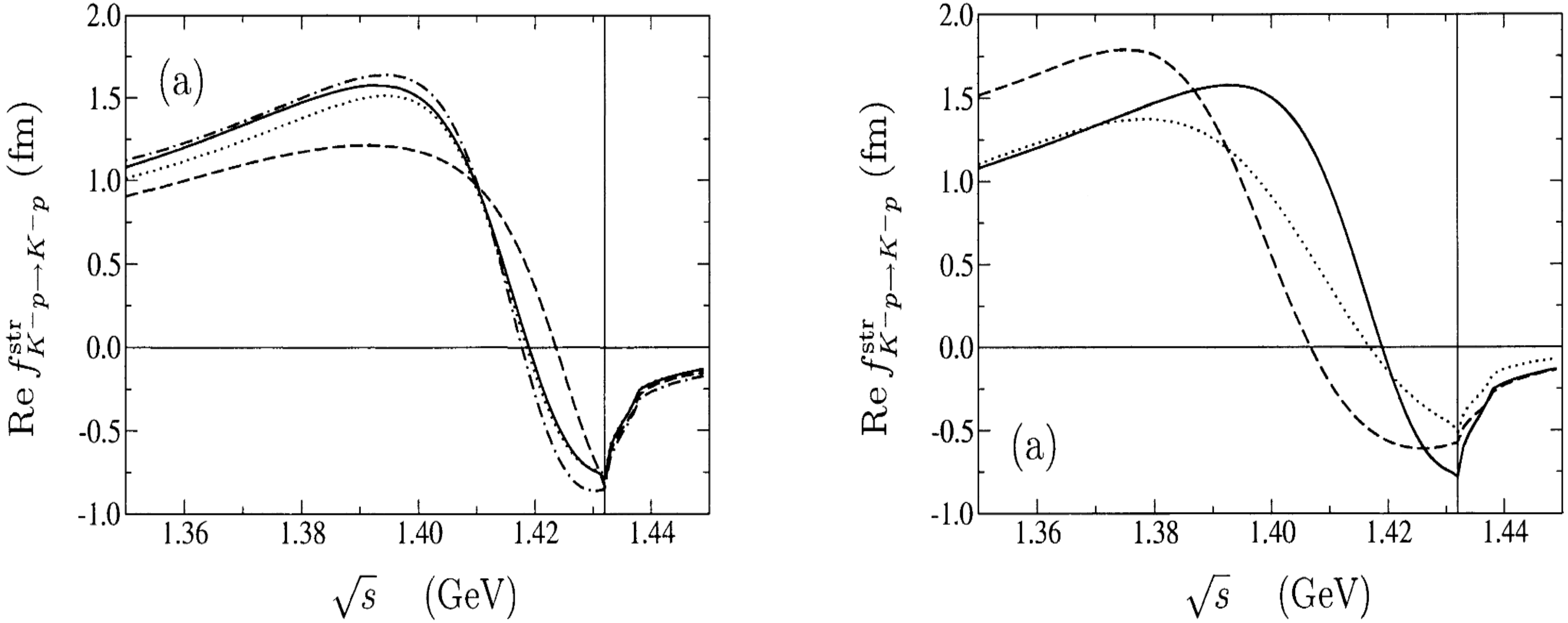
- Bulk of data from 1970-1980, 4-5 laboratories, single Ge(Li) detector, ≈ 0.6 keV FWHM @ 100 keV, solid targets. Good consistency.

- 1995- KEK & DAΦNE: many detectors (Si(Li) and CCD), 0.2-0.4 keV FWHM @ 6 keV, vertex reconstruction and background suppression, gaseous targets (H_2 and ^{4}He).

- Always repulsive shifts ($\epsilon < 0$), dominance of widths ($|\epsilon| << \Gamma$).

Typical experimental results for kaonic atoms (keV)

Z	A	N	L	ϵ	$\pm$	Γ	$\pm$
8.0	16.000	3	2	-0.02500	0.01500	0.01700	0.01400
12.0	24.305	3	2	-0.02700	0.01500	0.21400	0.01500
13.0	26.982	3	2	-0.08000	0.01300	0.44300	0.02200
14.0	28.086	3	2	-0.13900	0.01400	0.80100	0.03200
15.0	30.974	3	2	-0.33000	0.08000	1.44000	0.12000
16.0	32.060	3	2	-0.49400	0.03800	2.19000	0.10000
17.0	35.453	3	2	-0.99000	0.17000	2.91000	0.24000
27.0	58.933	4	3	-0.09900	0.10600	0.64000	0.25000
28.0	58.710	4	3	-0.22300	0.04200	1.03000	0.12000
29.0	63.550	4	3	-0.37000	0.04700	1.37000	0.17000



Examples of K^-p scattering amplitudes near threshold,
Borasoy, Nissler and Weise, EPJ A **25** 79 (2005).

k^-H puzzle solved: Iwasaki et.al., PRL **78** 3067 (1997).

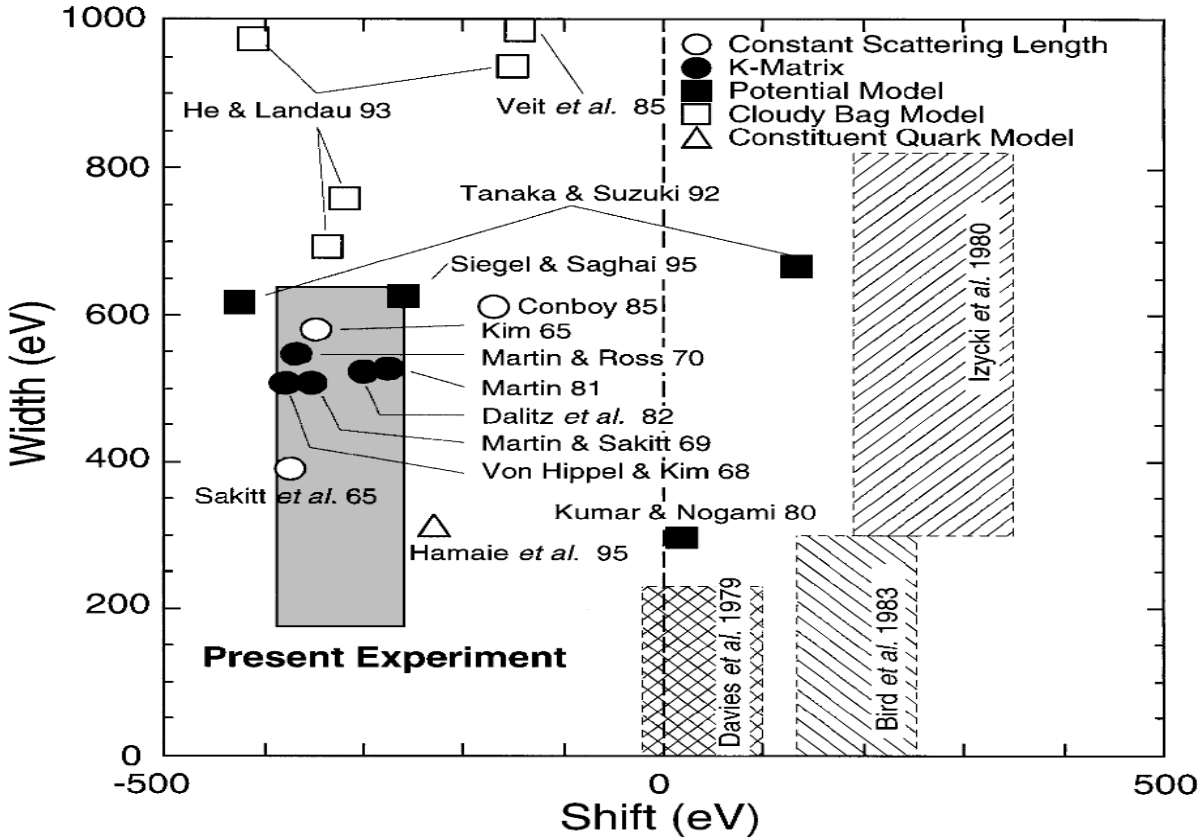


FIG. 1. The energy shift and width of 1*s* state. One-standard-deviation region of shift and width of the previous experiments are plotted together with theoretical calculations. The present result is shown in bold.

Results from SIDDHARTA, nucl-ex 1105.3090

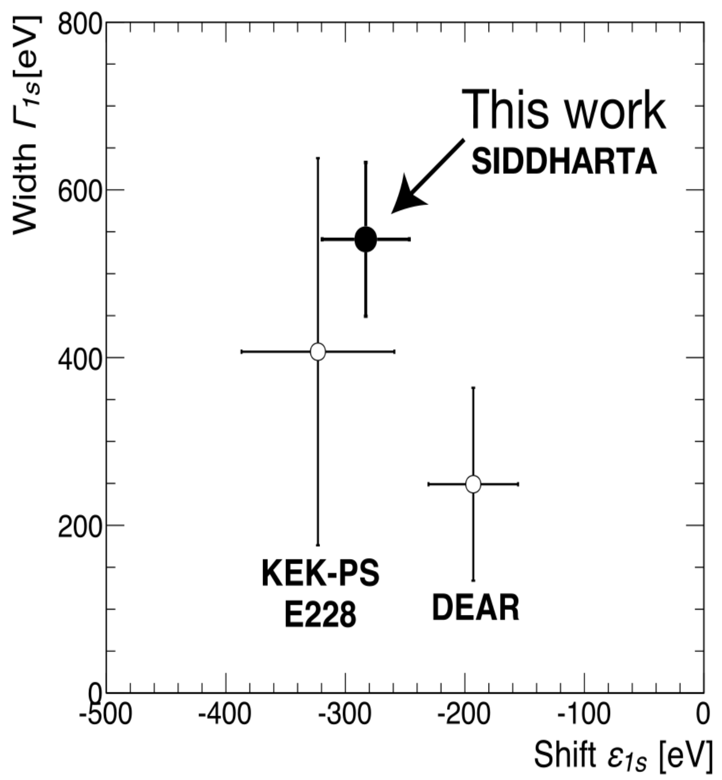


Figure 5: Comparison of experimental results for the strong-interaction 1s-energy-level shift and width of kaonic hydrogen, KEK-PS E228 [9] and DEAR [13]. The error bars correspond to quadratically added statistical and systematic errors.

Experiments with π^{-}H atoms:

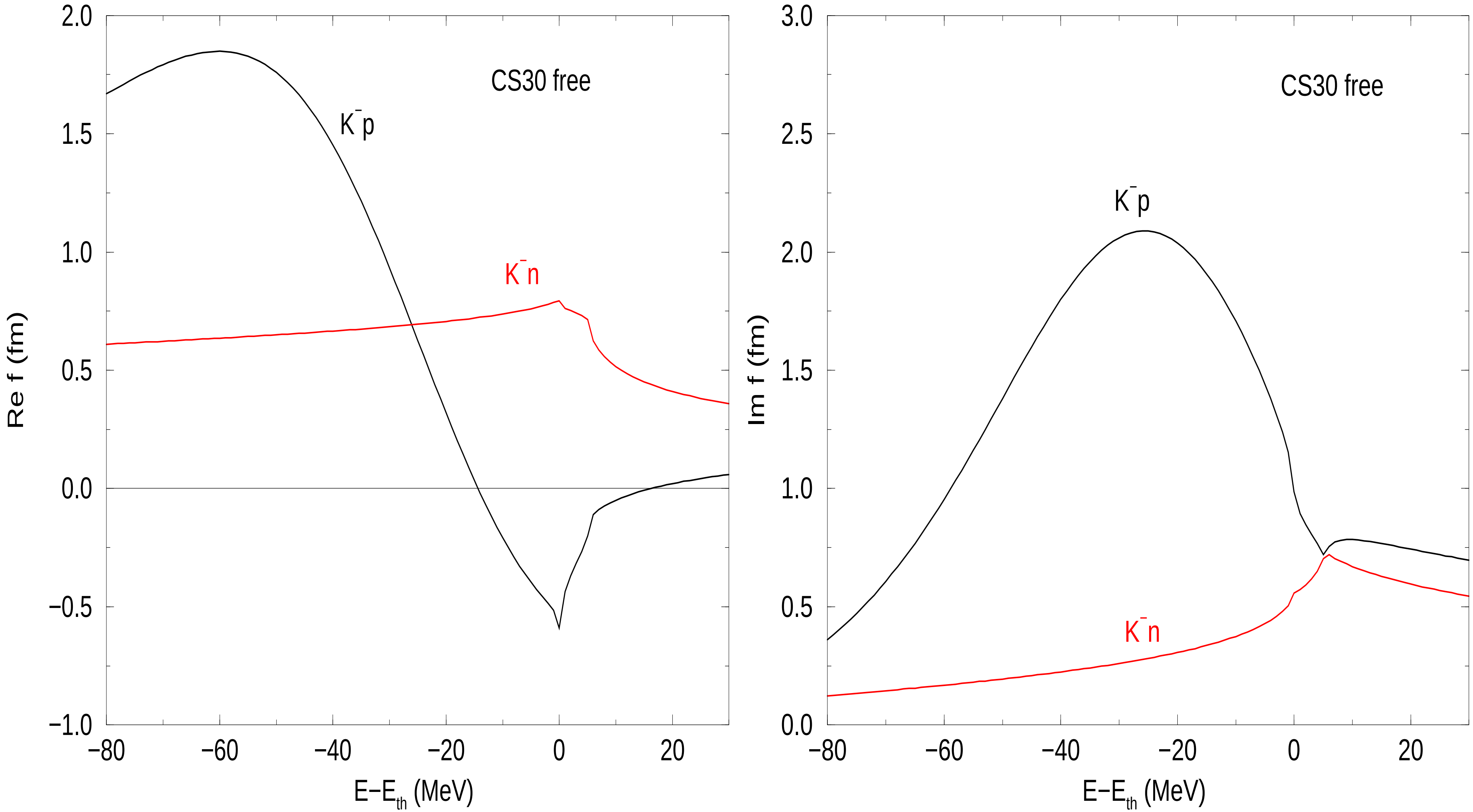
Quartz crystal spectrometer, CCD detecors,

FWHM $\approx$ 0.7 eV,

for $E_x \approx$ 2.9 keV, $\epsilon \approx$7 ev, $\Gamma \approx$ 0.9 eV.

Experiments with K^{-}H atoms:

$E_x \approx$ 6 keV, $\epsilon \approx$-0.3 kev, $\Gamma \approx$ 0.4 keV.



K^-p and K^-n scattering amplitudes near threshold,
Cieplý and Smejkal, Eur. Phys. J. A **43** 191 (2010).

Phenomenology

- Strong interaction effects dominated by absorption.
- Perturbation approach inapplicable due to strong local effects.
- Localized strong absorption produces repulsion; with attractive real amplitude the net effect is still repulsion.
- Quantitative analyses using optical model approach.

Phenomenological analyses of data:

- Handle large sets of data.
- Could identify characteristic quantities.
- Serve as intermediaries between 'microscopic' theories and experiment (e.g. in reproducing the characteristic quantities).

Tools of the trade: variants of an optical potential.

When analyzing several nuclear species together one must have some model for the nuclear geometry, e.g. make the potential a functional of the nuclear density.

The simplest class of optical potentials $V_{\rm opt}$ is the generic $t\rho(r)$ potential: (isoscalar)

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

ρ_n and ρ_p are neutron and proton densities normalized to N and Z, respectively, M is the mass of the nucleon.

Results of global fits apply to <u>average</u> behaviour.

Beyond the $t\rho$ model

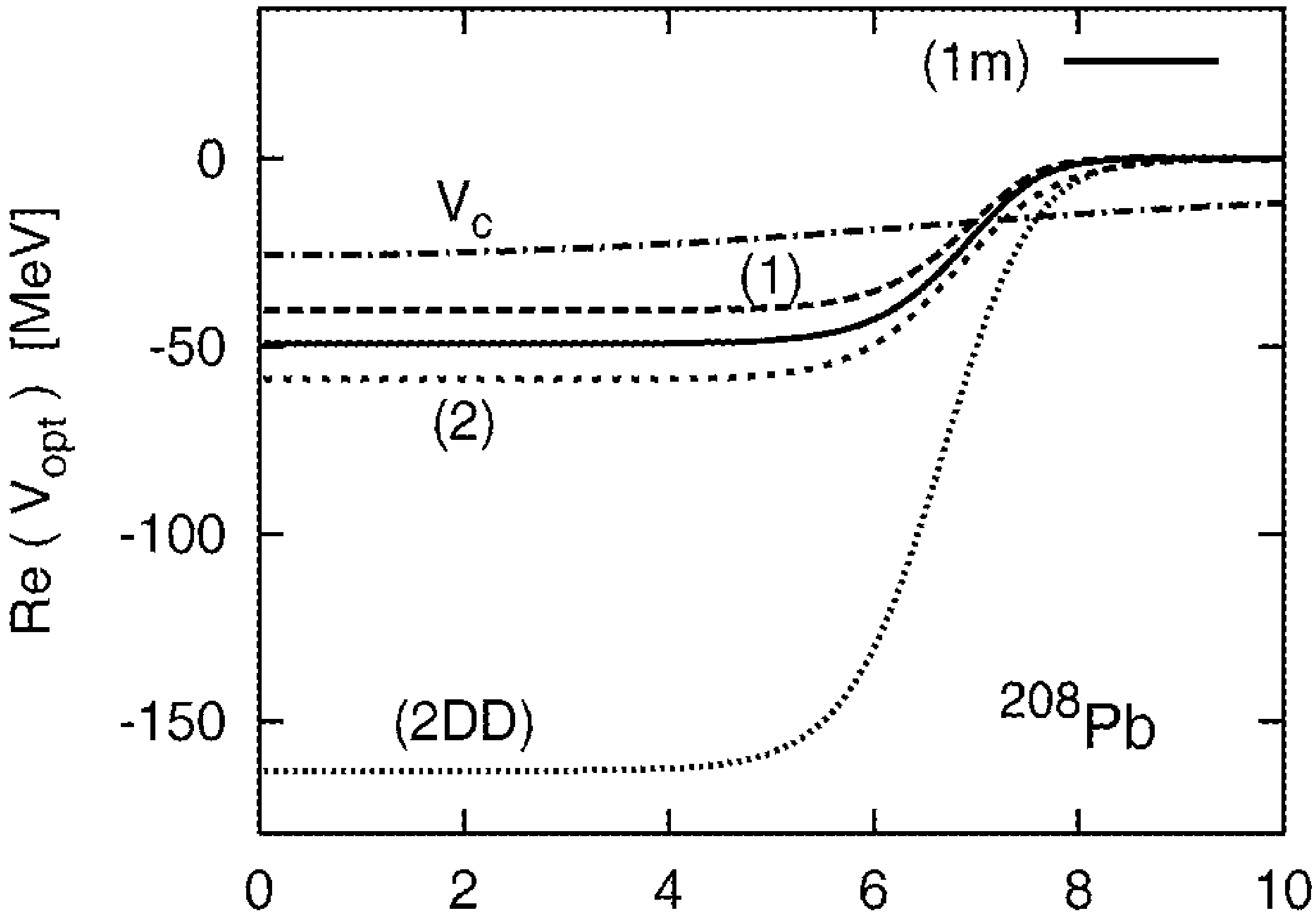
The *empirical* DD form is based on making the effective amplitude density-dependent

$$b_0 \rightarrow b_0 \ + \ B_0 \ \{\frac{\rho(r)}{\rho_0}\}^\alpha \ , \quad \alpha > 0 \ , \rho_0 = 0.17 \ \mathrm{fm}^{-3}.$$

Fixed b_0, χ^2 =130 for 65 points, Re $V_{\mathrm{opt}} = -80$ MeV.

For DD, χ^2 =90-100, Re $V_{\mathrm{opt}} = -180$ MeV.

Deep potentials have consequences for neutron stars and for $K^- NN$ clusters.


(1m)
0
-50
-100
-150
Re (V_opt) [MeV]
V_c
(1)
(2)
(2DD)
208Pb
0
2
4
6
8
10

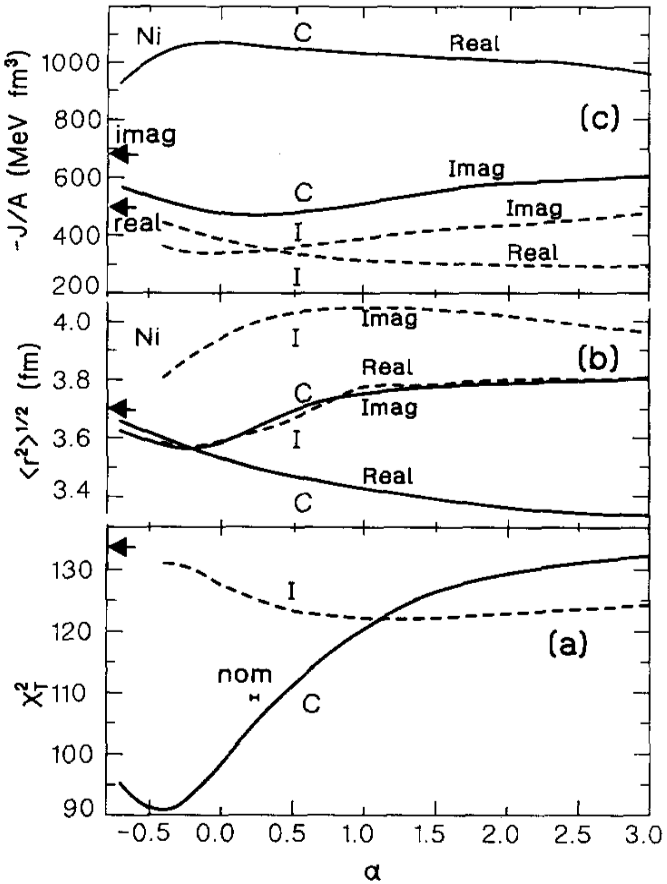
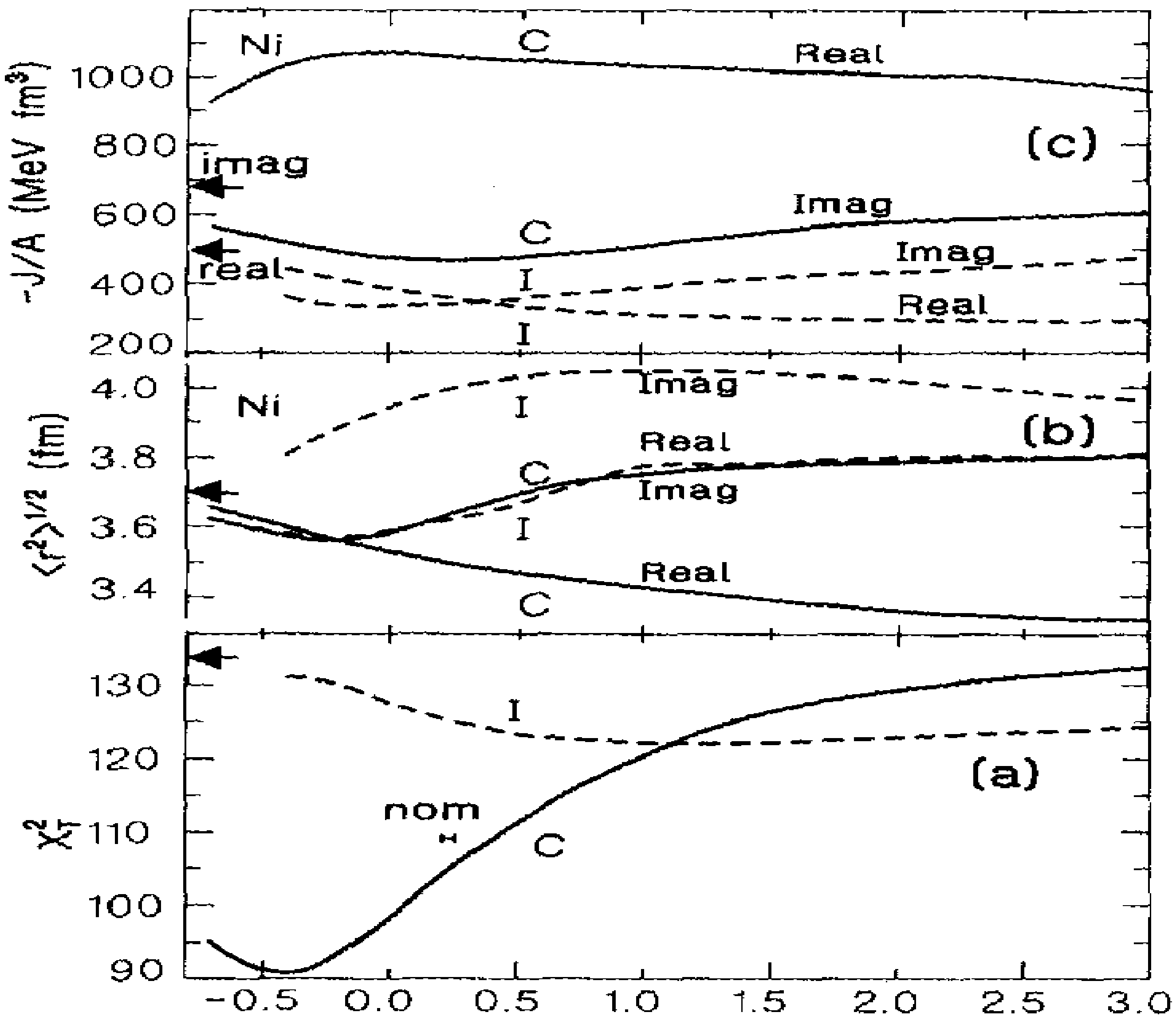


Fig. 1. (a) Total χ^2 values for the "compression" (C) and "inflation" (I) families of solutions as a function of the DD parameter α. The arrow on the left shows the corresponding value for the $t_{\text{eff}}\rho$ solution. The bar marked "nom" is for the "nominal" solution (see text). (b) Root-mean-square radii of the potential for Ni for the various solutions. (c) Volume integrals per nucleon of the potentials.



-J/A (MeV fm^3)
1000
800
600
400
200
Ni
C
Real
(c)
imag
Imag
C
Imag
real
I
Real
I
$\langle r^2 \rangle^{1/2}$ (fm)
4.0
3.8
3.6
3.4
Ni
Imag
I
Real
(b)
C
Imag
I
Real
C
χ^2_T
130
120
110
100
90
I
(a)
nom
C
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Some comments on geometry (r.m.s. radii)

For fixed-t $t\rho$ potential, $r_{potl} \; = \; r_\rho$

(Including finite-range folding, $r_{potl} \; > \; r_\rho$)

When $t(\rho)$ decreases with increasing ρ, $r_{potl} \; > \; r_\rho$

When $t(\rho)$ increases with ρ, $r_{potl} \; < \; r_\rho$

Compression of the potential must result from an underlying K^-N interaction that *increases* with density (overshadowing any finite-range effects).

Turn to $t_{K-N}(\vec{p}, \rho, \sqrt{s})$.

($\sqrt{s} = K^-N$ Mandelstam variable.)

Going subthreshold: average kinematics

A. Cieplý, E. Friedman, A. Gal, D. Gazda and J. Mareš

Phys. Lett. B **702** (2011) 402,

arXiv:1108.1745

Earlier approaches for *specific* kaonic atoms:

S. Wycech, NPB **28** (1971) 541

W.A. Bardeen and E.W. Torigoe, PLB **38** (1972) 135

J.R. Rook, NPA **249** (1975) 466

R. Brockmann, W. Weise and L. Tauscher, NPA **308** (1978) 365.

In the K^-N c.m. system

$$s = (E_{K^-} + E_N)^2 - (\vec{p}_{K^-}^{\,cm} + \vec{p}_N^{\,cm})^2.$$

Embedded in the nuclear medium $\vec{p}_{K^-}^{\,cm} + \vec{p}_N^{\,cm} \neq 0$.

Averaging over angles,

$$(\vec{p}_{K^-}^{\,cm} + \vec{p}_N^{\,cm})^2 \longrightarrow (p_{K^-}^{cm})^2 + (p_N^{cm})^2.$$

Averaging the relative c.m. momentum squared

$$(\vec{p}_{rel})^2 = (\vec{p}_{K^-}^{\,cm} - \vec{p}_N^{\,cm})^2 \longrightarrow (p_{K^-}^{cm})^2 + (p_N^{cm})^2.$$

Hence

$$s = (E_{K^-} + E_N)^2 - p_{rel}^2.$$

Evaluating p_{rel}^2 from *in medium* $p_{K^-}^2$ and p_N^2:

$$p_{rel}^2 = \frac{2m_N^2 m_K}{(m_N + m_K)^2} \, \frac{p_K^2}{2m_K} + \frac{2m_N m_K^2}{(m_N + m_K)^2} \, \frac{p_N^2}{2m_N}.$$

Substituting locally

$$\frac{p_K^2}{2m_K} \rightarrow -B_K - \mathrm{Re}\, V_{\mathrm{opt}} - V_c$$

$$\frac{p_N^2}{2m_N} \rightarrow 23.0(\rho/\rho_0)^{2/3} \text{ (in MeV, Fermi gas model}, \rho_0 = 0.17 fm^{-3})$$

$$E_K = m_K - B_K, \qquad E_N = m_N - B_N.$$

Keeping only linear terms in B/m:

$$\sqrt{s} \approx E_{th} - B_N - \xi_N B_K - 15.1(\rho/\rho_0)^{2/3} + \xi_K(\mathrm{Re}\ V_{\mathrm{opt}} + V_c).\ (\mathrm{MeV})$$

with

$$E_{th} = m_N + m_K, \quad \xi_N = \frac{m_N}{m_N+m_K}, \quad \xi_K = \frac{m_K}{m_N+m_K}.$$

With V_{opt} proportional to $t_{K^-N}(\vec{p}, \rho, \sqrt{s})$ locally, a self-consistent process is required.

≈ 6 iterations at each radial point for every target.

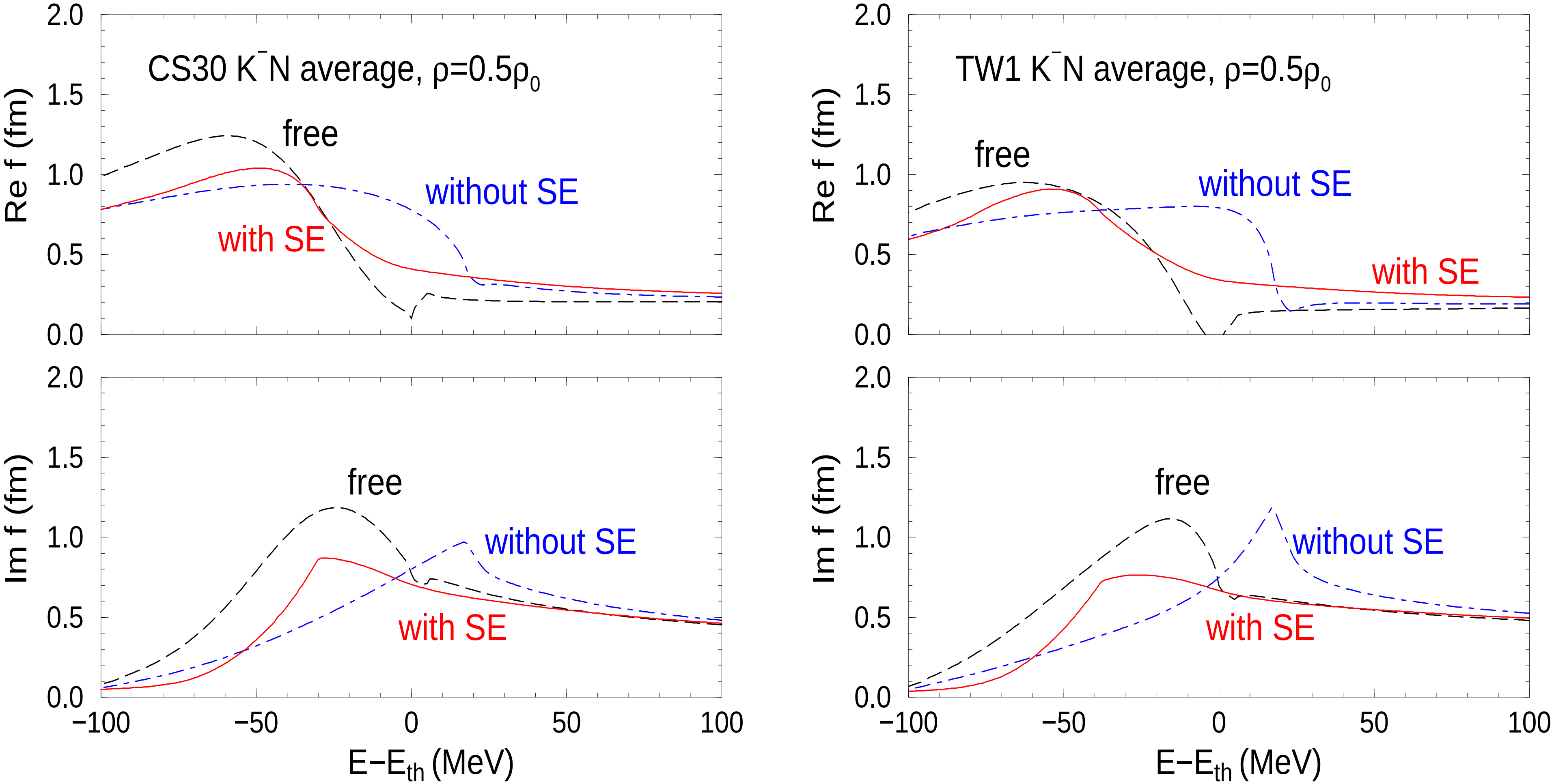
$$\sqrt{s} \approx E_{th} - B_N - \xi_N B_K - 15.1(\rho/\rho_0)^{2/3} + \xi_K(\mathrm{Re}\ V_{\mathrm{opt}} + V_c).\ (\mathrm{MeV})$$

Subthreshold: for attractive V_{opt}, $\quad \sqrt{s}\ <\ E_{th}$.

Possible variations:

$\sqrt{s}\ \rightarrow\ \sqrt{s} - V_c\ , \qquad B_N\ \rightarrow\ B_N\ \rho(r)/\bar{\rho}$.

For a given model for $t_{K-N}(\vec{p}, \rho, \sqrt{s})$ we have a simple algorithm for constructing V_{opt}.



CS30 and TW1 *average* amplitudes, free and for $0.5\rho_0$, with and without self energy.

Note sharp drop of Im f towards $\pi\Sigma$ threshold.

Use separate proton and neutron densities and replace

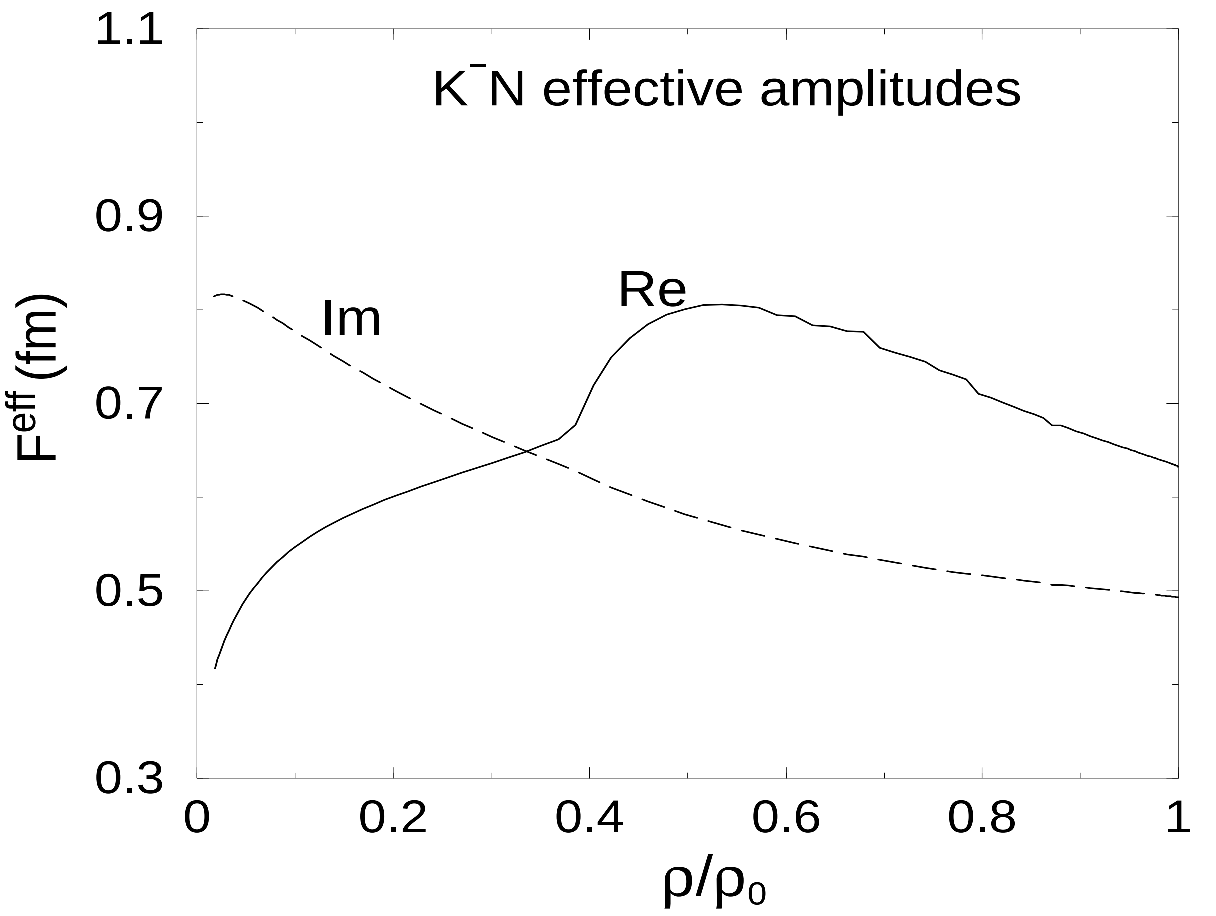
$F_{K^-N}(\sqrt{s}, \rho)\rho(r)$ by

$\mathcal{F}^{\text{eff}}_{K^-N}(\sqrt{s}, \rho)\rho(r) = F_{K^-p}(\sqrt{s}, \rho)\rho_p(r) + F_{K^-n}(\sqrt{s}, \rho)\rho_n(r)$.

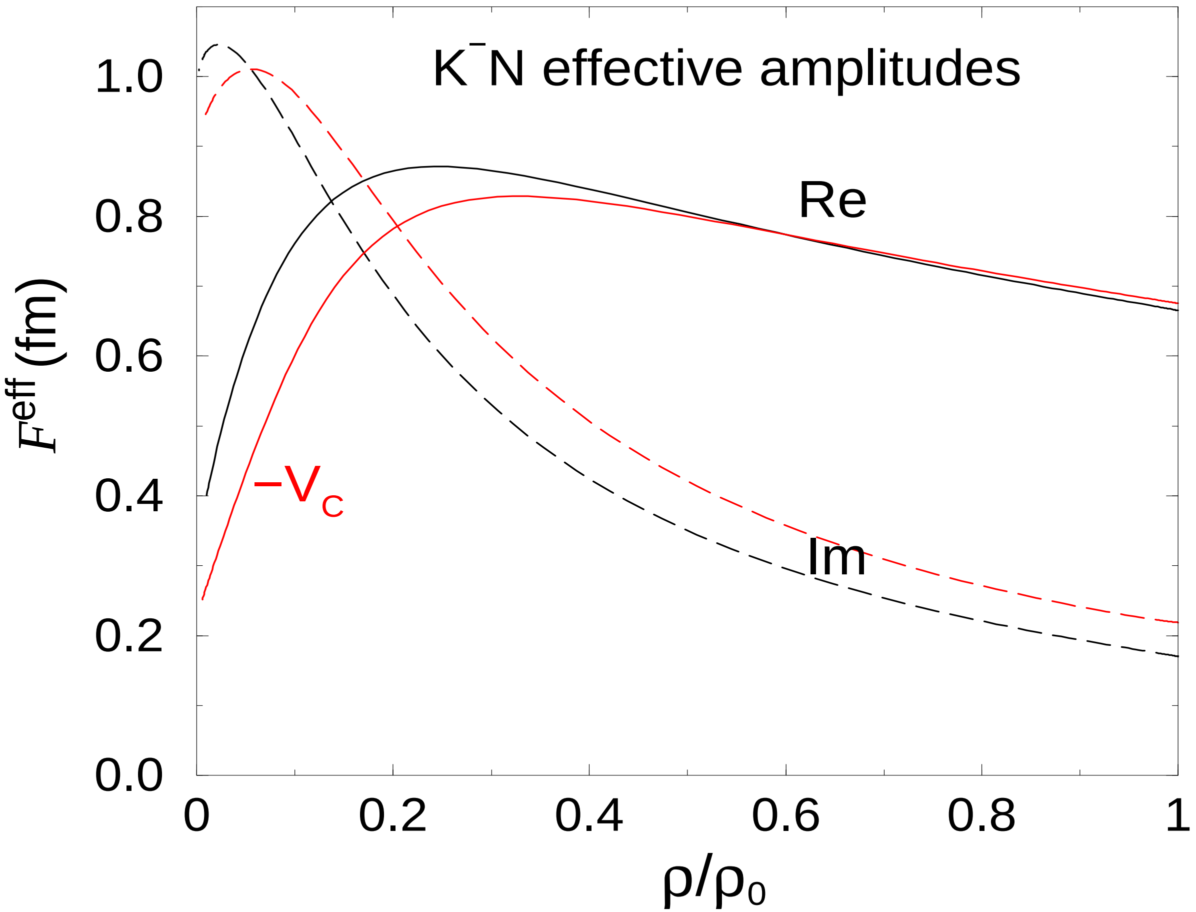
BUT processes beyond K^-N are excluded

(K^-NN absorptions etc.)

Additional terms will be required.



Effective CS30 amplitudes for K^- Ni interaction, SE included.
'Compression' of Re $V_{\rm opt}$ and 'inflation' of Im $V_{\rm opt}$ are observed.



Effective CS30 amplitudes for K^- Ni interaction, SE excluded. 'Compression' of Re $V_{\rm opt}$ and 'inflation' of Im $V_{\rm opt}$ are observed.

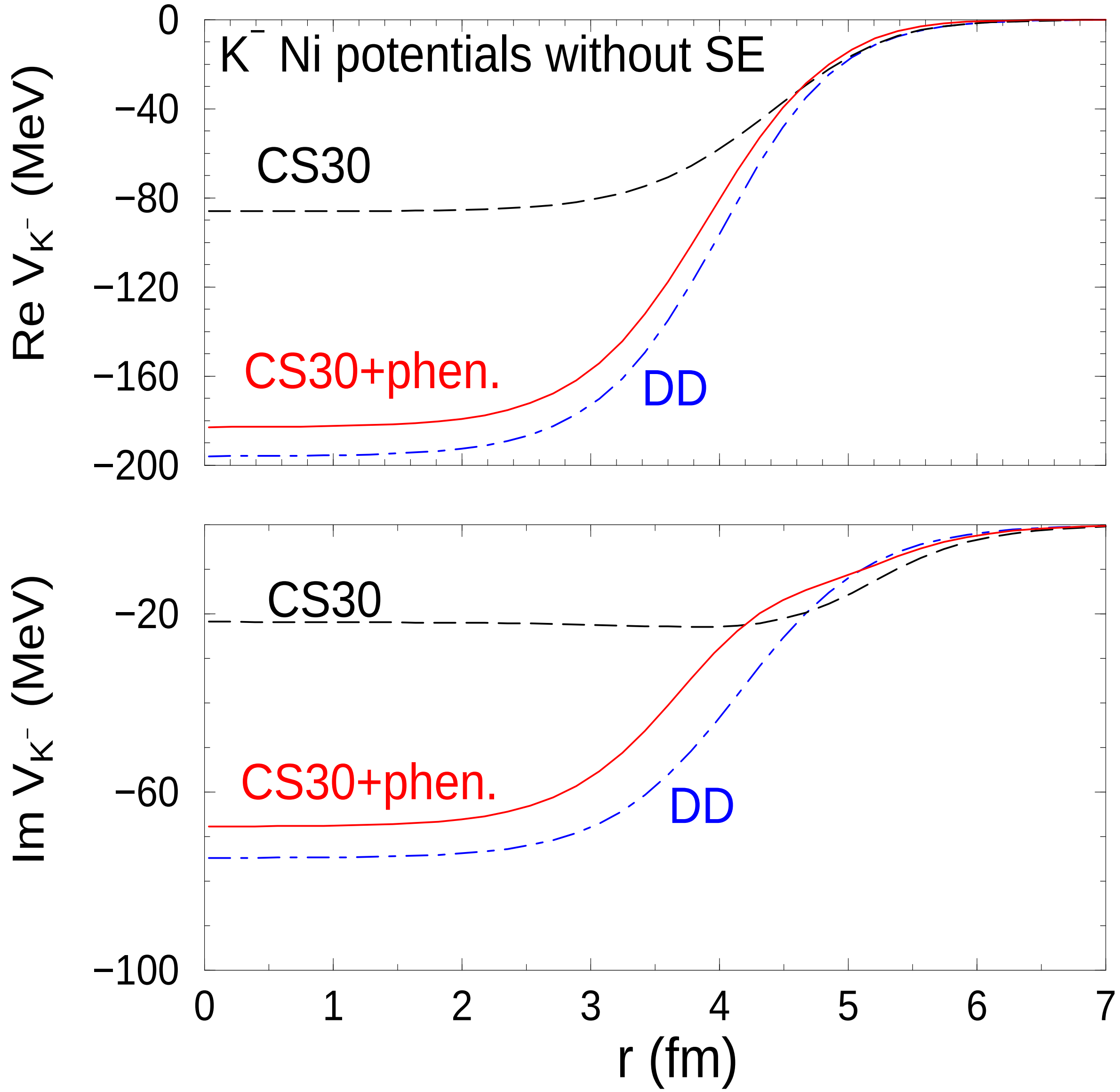
Results of global fits to 65 data points

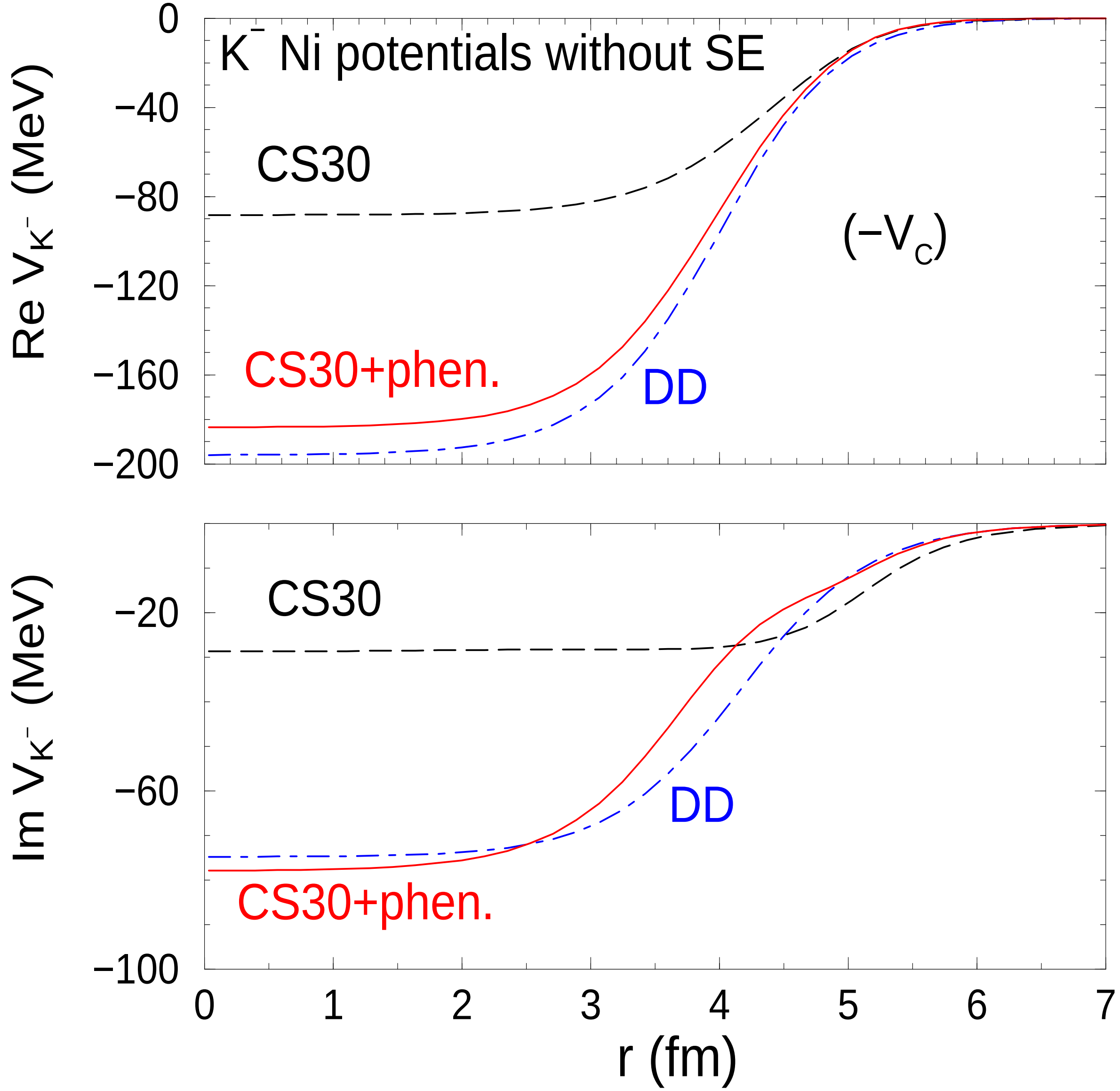
Adding a phenomenological $b\rho + B\rho^2/\rho_0$ term.

No self enery, include $\sqrt{s} \to \sqrt{s} - V_c$

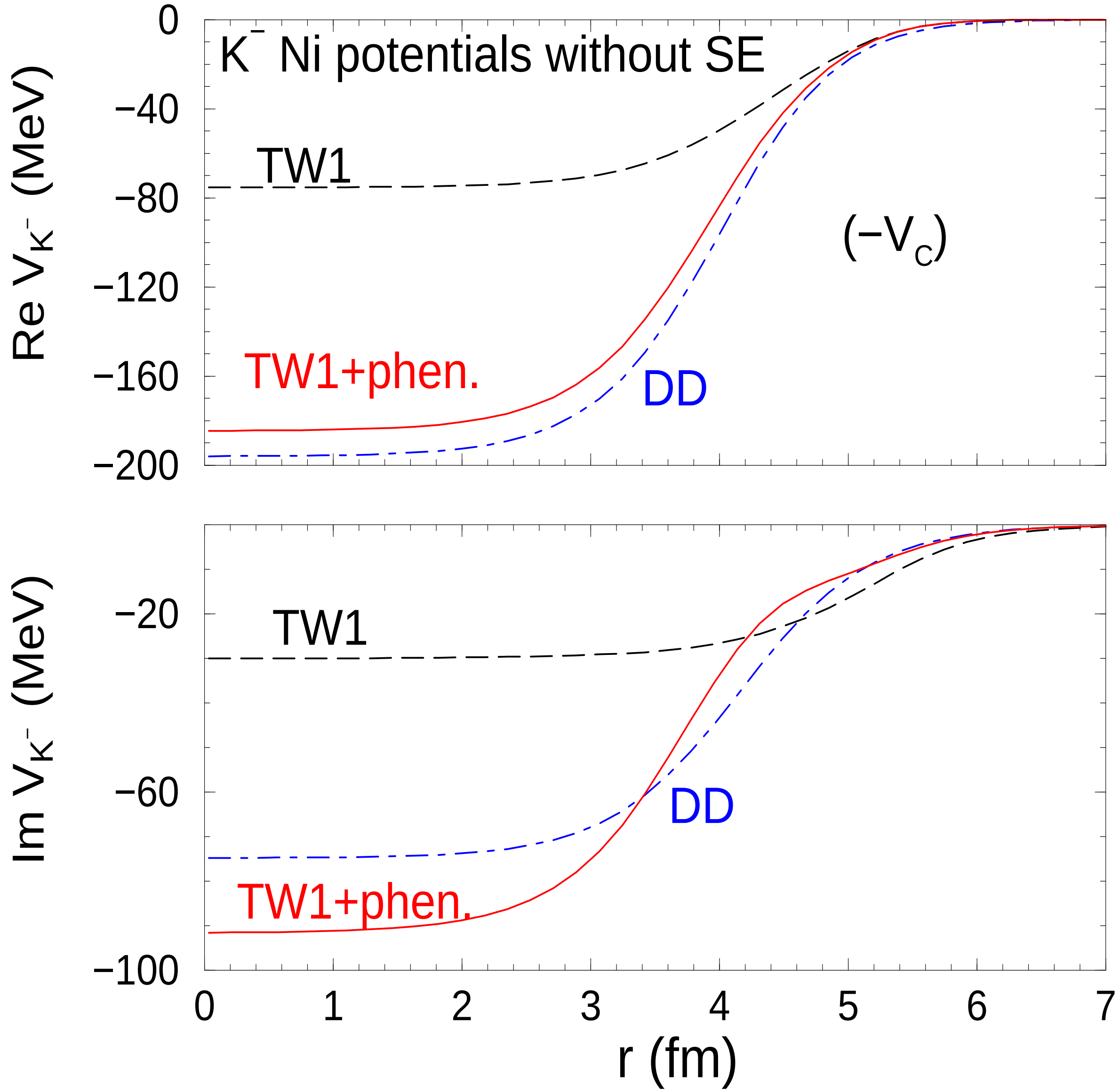
ampl.	χ^2	Reb(fm)	Imb(fm)	ReB(fm)	ImB(fm)
CS30	647	–	–	–	–
	138	-0.10 ± 0.06	-0.39 ± 0.06	0.82 ± 0.13	0.76 ± 0.12
TW1	655	–	–	–	–
	124	-0.06 ± 0.05	-0.41 ± 0.05	0.89 ± 0.23	0.87 ± 0.13

Keeping the amplitudes at threshold, Im$B < 0$ is obtained.


K⁻ Ni potentials without SE
Re V_{K^-} (MeV)
Im V_{K^-} (MeV)
CS30
CS30+phen.
DD
0
−40
−80
−120
−160
−200
−20
−60
−100
0
1
2
3
4
5
6
7
r (fm)

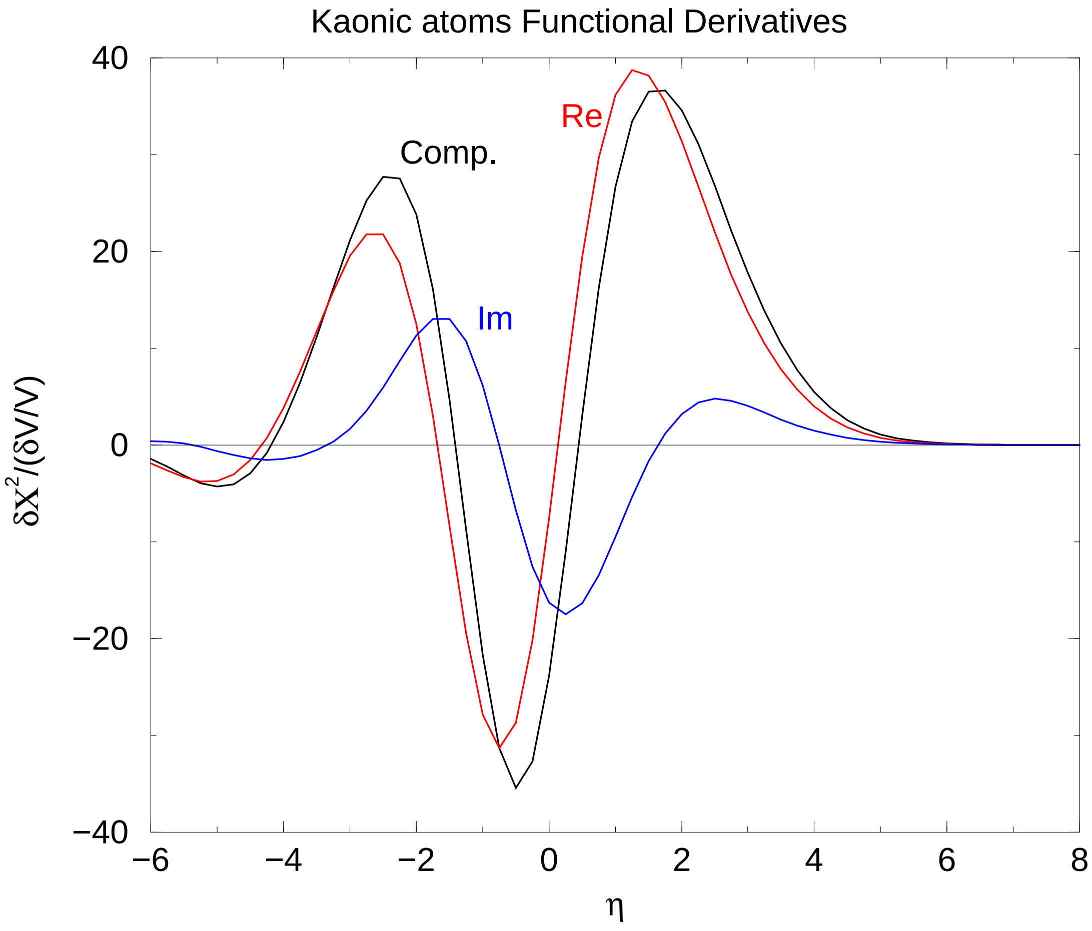


K$^-$ Ni potentials without SE
Re V_{K^-} (MeV)
0
−40
−80
−120
−160
−200
CS30
CS30+phen.
DD
$(-V_C)$
Im V_{K^-} (MeV)
−20
−60
−100
CS30
DD
CS30+phen.
0
1
2
3
4
5
6
7
r (fm)

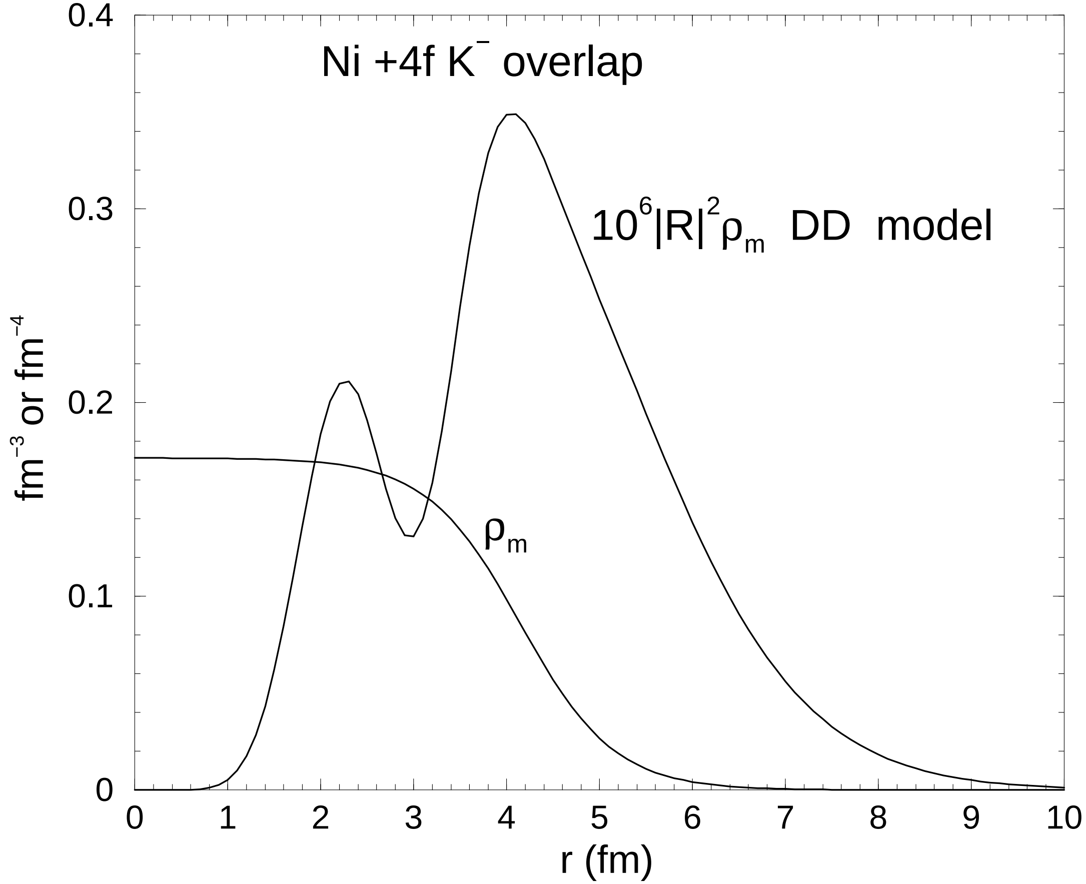


K⁻ Ni potentials without SE
Re V_{K^-} (MeV)
0
−40
−80
−120
−160
−200
TW1
TW1+phen.
DD
(−V_C)
Im V_{K^-} (MeV)
−20
−60
−100
TW1
DD
TW1+phen.
0
1
2
3
4
5
6
7
r (fm)

How large is the phenomenological potential?

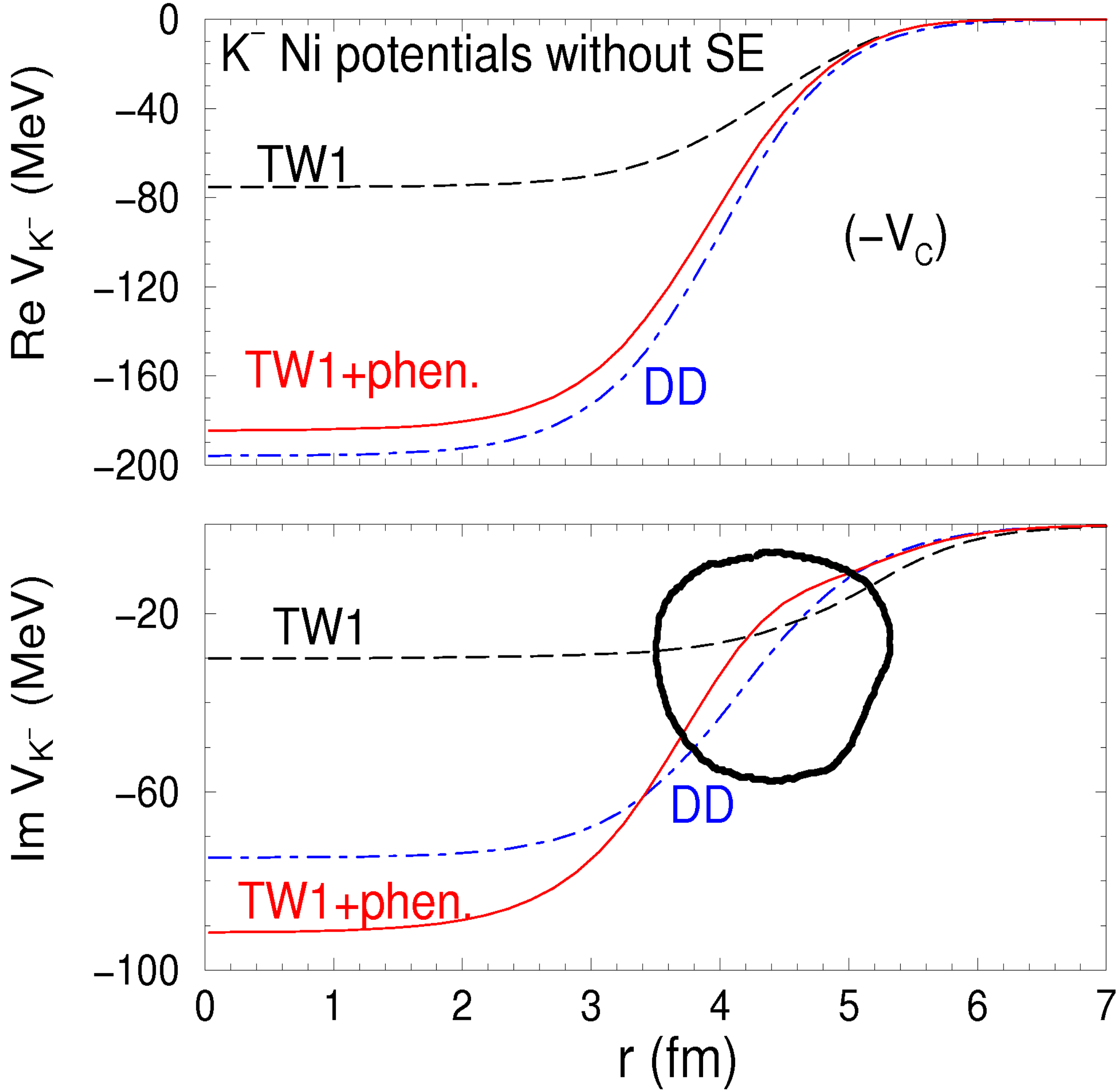


N. Barnea, E. Friedman, PRC **75** (2007) 022202(R).



Overlap of K^- atomic density with the nuclear density.

R_B =31.5 fm.



K⁻ Ni potentials without SE
Re V_{K^-} (MeV)
TW1
TW1+phen.
DD
(−V_C)
Im V_{K^-} (MeV)
TW1
DD
TW1+phen.
r (fm)
0
−40
−80
−120
−160
−200
−20
−60
−100
0 1 2 3 4 5 6 7

In the sensitive region near the surface the K^-N-based imaginary potential undergoes a *shape* change and is modified by up to 30%, consistent with emulsion data.

The real potential near the half-density point is 80-90 MeV deep.

The phenomenology is similar to that for pionic atoms where empirical ρ^2 contributions augment one-nucleon terms.

Contributions from the $I = 1$ $\Sigma(1385)$ resonance?

$$c_{K^-p} = \frac{\sqrt{s}\ \gamma_1}{s_0 - s - \mathrm{i}\sqrt{s}\ \Gamma} + d$$

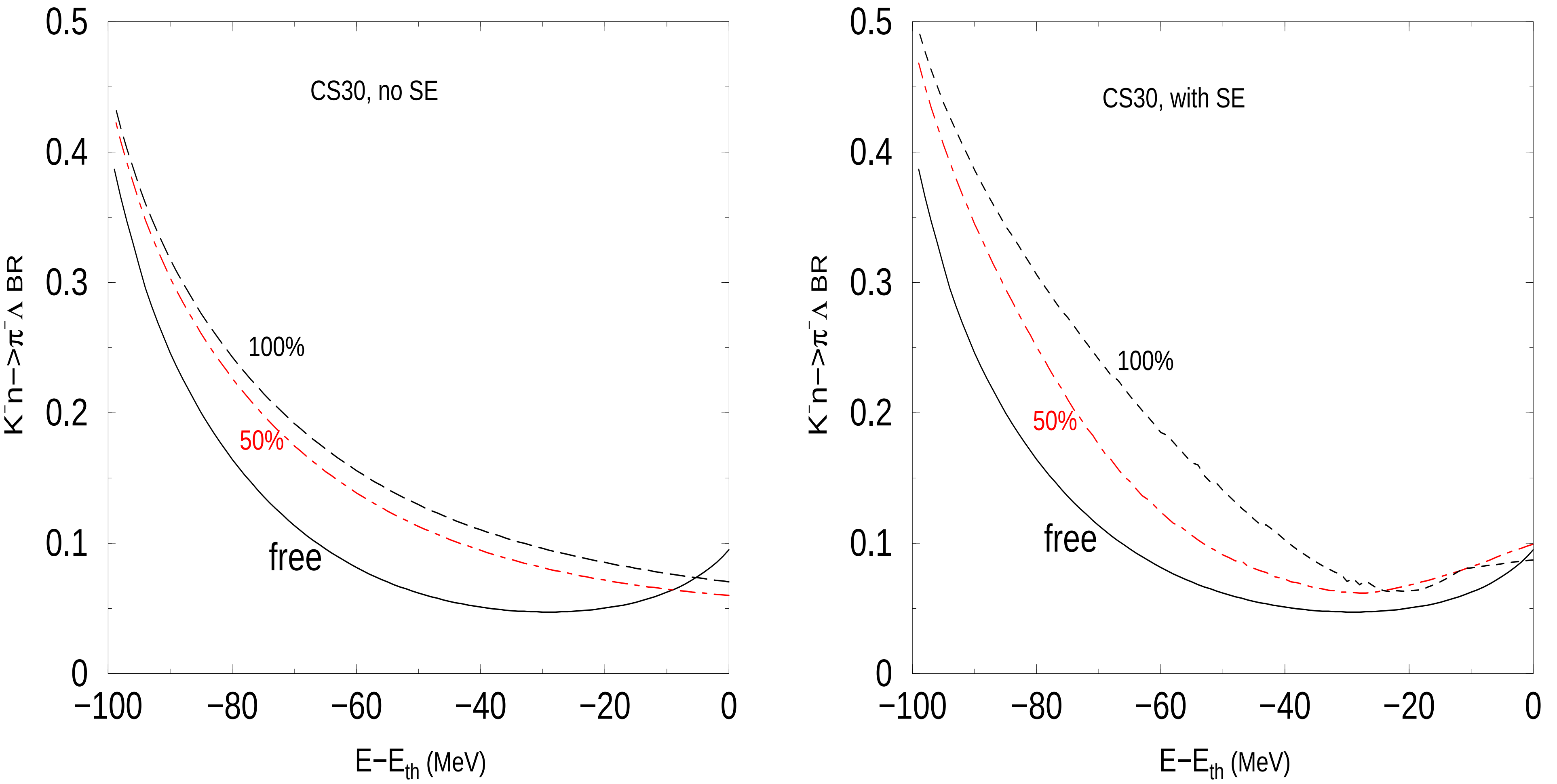
with $\sqrt{s}_0$=1385 MeV, γ_1=0.42/m_K^3, Γ=40 MeV and a background term d=0.06 fm^3.

Values of a 'microscopic' p-wave amplitude $c_0^m = (3/2)c_{K^-p}$ to be compared with the empirical $c_0 = -0.79 \pm 0.32 + \mathrm{i}(0.75 \pm 0.30)$ fm^3.

ρ/ρ_0	$\sqrt{s}$ (MeV)	Re c_0^m (fm^3)	Im c_0^m (fm^3)
0	1432	−0.09	0.08
0.25	1420	−0.12	0.12
0.50	1404	−0.16	0.25
0.75	1392	−0.06	0.44
1.00	1382	0.10	0.49

Studies of K^- nuclear capture at rest (branching ratios, absolute scales)

Constraints on the threshold K^- nuclear potential from FINUDA ${}^{A}Z(K^-_{stop},\pi^-)^{A}_{\Lambda}Z$ spectra, Phys. Lett. B **698** (2011) 226,
A. Ciepl ý, E. Friedman, A. Gal, V. Krejčiřík



Subthreshold energy dependence of the $K^- n \to \pi^- \Lambda$ branching ratio BR in the CS30 version.

For a given branching ratio function $\mathrm{BR}(\sqrt{s}, \rho)$ replace the threshold value of BR by

$$\overline{\mathrm{BR}} = \frac{1}{\overline{\rho}} \int \mathrm{BR}(\sqrt{s}, \rho)\, \rho(r) \mid \Psi_{nLM}(\mathbf{r}) \mid^2 \ d^3r$$

with the average density determined by the overlap with the atomic K^- wavefunction

$$\overline{\rho} = \int \rho(r) \mid \Psi_{nLM}(\mathbf{r}) \mid^2 \ d^3r.$$

Future directions

- Multi-nucleon processes

In analogy with pionic atoms, need a phenomenological $B\rho^2/\rho_0$ term for absorption. A disperssive term is also found. 'Microscopic' theory is lacking in both cases.

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- p-wave term

So far data do not support a p-wave sub-threshold term. More studies required.

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- p-wave term

So far data do not support a p-wave sub-threshold term. More studies required.

- Can studies of 'lower' and 'upper' levels in a <u>given</u> atom supplement 'global' results?

- Studies of K^- nuclear capture at rest (branching ratios, absolute scales)

Constraints on the threshold K^- nuclear potential from FINUDA ${}^AZ(K^-_{stop},\pi^-){}^A_\Lambda Z$ spectra, Phys. Lett. B **698** (2011) 226,
A. Cieplý, E. Friedman, A. Gal, V. Krejčiřík

Deep or shallow: additional experiments ?

Comparing full and reduced data sets

N	χ^2	Reb(fm)	Imb(fm)	χ^2	ReB(fm)	ImB(fm)
65	130	0.62±0.05	0.93±0.04	84	1.44±0.03	0.59±0.03
12	37	0.80±0.15	0.95±0.12	22	1.47±0.05	0.56±0.06
		shallow			deep	

Fits to a reduced data set of C, Si, Ni and Pb produce all the features obtained from fits to the full data.

Repeating some of the K^- atom experiments?

Typical quantities for the reduced set of kaonic atoms

target	C	Si	Ni	Sn	Pb
ref	(a)	(b)	(b),(c)	(b)	(d)
(n,l)	2p	3d	4f	5g	7i
$-\epsilon$ (keV)	0.50 ± 0.08	0.130 ± 0.015	0.223 ± 0.042	0.41 ± 0.18	0.020 ± 0.012
Γ (keV)	1.73 ± 0.15	0.800 ± 0.033	1.03 ± 0.12	3.18 ± 0.64	0.37 ± 0.15
yield	0.070 ± 0.013	0.49 ± 0.03	0.30 ± 0.08	0.39 ± 0.07	0.70 ± 0.08
Γ_u (eV)	0.99 ± 66	0.53 ± 0.06	5.9 ± 2.3	15.1 ± 4.4	4.1 ± 2.0
EM n+1$\rightarrow$n energy (keV)	63.3	123.7	231.6	403.9	426.2

(a) PLB **38** 181 (1972)

(b) NPA **329** 407 (1979)

(c) NPA **231** 477 (1974)

(d) NPA **254** 381 (1975)

The ^{4}He 'puzzle' essentially solved:

Old result (average of three experiments)

shift($2p$)$=-43 \pm 8$ eV.

All reasonable predictions shift($2p$)$\approx 0 \pm 2$ eV.

E570 @ KEK shift($2p$)$=2 \pm 2$(stat)± 2(sys) eV.

SIDDHARTA shift($2p$)$=0 \pm 6$(stat)± 2(sys) eV.

J-PARC E17 scheduled for 'Day-1' for kaonic ^{3}He.

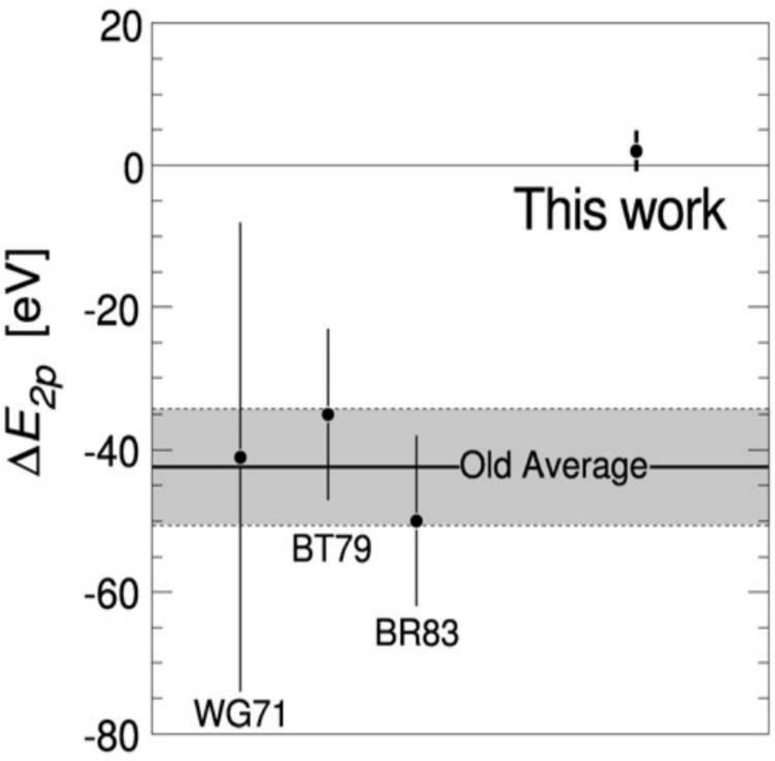

Fig. 4. The $2p$-level shift of kaonic ^{4}He, ΔE_{2p}, obtained from this work and the past three experiments (WG71 [2], BT79 [3], BR83 [4]). Error bars show quadratically added statistical and systematic errors. The average of these past experiments is indicated by the horizontal gray band.

Kaonic ^{4}He ‘puzzle’ solved: PLB **653** (2007) 387.

Predictions for the 2p level in kaonic He isotopes (in eV).

		^{3}He		^{4}He	
added phen.	1385 res.	shift	width	shift	width
no	no	0.2	1.9	0.4	2.1
no	yes	-0.1	1.9	-0.1	2.3
yes	no	0.3	2.1	-0.2	1.6
yes	yes	0.0	1.9	-0.3	1.9

Summary

- Geometry of 'global' potentials reveal ρ-dependence of underlying K^-N interaction.
- Self-consistent handling of sub-threshold amplitudes enable construction of *average* K^--nucleus potentials.
- Confronting with kaonic atom data the lack of K^-NN terms is evident. These can be a source of information on sub-threshold processes.
- Need to study absorption-at-rest, branching ratios and absolute scale.
- Role of p-wave term is unclear.

- Additional experiments on few selected nuclei will be useful.
- Complementary to ‘global’ fits: study two levels in a given atom.

Acknowledgements

Thanks to Aleš Cieplý, Avraham Gal, Daniel Gazda and Jiří Mareš for the collective 'subthreshold' efforts.