The kaonic atoms ‘puzzle’

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SPHERE meeting, Prague September 2010

OUTLINE

- Kaonic atoms as an itermediate scenario
- Deep or shallow real potential?
- Consequences for neutron stars
- Consequences for $\bar{K}NNN$.... clusters
- Radial sensitivity
- Reduced data and proposed experiments

Different scenarios for different exotic atoms

particle	real potl.	imaginary potl.	comments
π^-	repulsive in bulk	moderate	excellent data
	attractive on surface		well understood
K^-	attractive	moderate	good data
	deep or shallow?		open problems
$\bar{p}$	model dependent	very absorptive	excellent data
			understood
Σ^-	repulsive in bulk	moderate	limited data
	attractive outside		poorly understood

Phenomenological analyses of data:

- handle large sets of data
- Could identify characteristic quantities
- serve as intermediaries between 'genuine' 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.

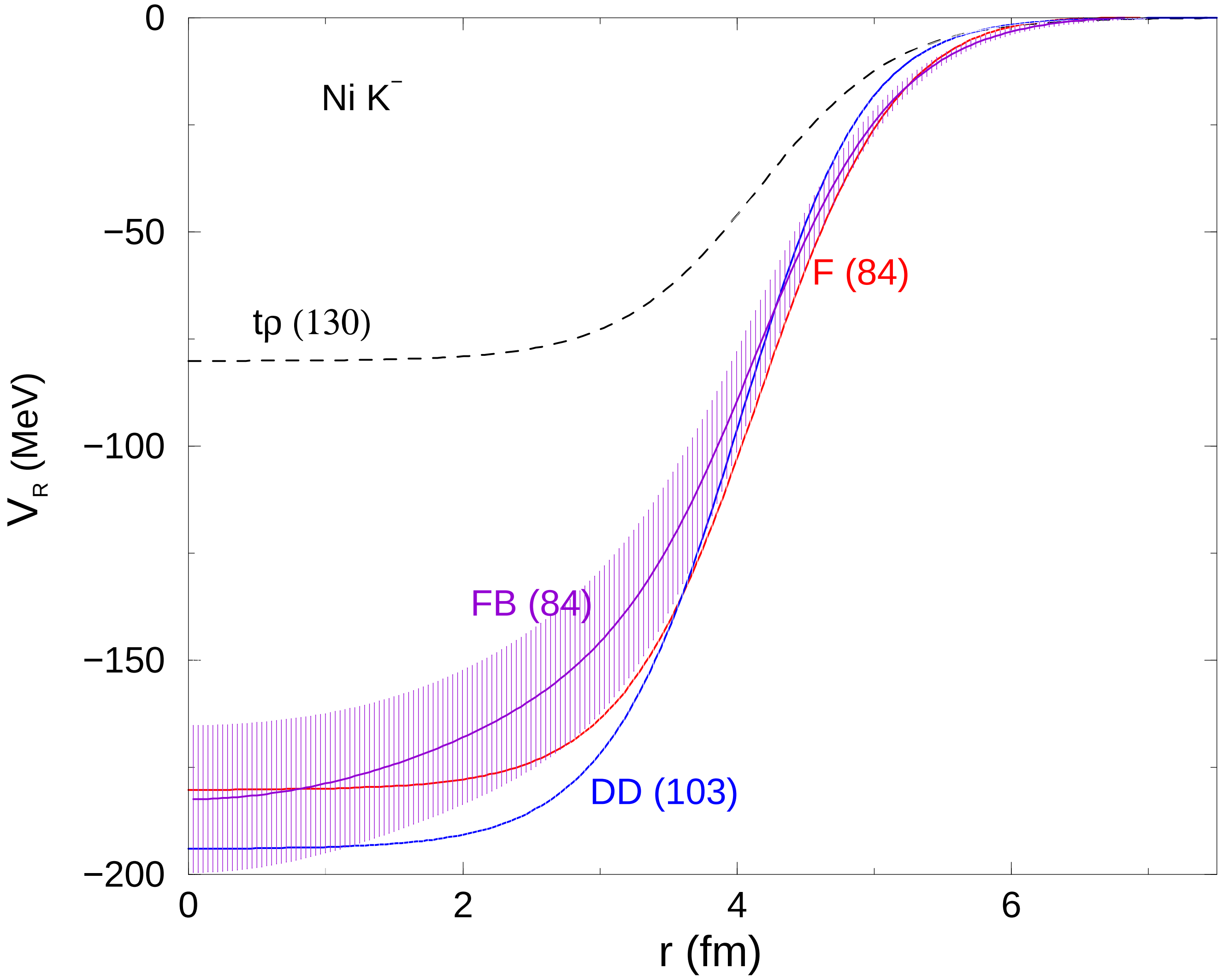
Results of global fits apply to average behaviour.

Global fits to kaonic atoms data (65 points)

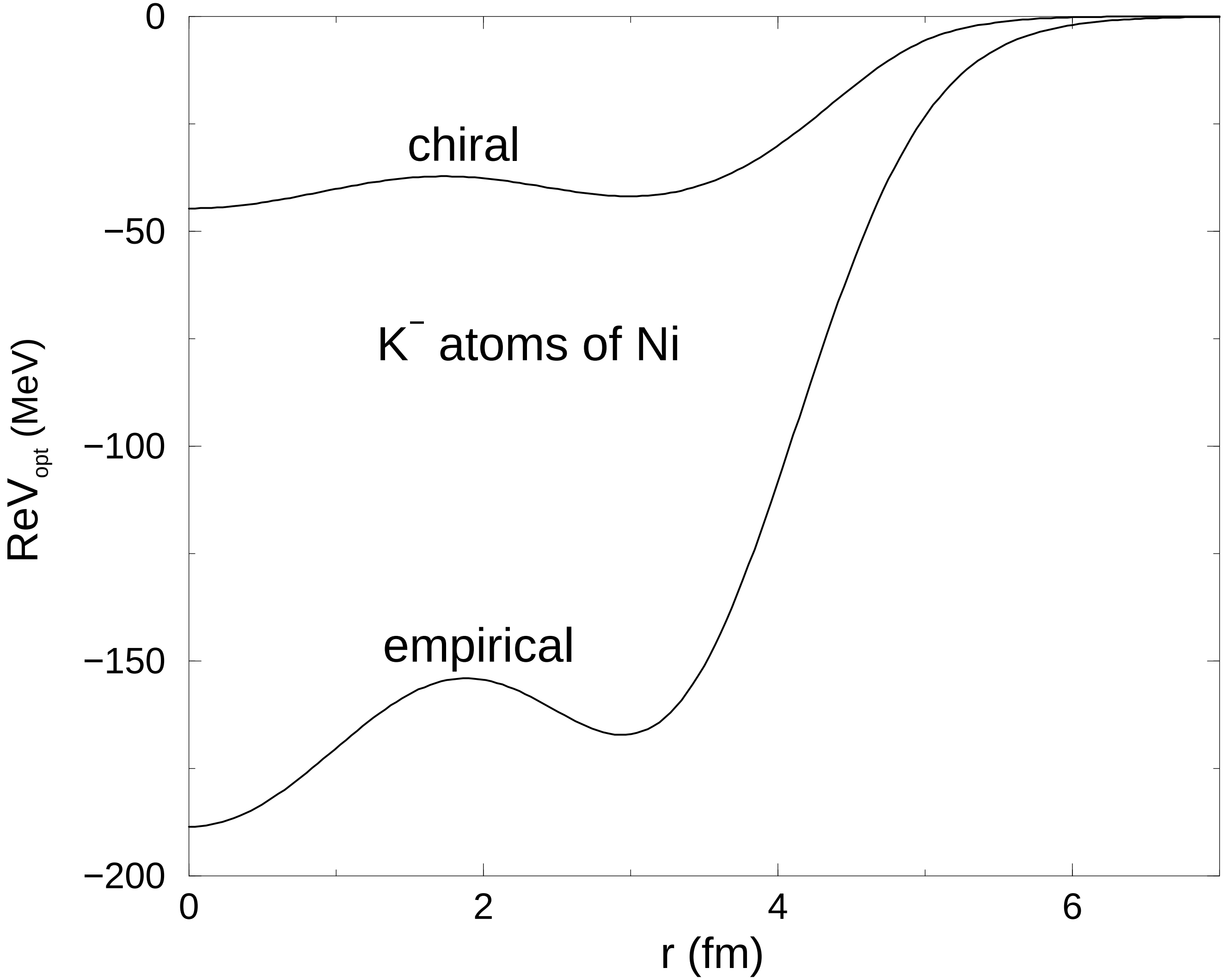
model	χ^2	$-\mathrm{Re}V(0)$ (MeV)	$-\mathrm{Im}V(0)$ (MeV)
$t\rho$	130	81(±10%)	122(±5%)
$t(\rho)\rho$	84	180(±3.5%)	82(±8%)
chiral *	266	33	45
chiral **	120	42	62

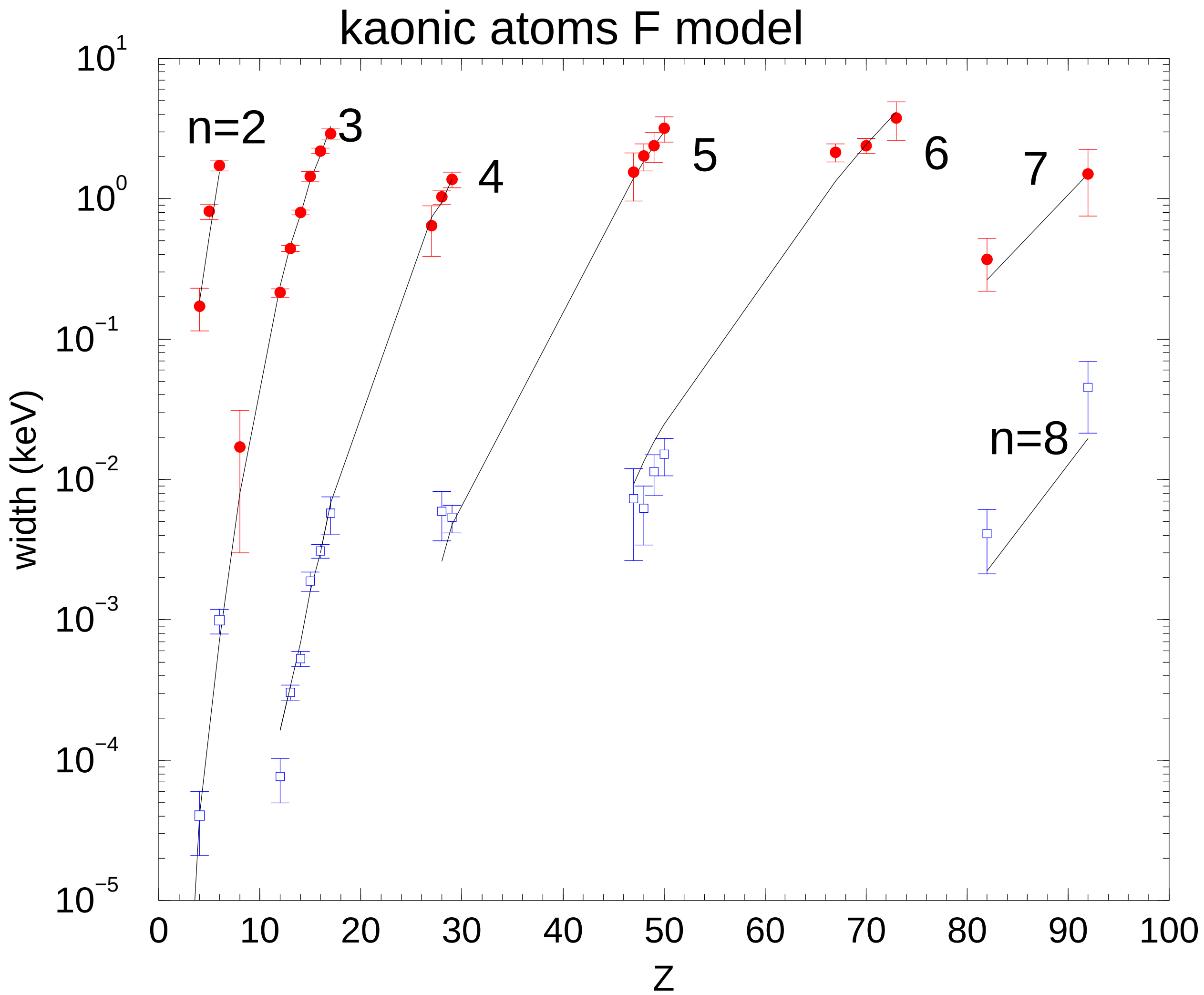
*Ramos & Oset, NPA **671** (2000) 481

** I=1 adjusted by +50% and +63% for Re and Im, respectively



In brackets values of χ^2 for 65 data points.


0
−50
−100
−150
−200
0
2
4
6
r (fm)
ReV$_{opt}$ (MeV)
chiral
K$^-$ atoms of Ni
empirical



Quality fits over five orders of magnitude.

ELSEVIER

Nuclear Physics A579 (1994) 518–538

NUCLEAR
PHYSICS A

Density-dependent K^- nuclear optical potentials from kaonic atoms

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Received 15 February 1994; revised 11 May 1994

On the list of most cited NPA papers in 1995.

159 citations till May 2010

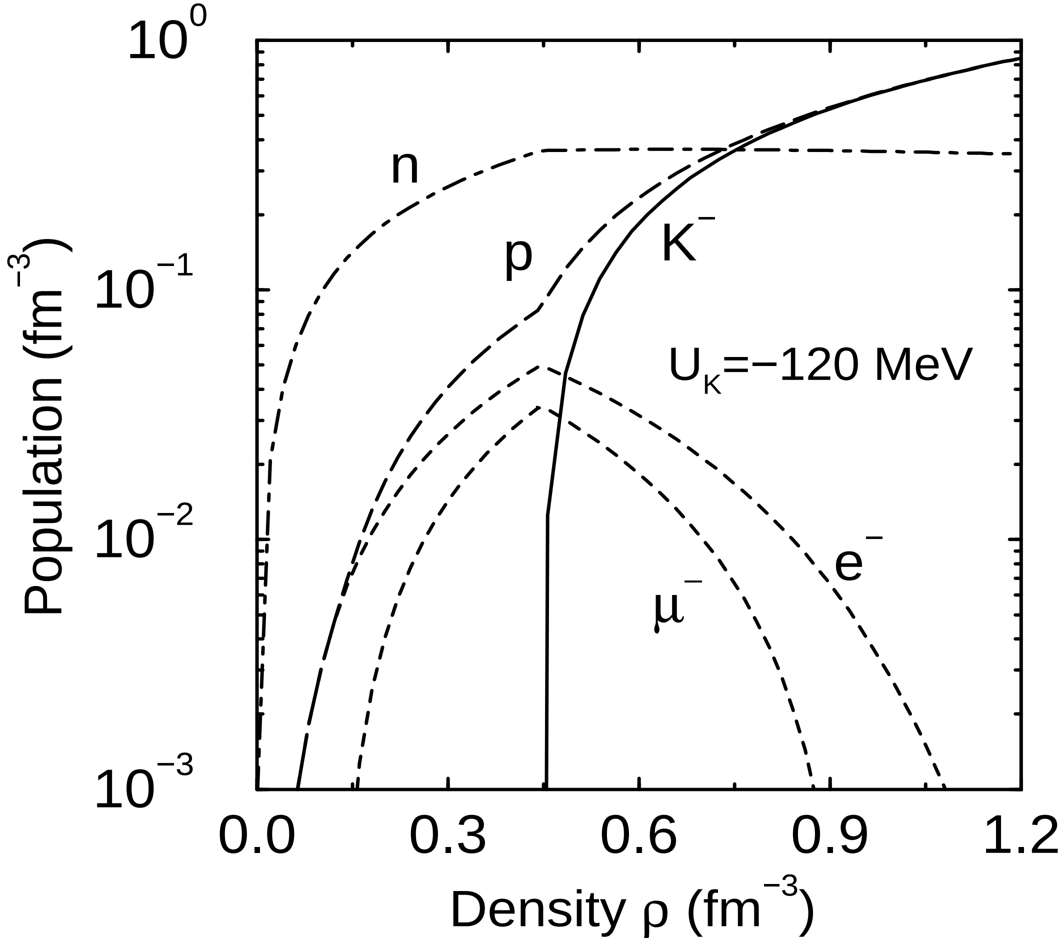
Kaon condensation in neutron stars, when weak decays are Pauli blocked:

$$n \longrightarrow p + K^-,$$

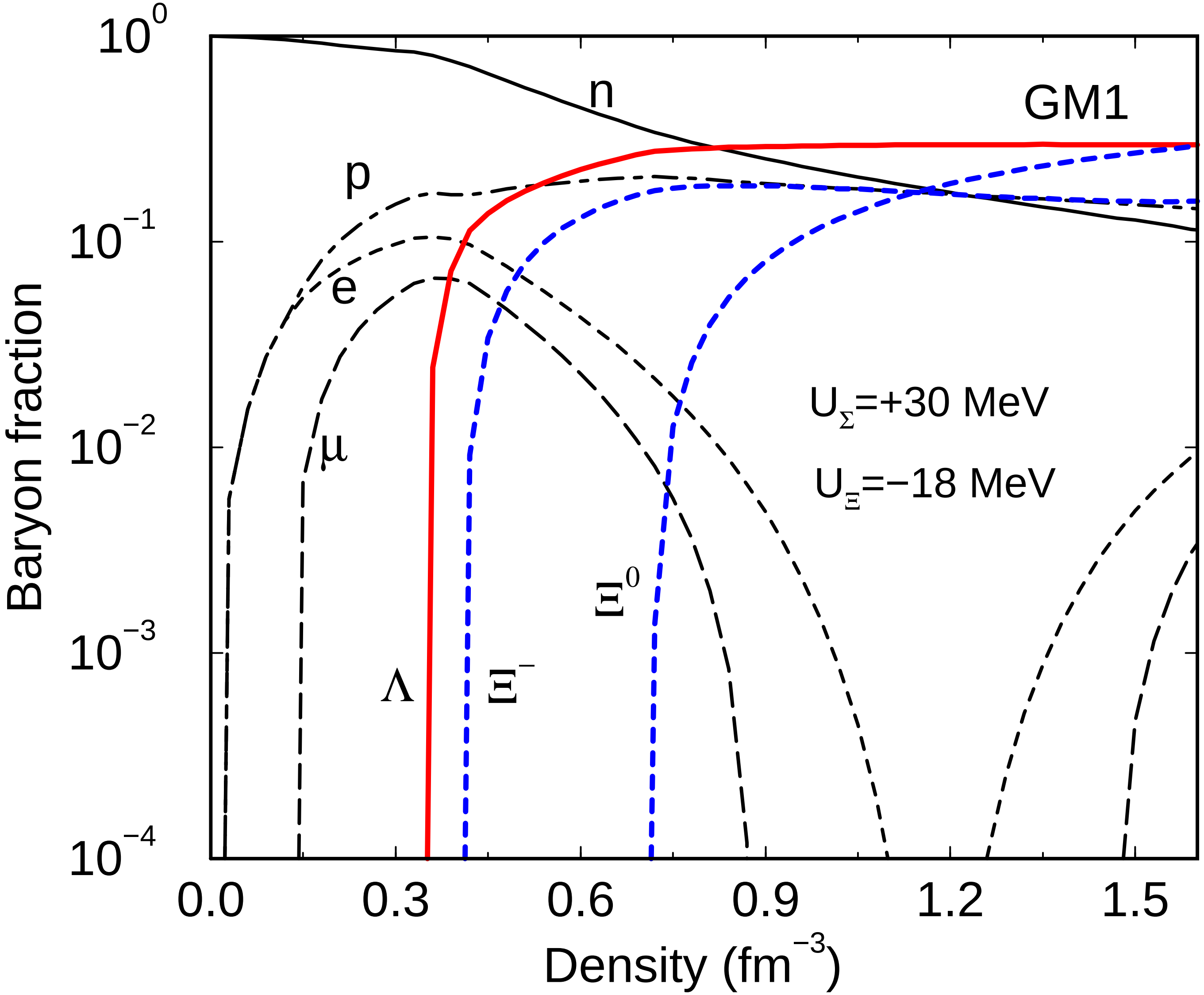
$$e^- \longrightarrow K^- + \nu_e.$$

Strangeness makes the Equation of State softer.

From Glendenning and Schaffner-Bielich, PRC **60** 025803 (1999)



From J. Schaffner-Bielich, NPA **835** (2010) 279.



From W. Weise, ECT* Trento, October 2009

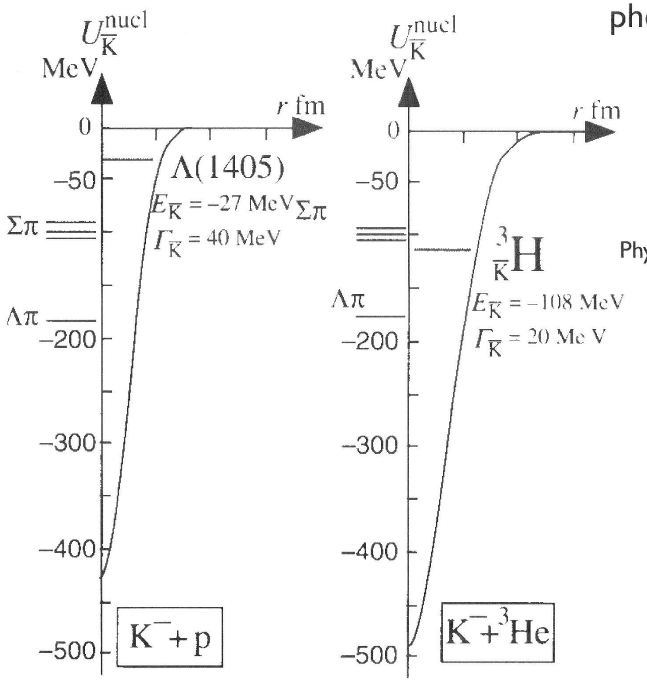
.

Brief History, Part III

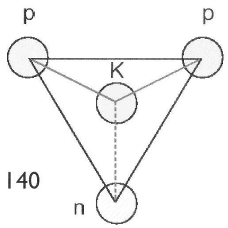
Deeply Bound Antikaon-Nuclear Clusters ?

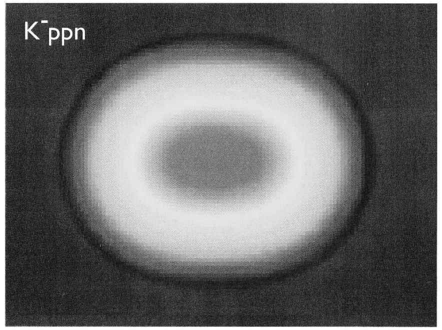
Y. Akaishi, T. Yamazaki, Phys. Rev. C65 (2002) 044005

- Calculation of deeply bound K^-ppn system using phenomenological $\bar{K}N$ and NN potentials



Y. Akaishi,
A. Doté,
T. Yamazaki,
Phys. Lett. B613 (2005) 140

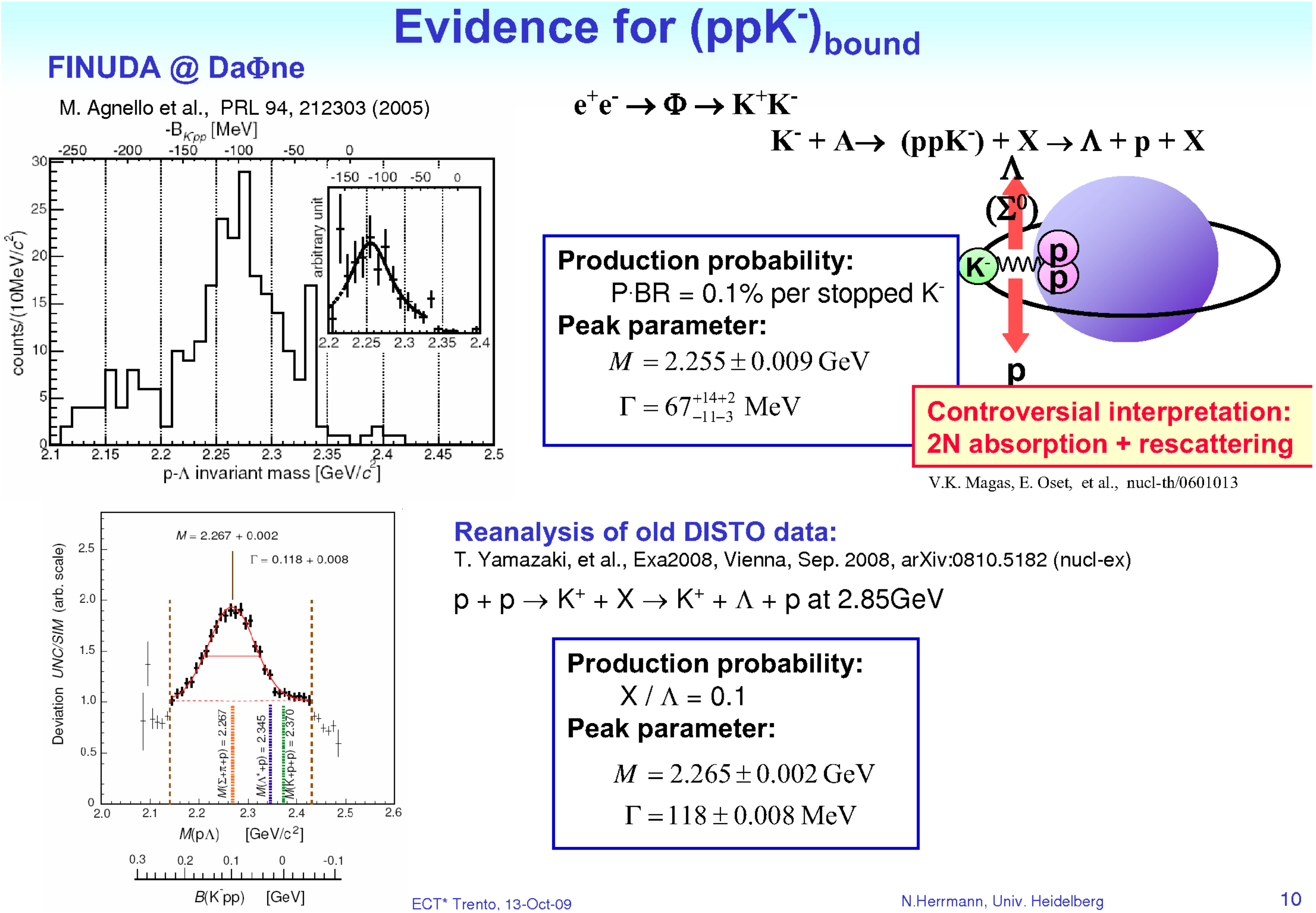




... **too simple**, but has motivated a great amount of recent activities

Technische Universität München

From N. Hermann, ECT* Trento, October 2009



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Nuclear Physics A 770 (2006) 84–105

NUCLEAR PHYSICS A

$\bar{K}$–nuclear bound states in a dynamical model

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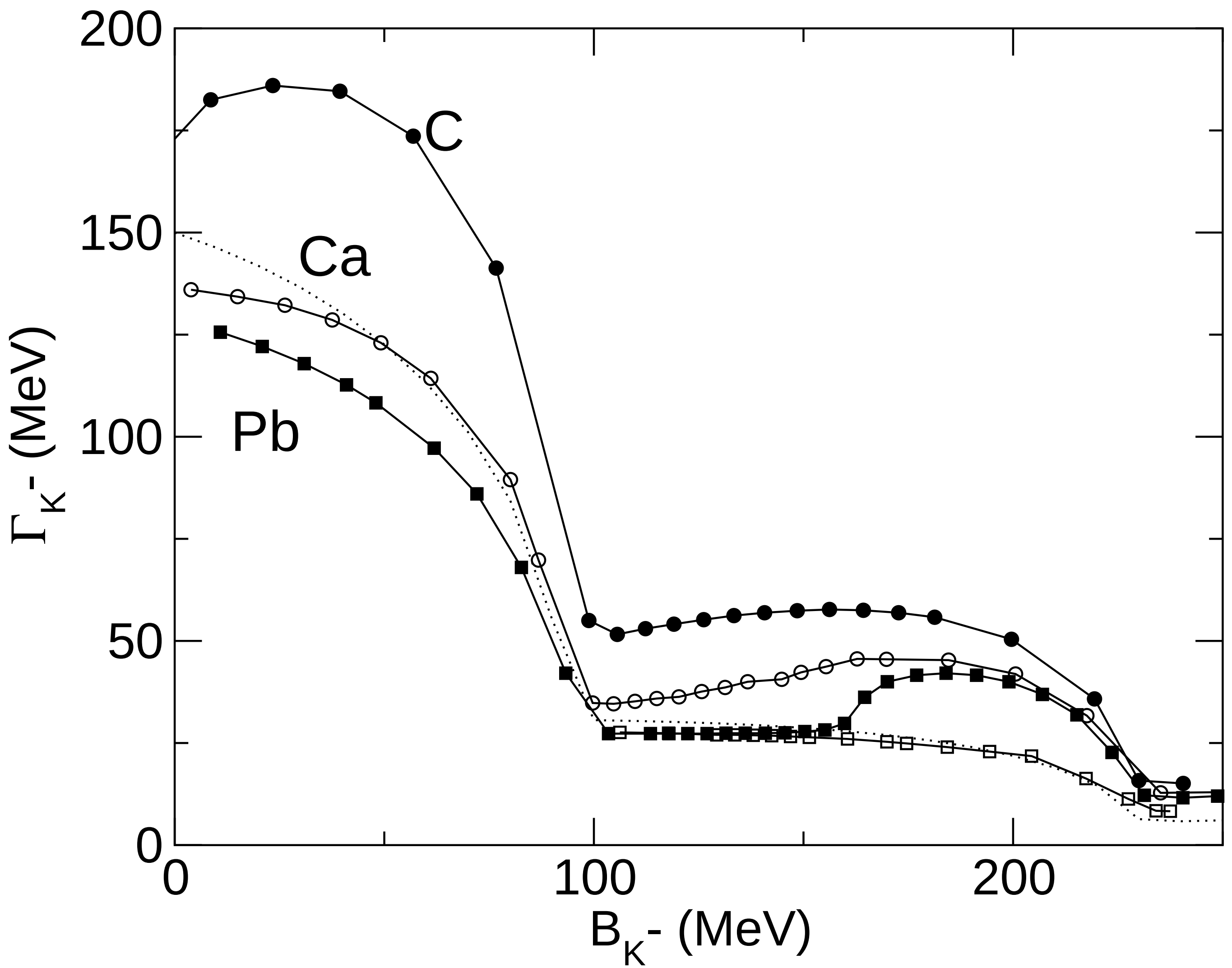
Received 5 January 2006; received in revised form 2 February 2006; accepted 24 February 2006

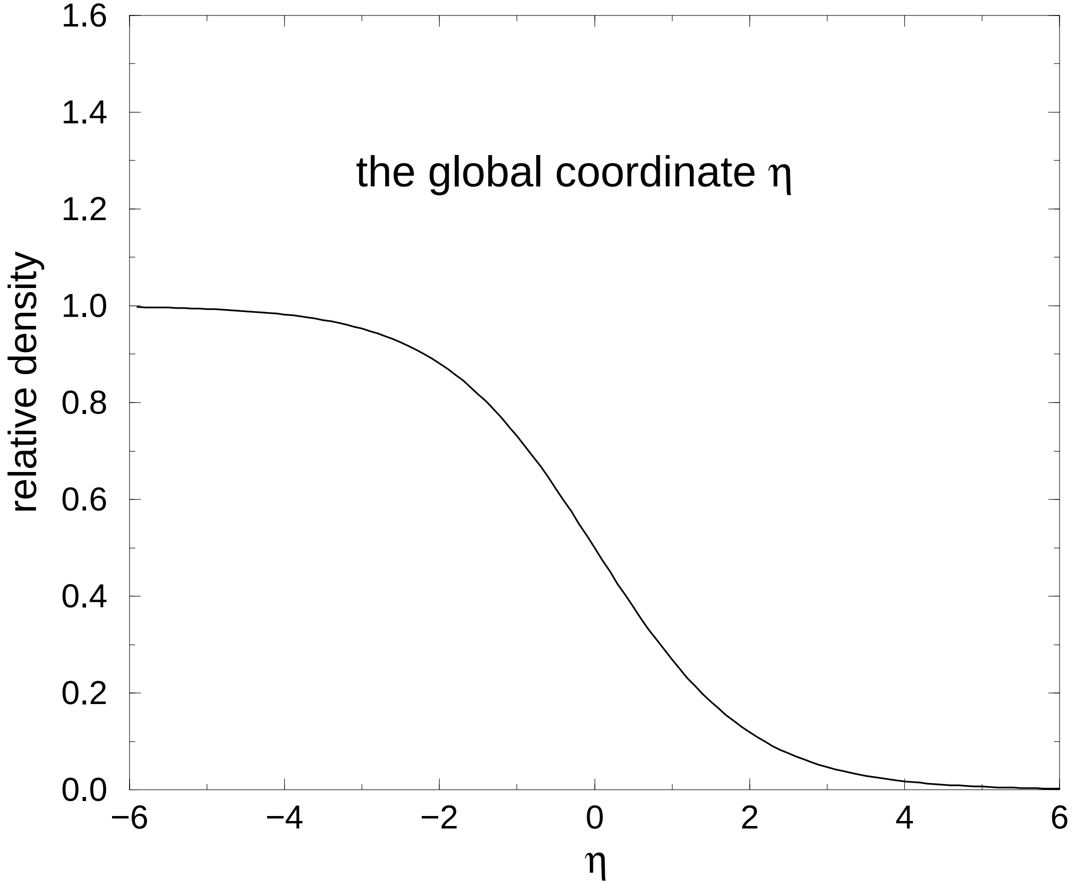
Available online 10 March 2006

(60 citations till May 2010)



The importance of widths!

Are exotic atom data sensitive to the nuclear interior?



Define η by $r = R_c + \eta\, a_c$. The value of χ^2 becomes a functional of a global optical potential $V(\eta)$.

The functional derivative method

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

The variation of χ^2 due to a small change in η is

$$d\chi^2 = \int d\eta \frac{\delta \chi^2}{\delta V(\eta)} \delta V(\eta) \ ,$$

where

$$\frac{\delta \chi^2 [V(\eta)]}{\delta V(\eta')} =$$

$$\lim_{\sigma \to 0} \lim_{\epsilon_V \to 0} \frac{\chi^2 [V(\eta) + \epsilon_V \delta_\sigma (\eta - \eta')] - \chi^2 [V(\eta)]}{\epsilon_V}$$

is the functional derivatives (FD) of $\chi^2[V]$.

The FD can be approximated by

$$\approx \frac{1}{V(\eta')} \frac{\chi^2[V(\eta)(1+\epsilon\delta_\sigma(\eta-\eta'))] - \chi^2[V(\eta)]}{\epsilon} \ .$$

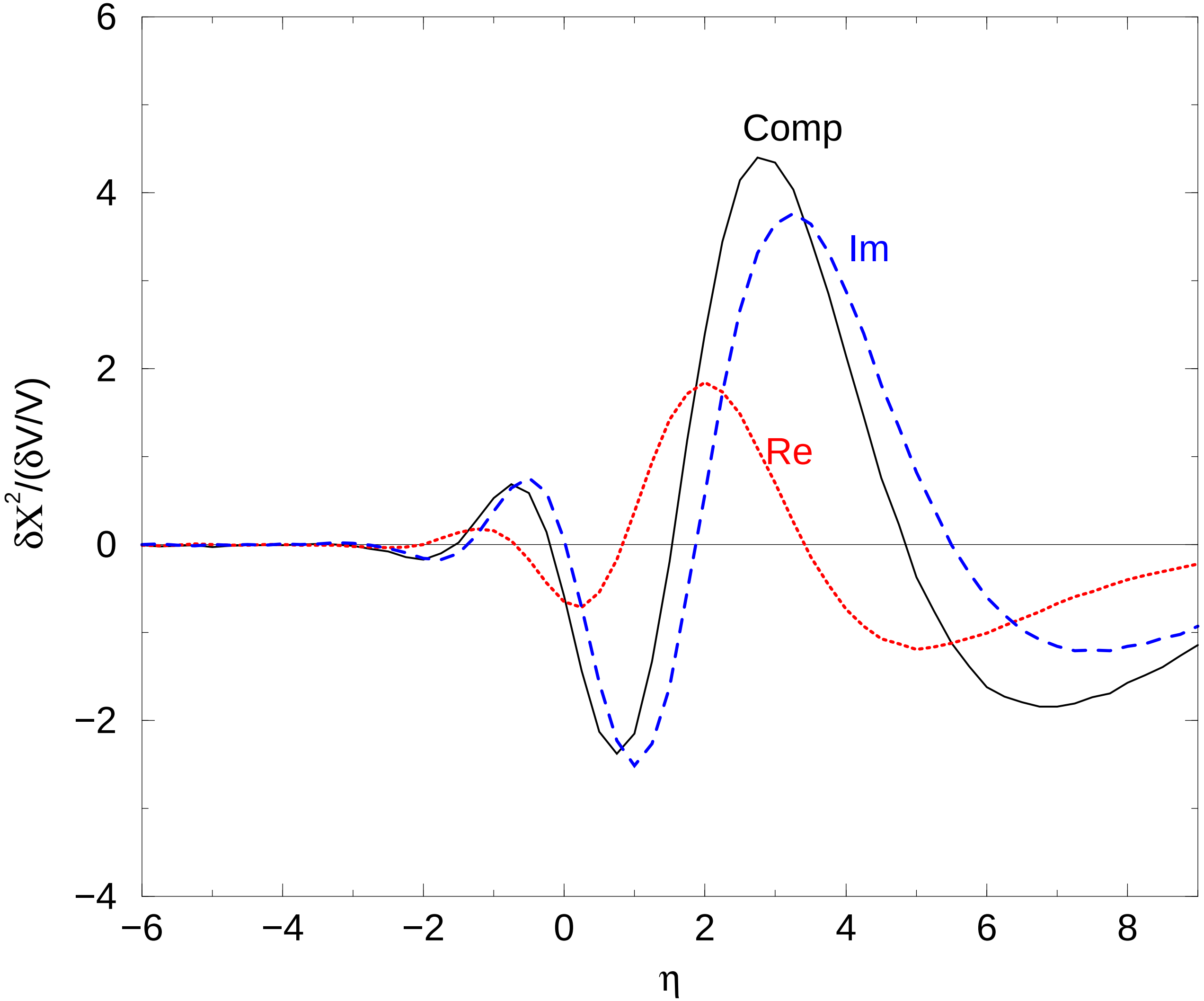
The limit $\epsilon \to 0$ is obtained numerically for several values of σ and then extrapolated to $\sigma = 0$.

In practice the calculation of the FD was carried out by multiplying the best fit potential by a factor

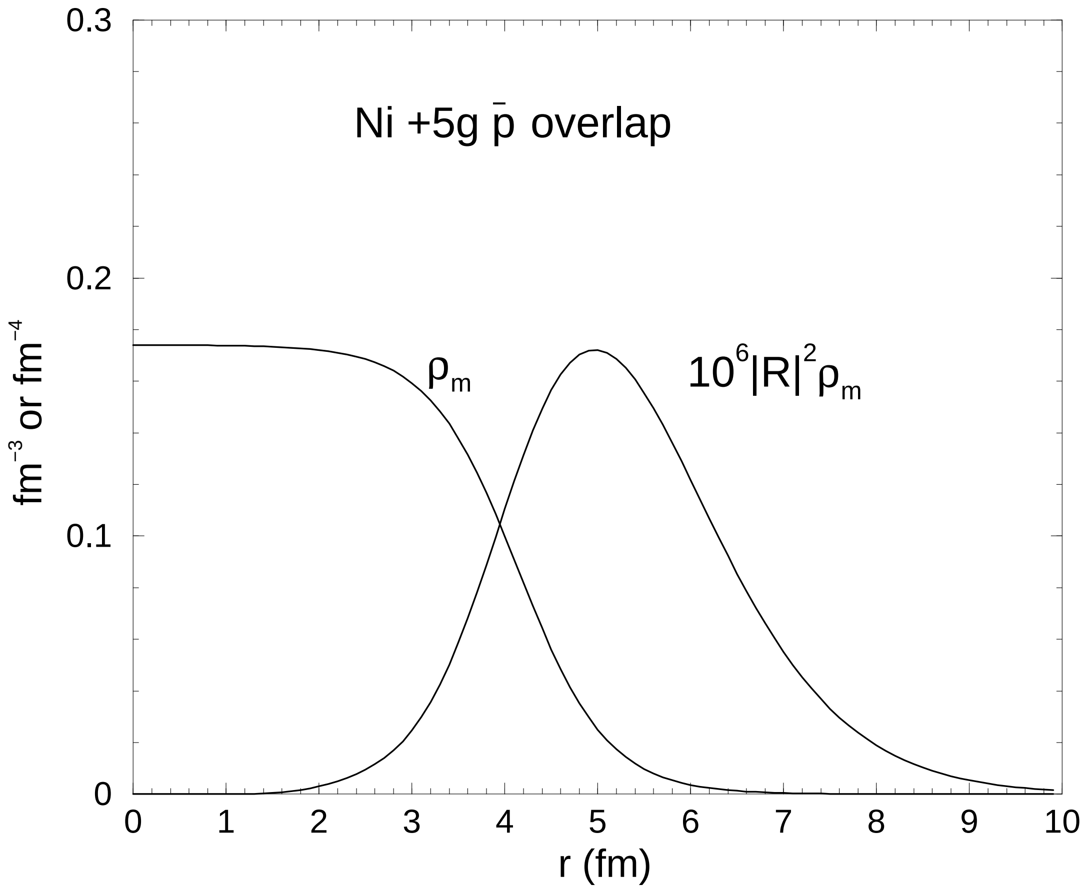
$$f = 1 + \epsilon\delta_\sigma(\eta - \eta') \tag{1}$$

using a normalized Gaussian with a range parameter σ for the smeared δ-function,

$$\delta_\sigma(\eta - \eta') = \frac{1}{\sqrt{2\pi}\sigma} e^{-(\eta-\eta')^2/2\sigma^2}. \tag{2}$$

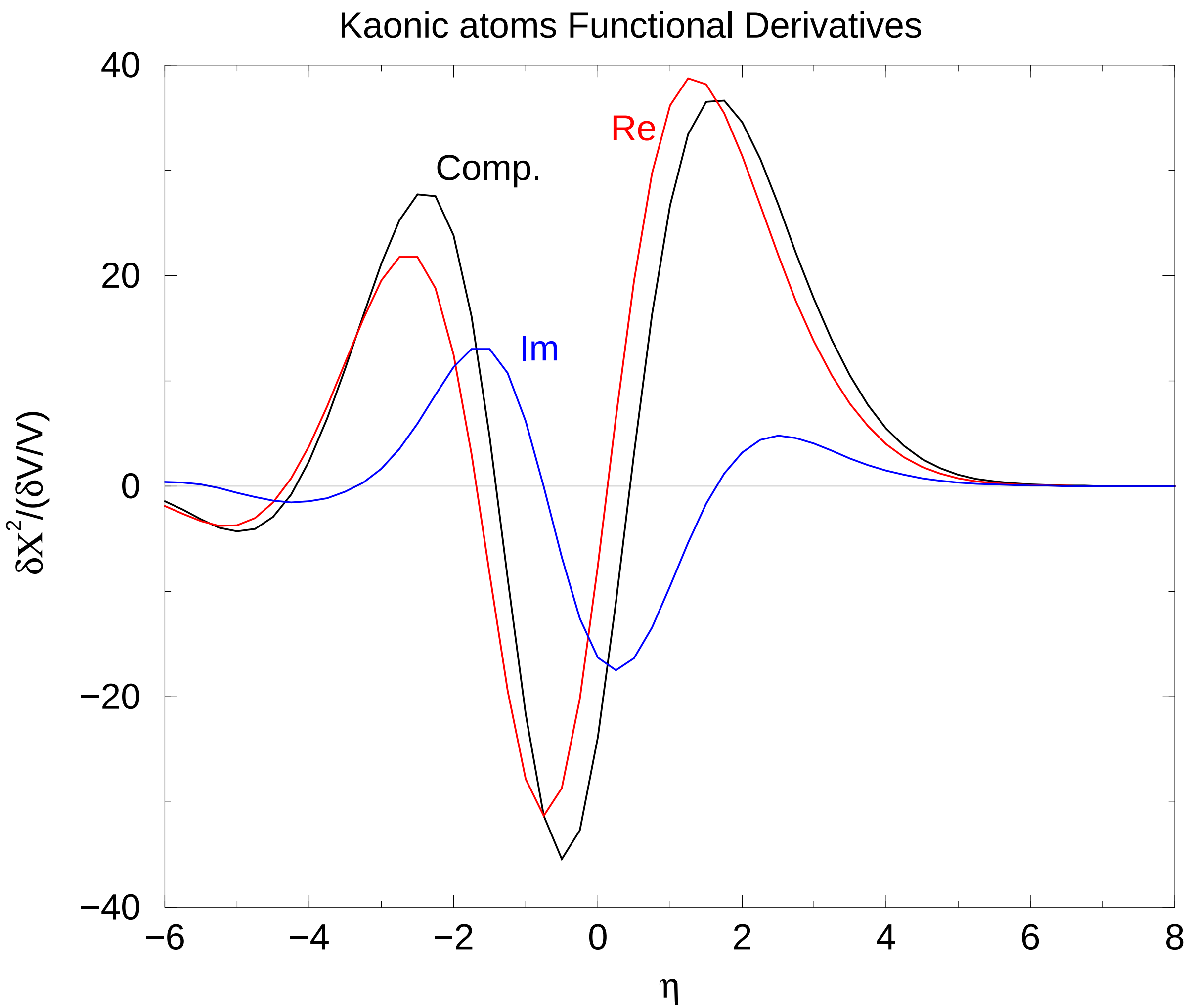


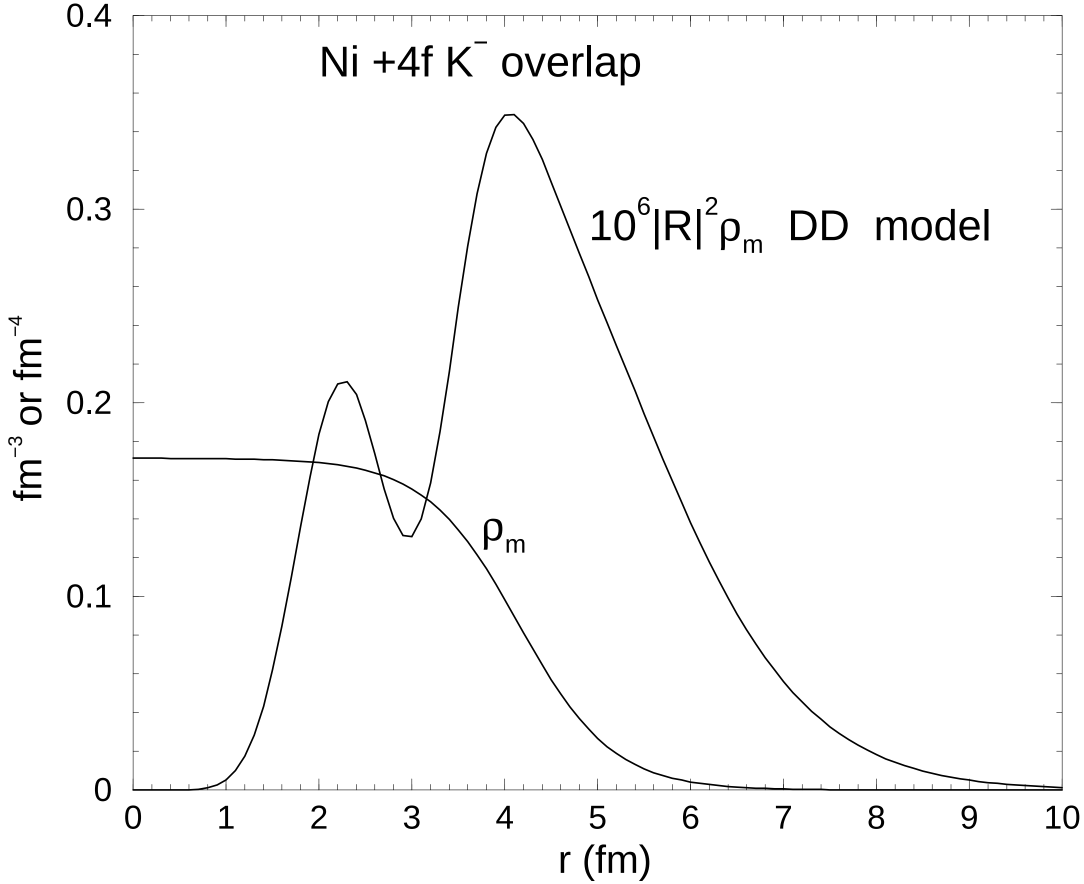
Functional derivatives for antiprotonic atoms χ^2



Overlap of $\bar{p}$ atomic density with the nuclear density.

R_B =26.1 fm.

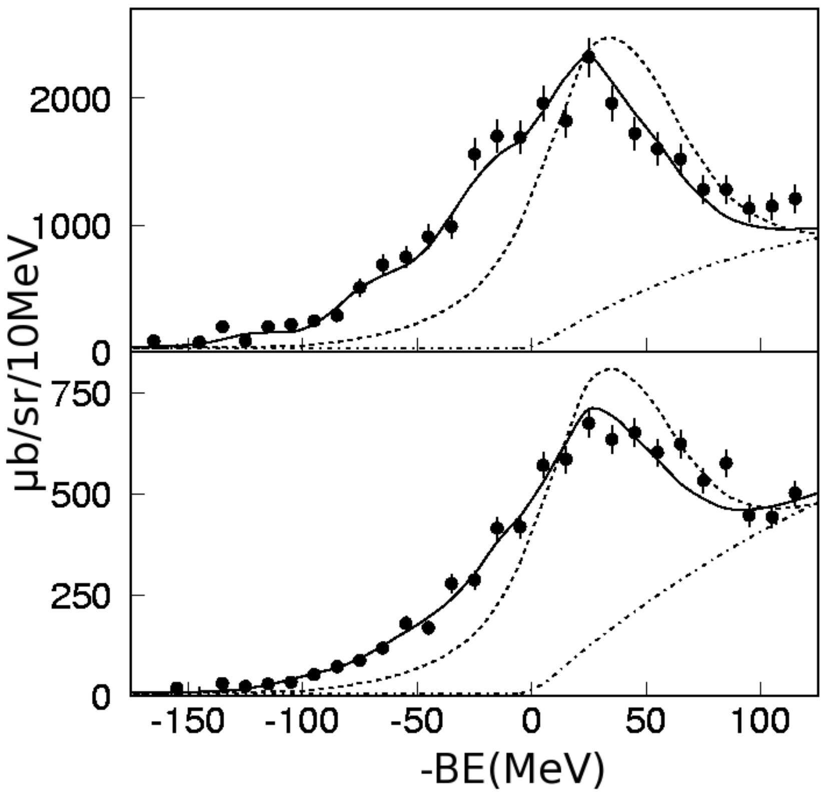

Kaonic atoms Functional Derivatives
Comp.
Re
Im
δX²/(δV/V)
η
40
20
0
−20
−40
−6
−4
−2
0
2
4
6
8



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

R_B =31.5 fm.

Supporting evidence for a deep potential, Kishimoto *et.al,* (2007)



KEK-PS E548 missing mass (K^-, n) (upper) & (K^-, p) (lower) spectra on ^{12}C at $p_{K^-} = 1$ GeV/c.

Is there an experimental problem?

Focusing on targets with large χ^2 for the shallow potential:

- conflicting χ_Γ and χ_Y, i.e. no systematics
- when removed from data base, still the same two solutions (deep and shallow)

The two solutions are inherent property of the data.

Comparing full and 'less' 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
56	78	0.57±0.05	0.97±0.04	66	1.44±0.04	0.60±0.04
	shallow			deep		

Removing data for C, Mg and Si (three different experiments!) the two solutions are still there.

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$\longrightarrow$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)

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.

Shallow best-fit kaonic atoms potentials

targets	N	χ^2	Re(fm)	Im(fm)
all	65	130	0.59 ± 0.05	0.94 ± 0.05
C, Si, Ni, Sn, Pb	15	44	0.78 ± 0.13	0.92 ± 0.11
C, Si, Ni, Pb	12	37	0.80 ± 0.15	0.95 ± 0.12
C, Si, Ni, Sn,	12	43	0.78 ± 0.15	0.90 ± 0.14
Si, Ni, Sn,	9	31	0.68 ± 0.16	0.91 ± 0.14

Deep best-fit kaonic atoms potentials

targets	N	χ^2	Re(fm)	Im(fm)
all	65	84	1.44 ± 0.03	0.59 ± 0.03
C, Si, Ni, Sn, Pb	15	26	1.47 ± 0.05	0.55 ± 0.06
C, Si, Ni, Pb	12	22	1.47 ± 0.05	0.56 ± 0.06
C, Si, Ni, Sn,	12	24	1.47 ± 0.05	0.55 ± 0.06
Si, Ni, Sn,	9	13	1.47 ± 0.05	0.52 ± 0.05

Summary

- Kaonic atoms favour deep real K^--nucleus potential.
- Deep potentials have consequences for neutron stars and for K^-NNN... clusters.
- Functional-derivative analysis shows sensitivity to the interior.
- Fits to reduced data sets reveal all the features of full fits.
- 4-5 targets are proposed for new measurements.

Summary

- Kaonic atoms favour deep real K^--nucleus potential.
- Deep potentials have consequences for neutron stars and for K^-NNN... clusters.
- Functional-derivative analysis shows sensitivity to the interior.
- Fits to reduced data sets reveal all the features of full fits.
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THANKS to Avraham Gal for long time collaboration!