K^-NN-oriented phenomenology of kaonic atoms and future experiments

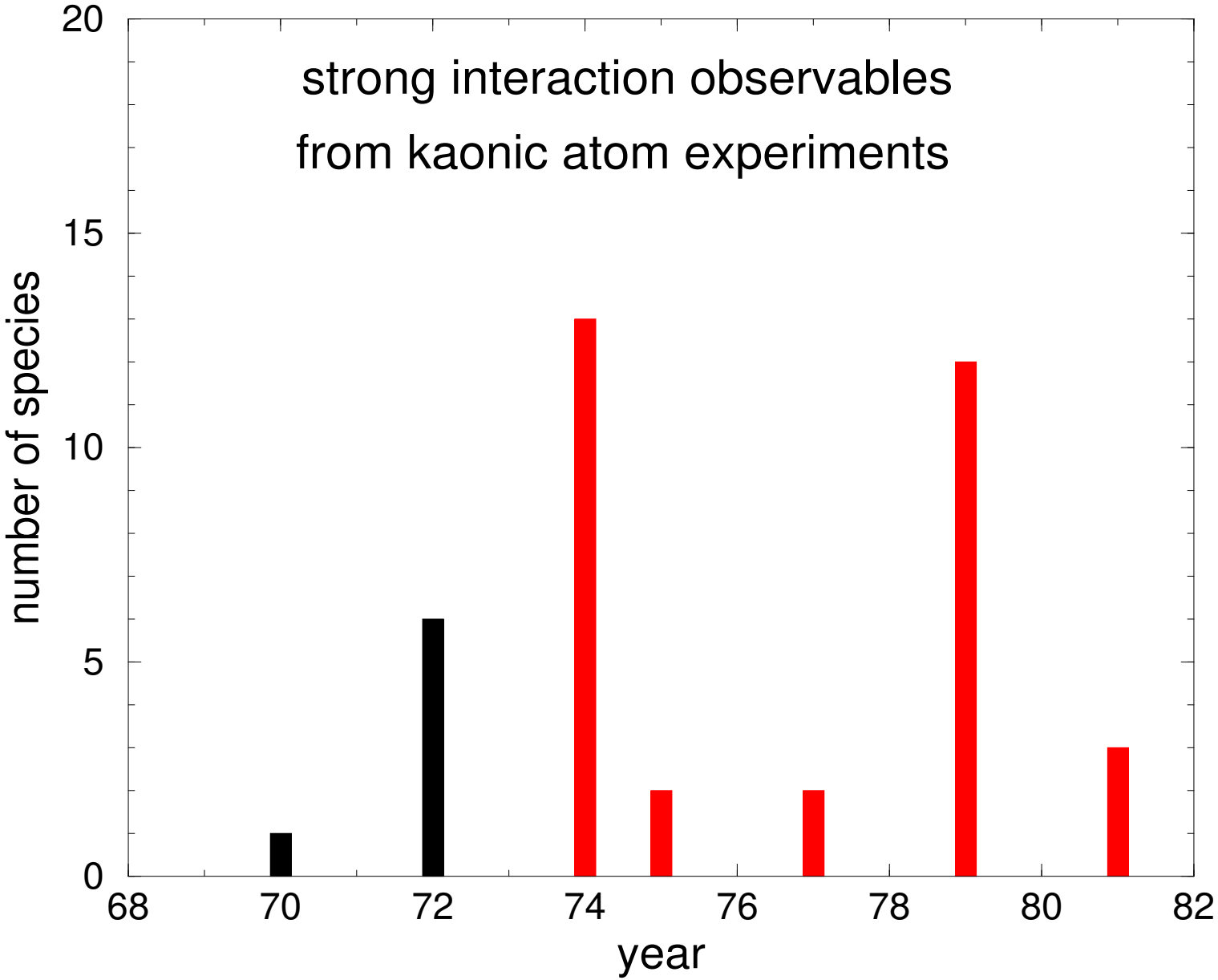
E. Friedman

Racah Institute of Physics, Hebrew University, Jerusalem

DAΦNE zoom meeting, 25-26 February 2021

Outline

- Experimental background
- Evolution of analyses
- K^-NN-guided phenomenology
- What next?


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

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. (1993)

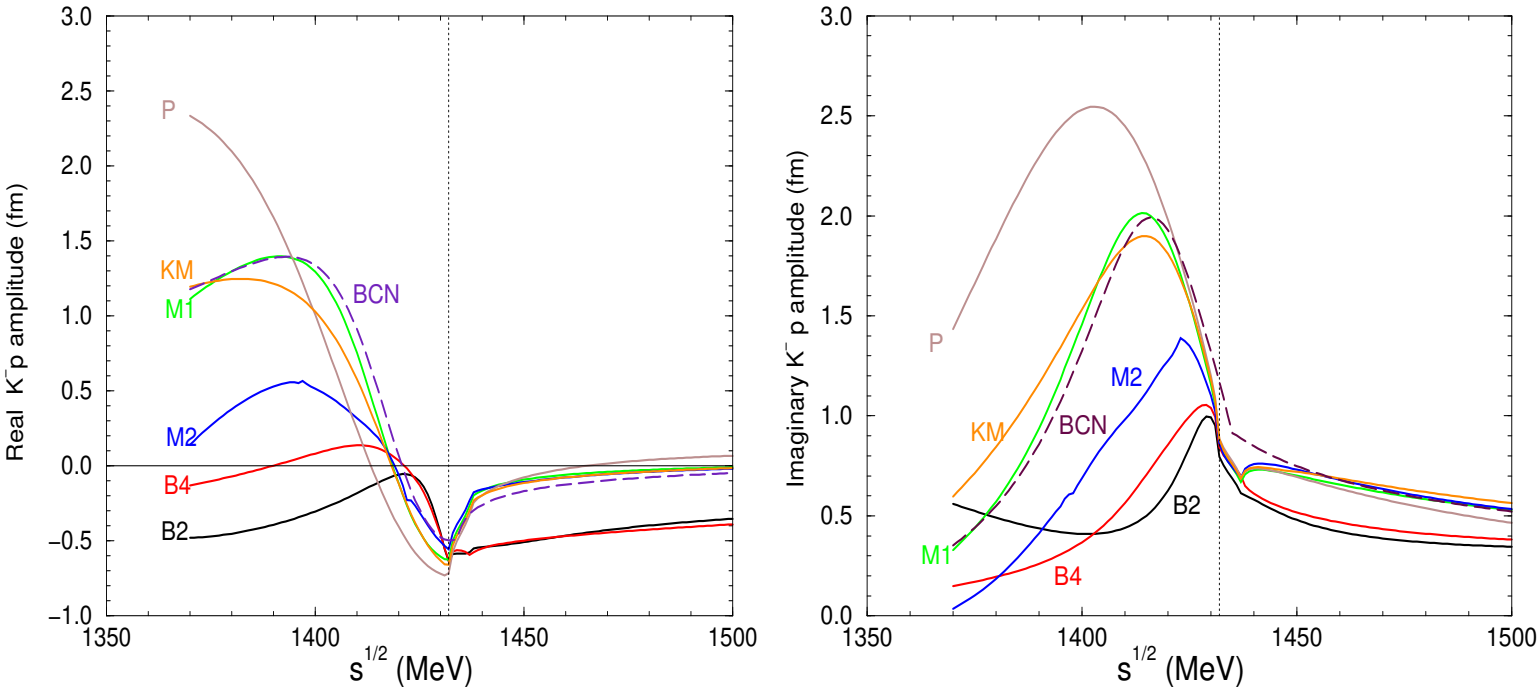
Early attempts to use chiral amplitudes

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!

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



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).

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

model	B2	B4	M1	M2	P	KM	BCN
$\chi^2(65)$	1174	2358	2544	3548	2300	1806	2829

Not fits!

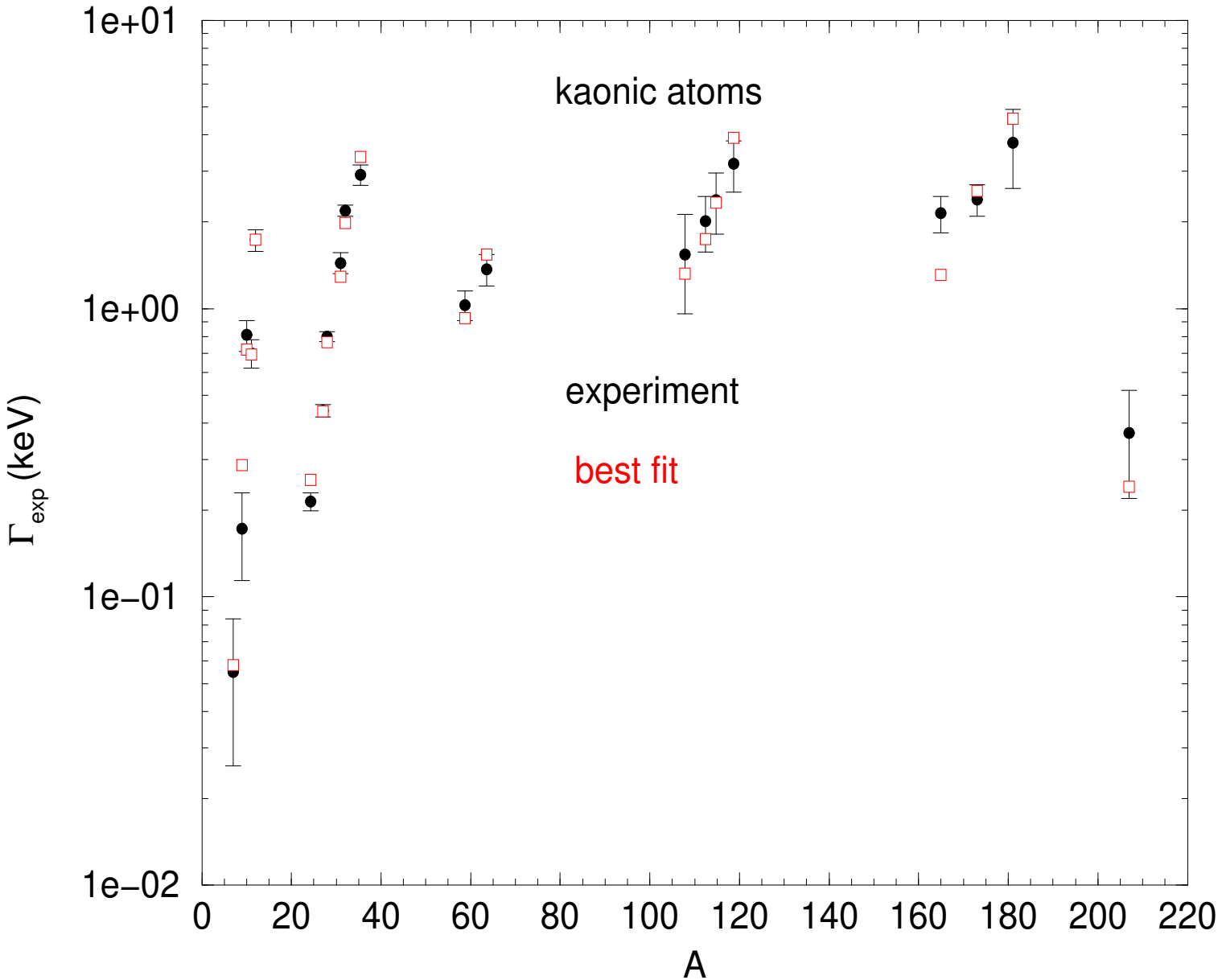
Fits to 65 kaonic atoms data points when single-nucleon amplitudes are supplemented by a $B_0(\rho/\rho_0)^\alpha$ amplitude with fixed α compatible with its best-fit value. B_0 in units of fm.

model	BCN	M1	M2	P	KM
α	1.0	0.3	1.0	1.0	1.0
ReB_0	-1.6 ± 0.3	0.3 ± 0.1	2.1 ± 0.2	-1.3 ± 0.2	-0.9 ± 0.2
ImB_0	2.0 ± 0.3	0.8 ± 0.1	1.2 ± 0.2	1.5 ± 0.2	1.4 ± 0.2
$\chi^2(65)$	112	121	109	125	123

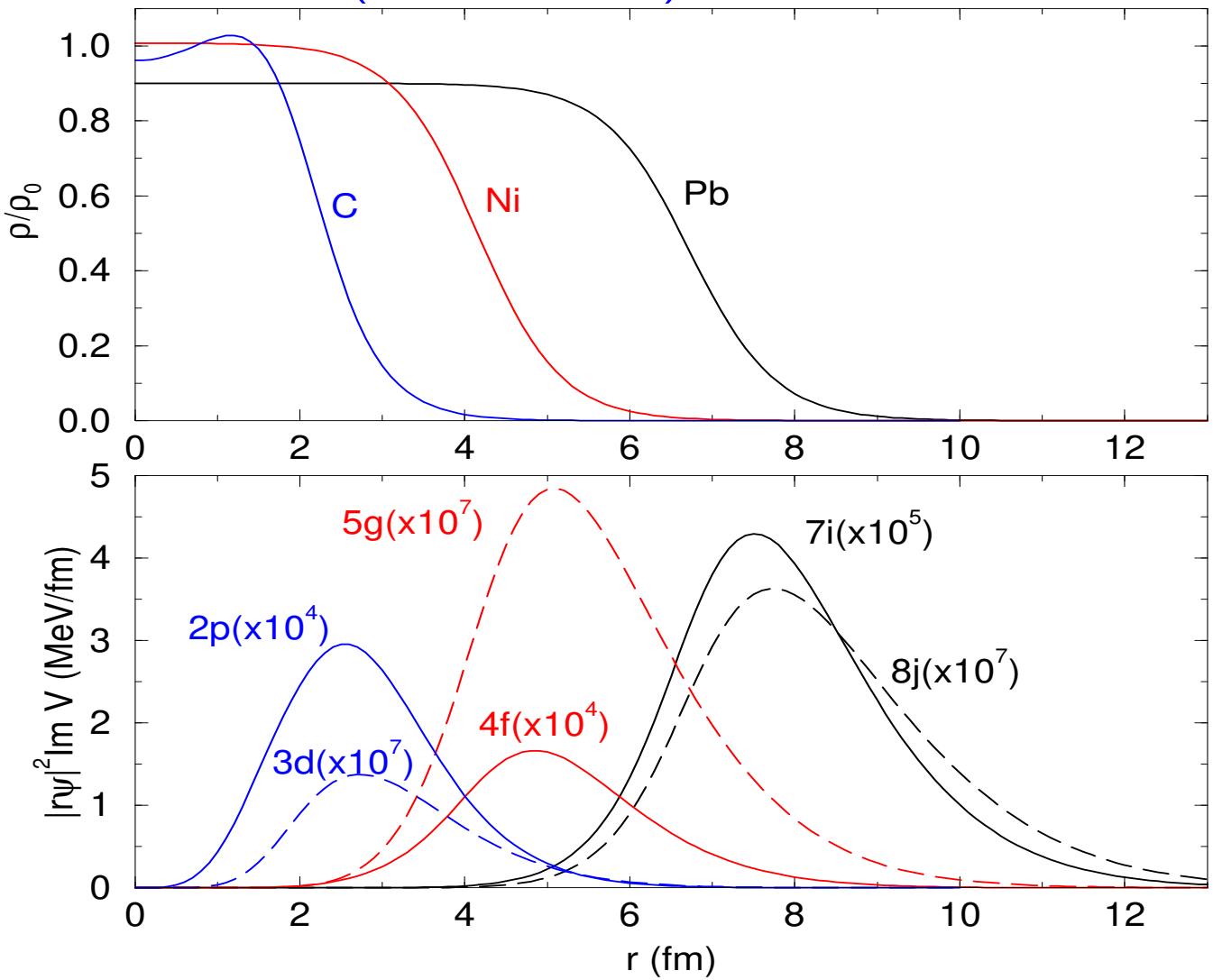
Is it necessary to go subthreshold?
Example for KM, when $\delta\sqrt{s}$=0:
$\alpha = 1.0$, Re$B_0 = -1.8 \pm 0.1$, Im$B_0 = -1.1 \pm 0.1$, $\chi^2(65)$ =139

Negative ImB_0 and/or significantly larger χ^2 obtained for all seven models when taken on threshold.
Similar problems when ignoring Pauli correlations.

Example of global fit to kaonic atoms data, L=1...6



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



It is an *atomic-nuclear* system!

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 $|\psi|^2$,

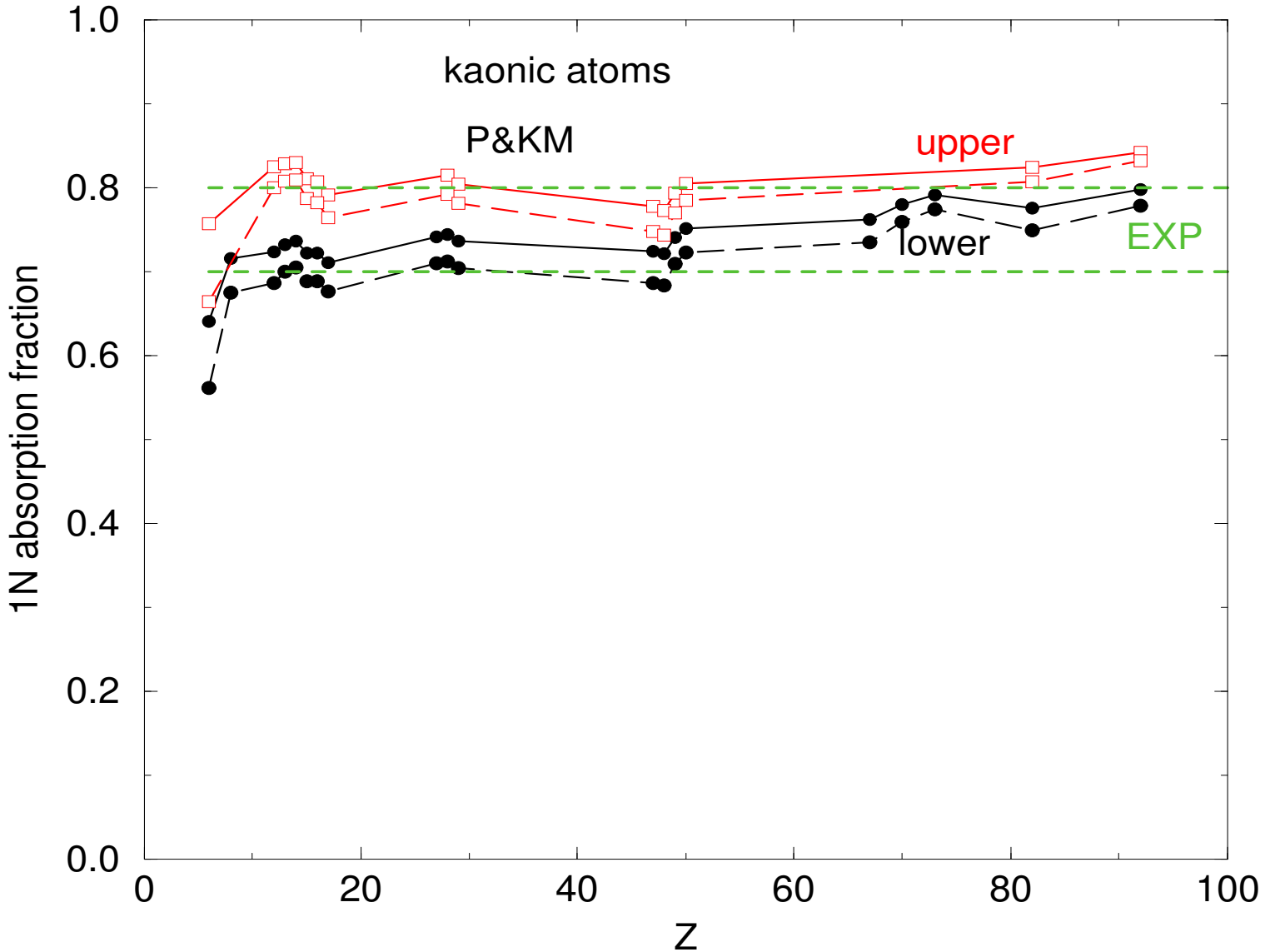
$$\Gamma = -2 \frac{\int \mathrm{Im}\, V_{K^-} \, |\psi|^2 \, d\vec{r}}{\int [1 - (B_{K^-} + V_{\mathrm{C}})/\mu_K] \, |\psi|^2 \, d\vec{r}}$$

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.

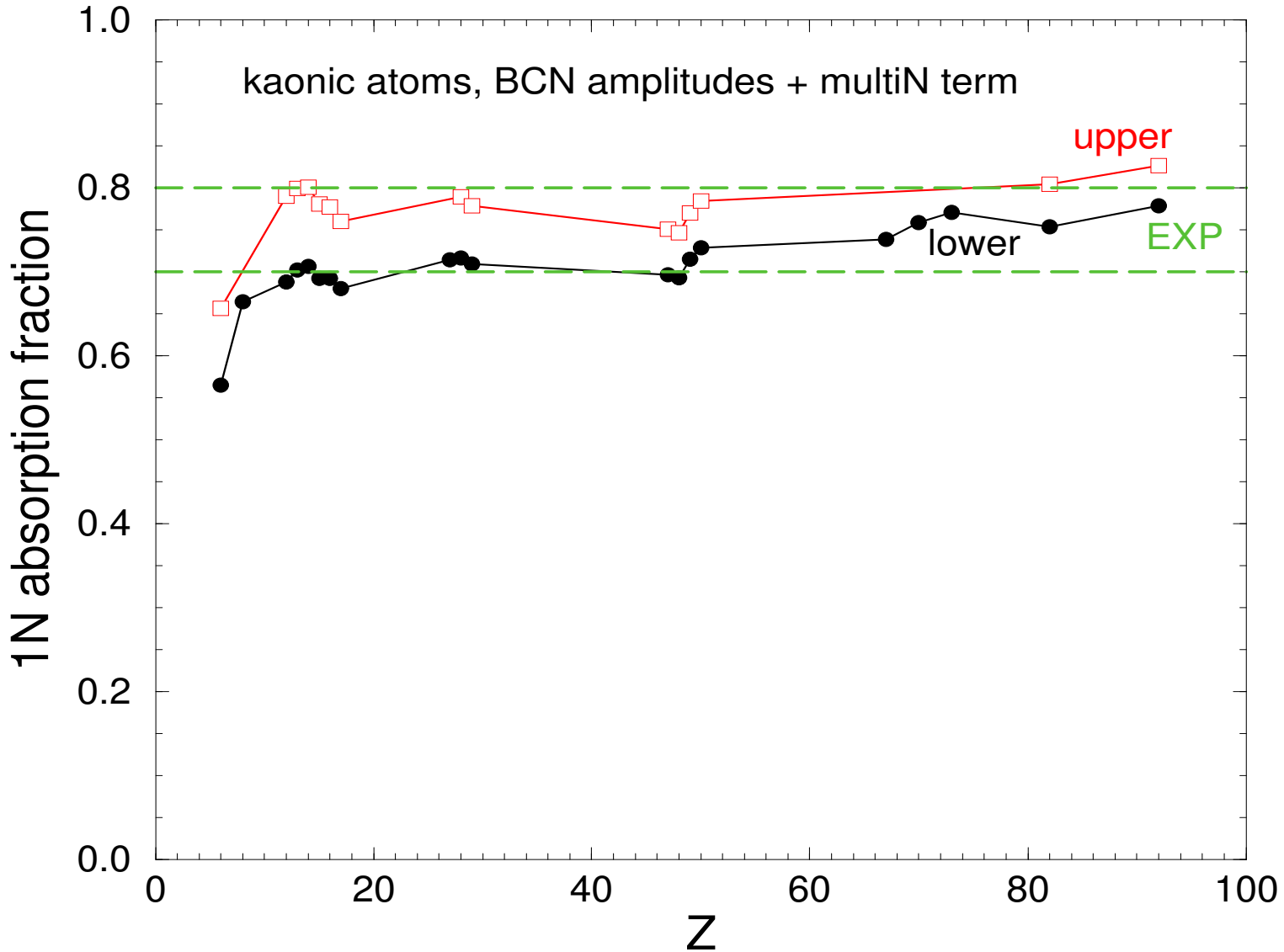
Focusing on the multinucleon absorption

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

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



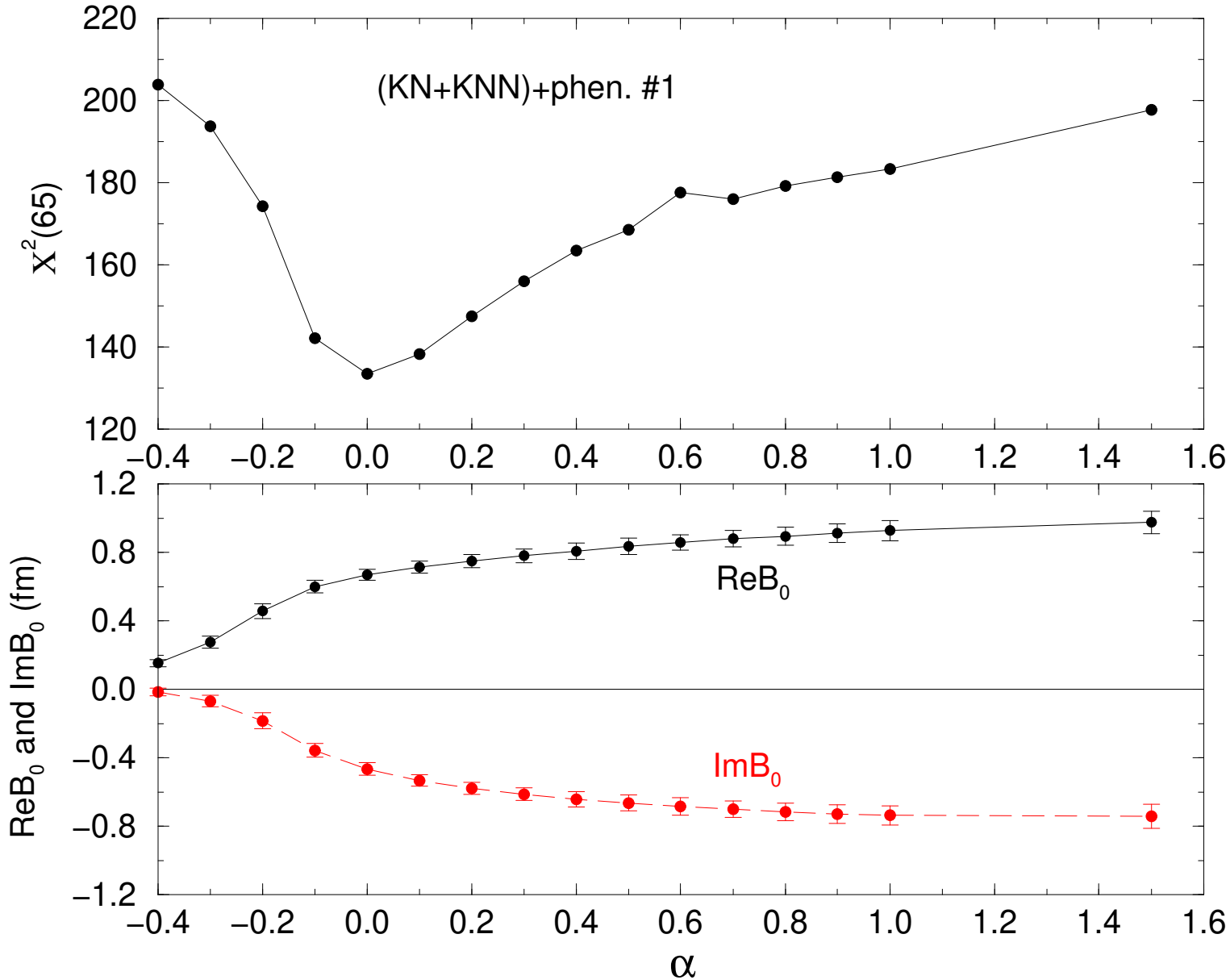
Fraction of single-nucleon absorption for amplitudes BCN. Solid circles for lower states, open squares for upper states.

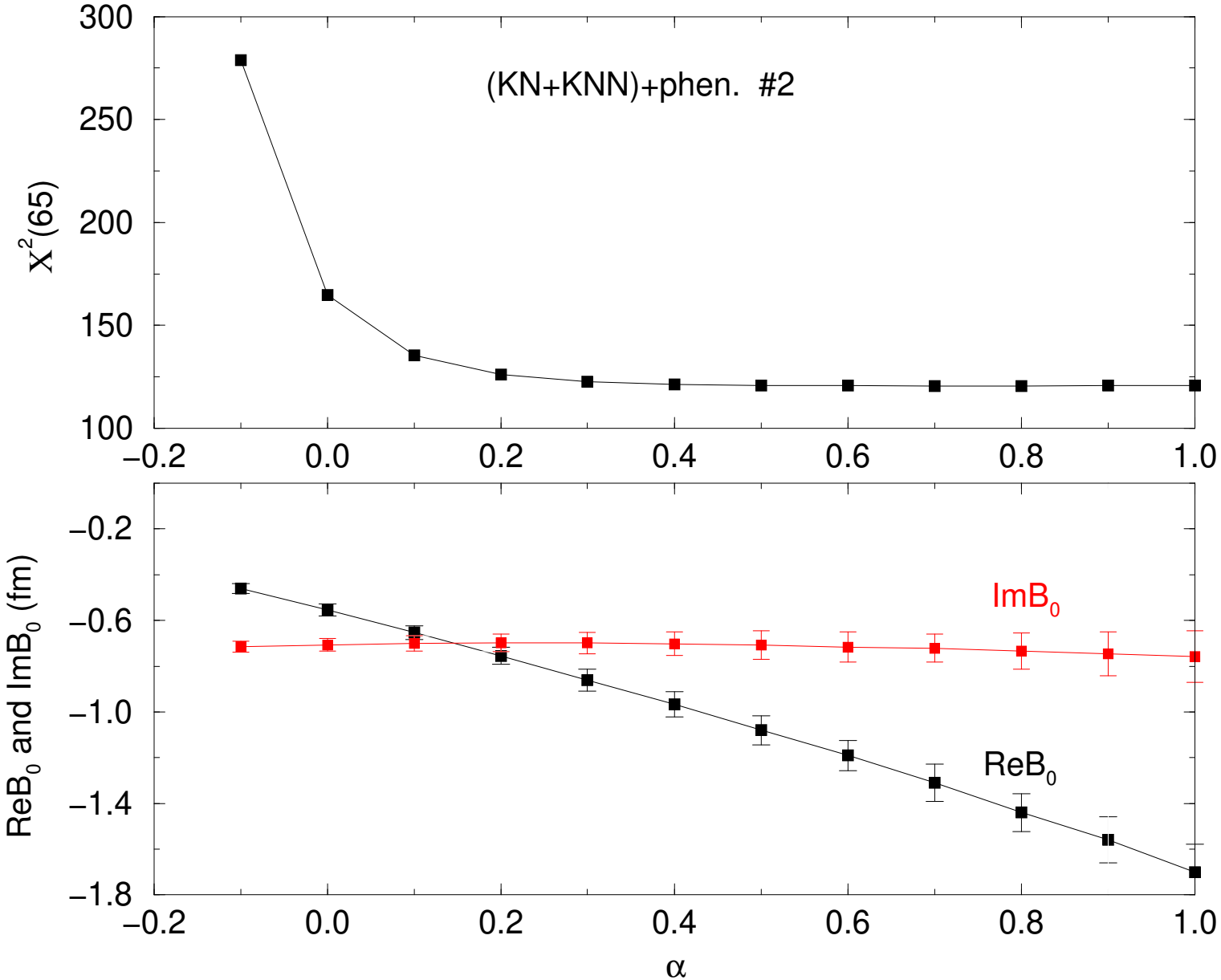


Interim Summary

phenomenology $\rightarrow$ (threshold single N+phen.) $\rightarrow$
(subthreshold $1N$+phen.) $\rightarrow$ (sub. $1N$+$2N$+phen.)

model	$\chi^2(65)$	comments
phen.	130	-
thresh.$1N$+phen.	300	Im$B_0 < 0$
subthresh. $1N$	2800	-
subthresh. $1N$+phen.	129	Im$B_0 > 0$
subthresh. $1N$+$2N$	338	-
subthresh. $1N$+$2N$ +phen.	134	yet incomplete


(KN+KNN)+phen. #1
$X^2(65)$
220
200
180
160
140
120
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
ReB_0 and ImB_0 (fm)
1.2
0.8
0.4
0.0
−0.4
−0.8
−1.2
ReB_0
ImB_0
α


(KN+KNN)+phen. #2
$X^2(65)$
300
250
200
150
100
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
ReB_0 and ImB_0 (fm)
−0.2
−0.6
−1.0
−1.4
−1.8
ImB_0
ReB_0
α

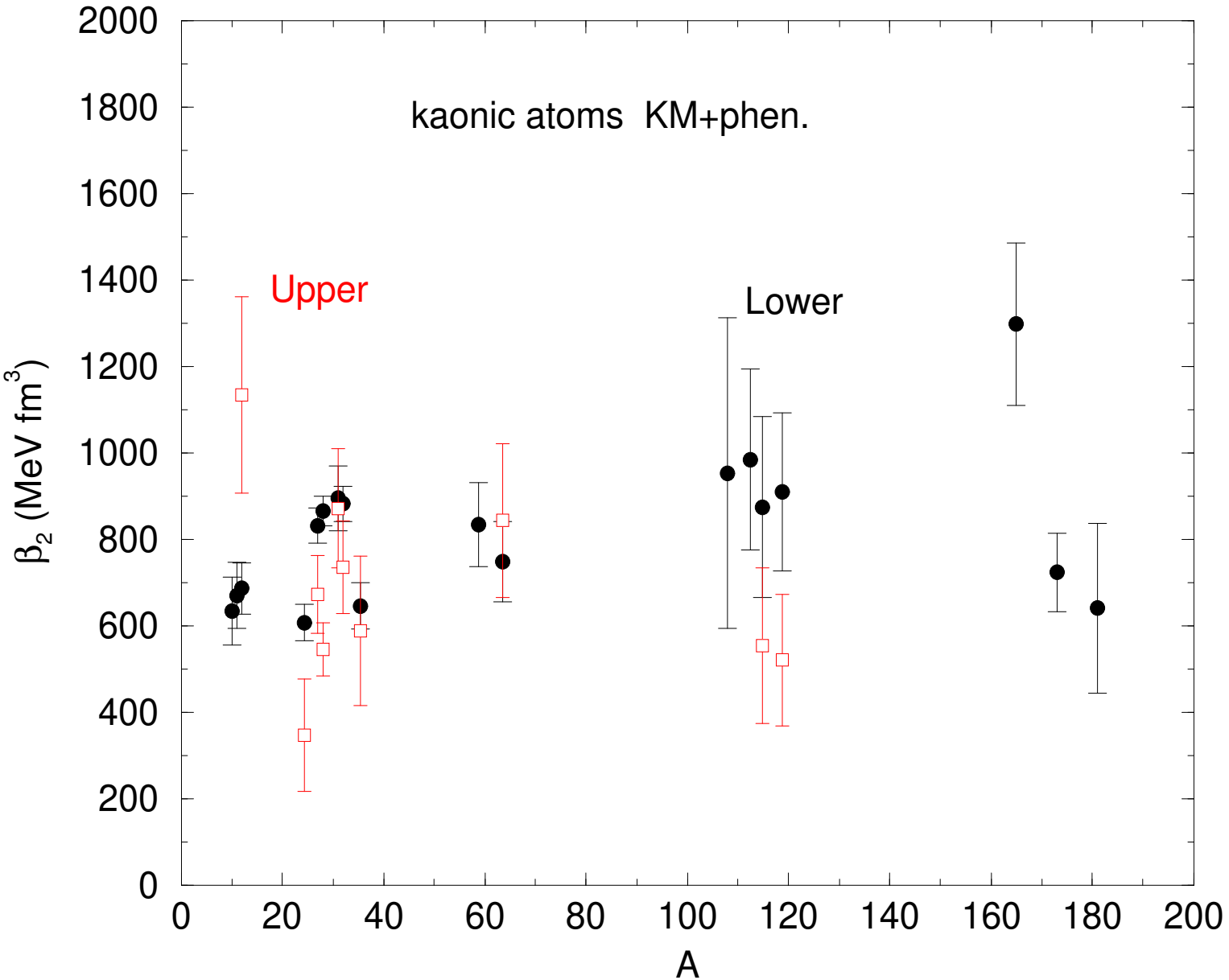
The simplest model of absorption on two nucleons calls for an imaginary part of the optical potential that is proportional to ρ^2 $\Gamma_{NN} \propto \int \rho^2 |\psi|^2 \, d\vec{r}$ where the kaonic atom wave function ψ is normalized to a volume integral of 1. Normalizing also the overlap integral with ρ^2 and normalizing on A nucleons, we define a parameter β_2 as follows

$$\Gamma_{NN} \; = \; \beta_2 \frac{\mathrm{A} \int \rho^2 |\psi|^2 \, d\vec{r}}{\int \rho^2 \, d\vec{r}}.$$

Studies of the parameter β_2 along the periodic table could lead to insight on absorption of K^- in nuclei beyond the absorption on a single nucleon,

$$\beta_2 \; = \; \Gamma_{NN} \; \frac{\int \rho^2 \, d\vec{r}}{\mathrm{A} \int \rho^2 |\psi|^2 \, d\vec{r}}$$

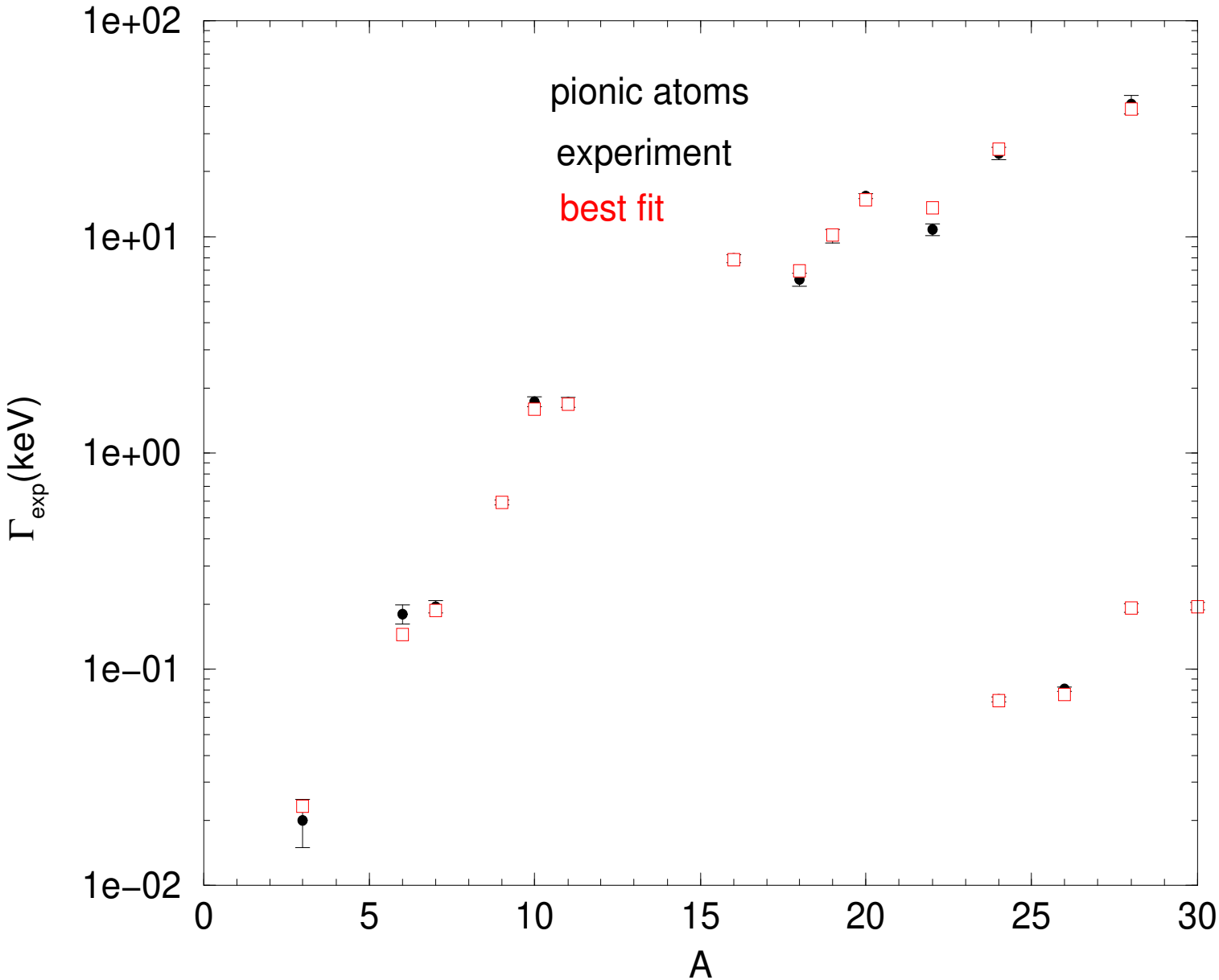
N. Barnea (Feb. 2020), private communication.

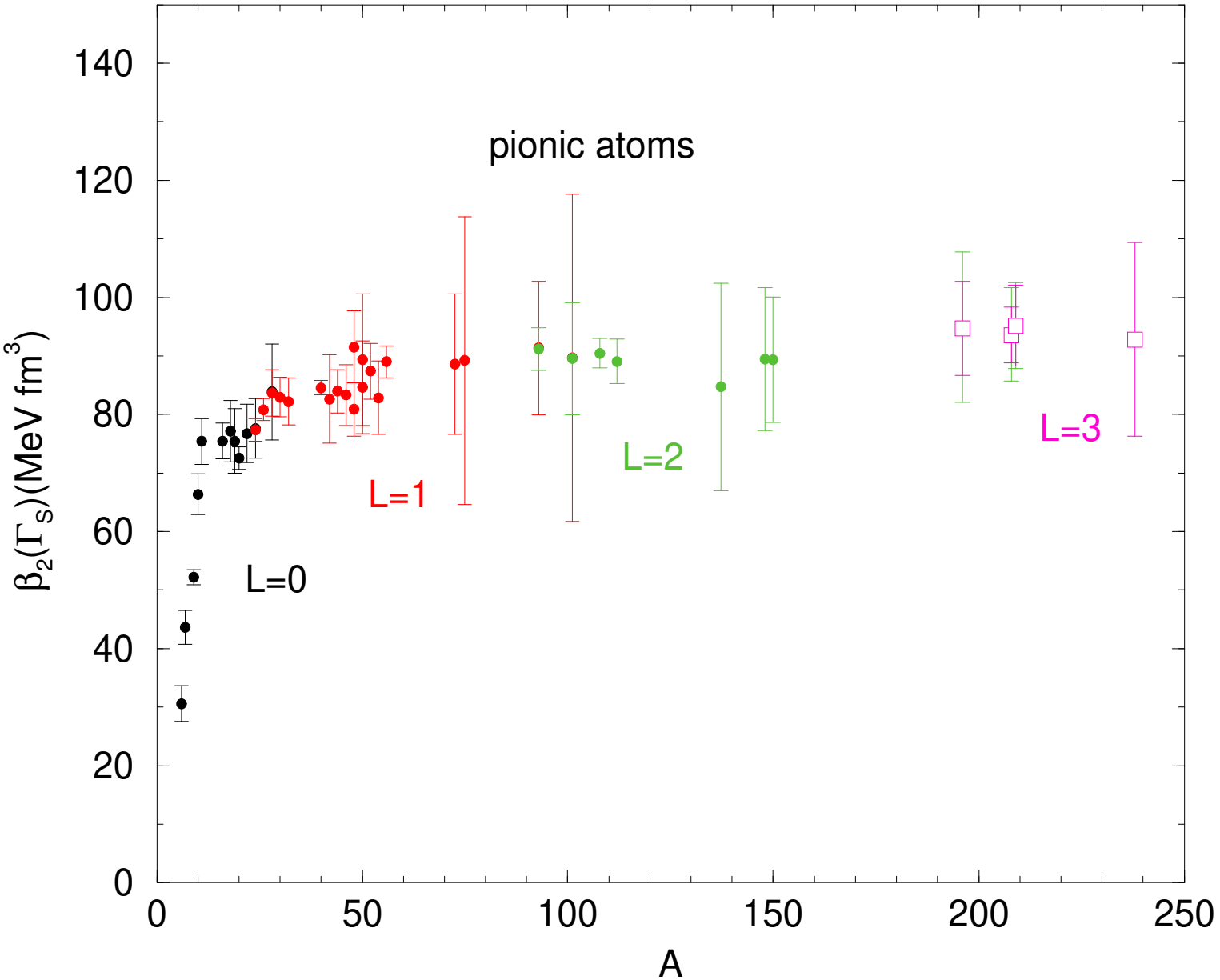

kaonic atoms KM+phen.
Upper
Lower
β_2 (MeV fm^3)
A
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
20
40
60
80
100
120
140
160
180
200

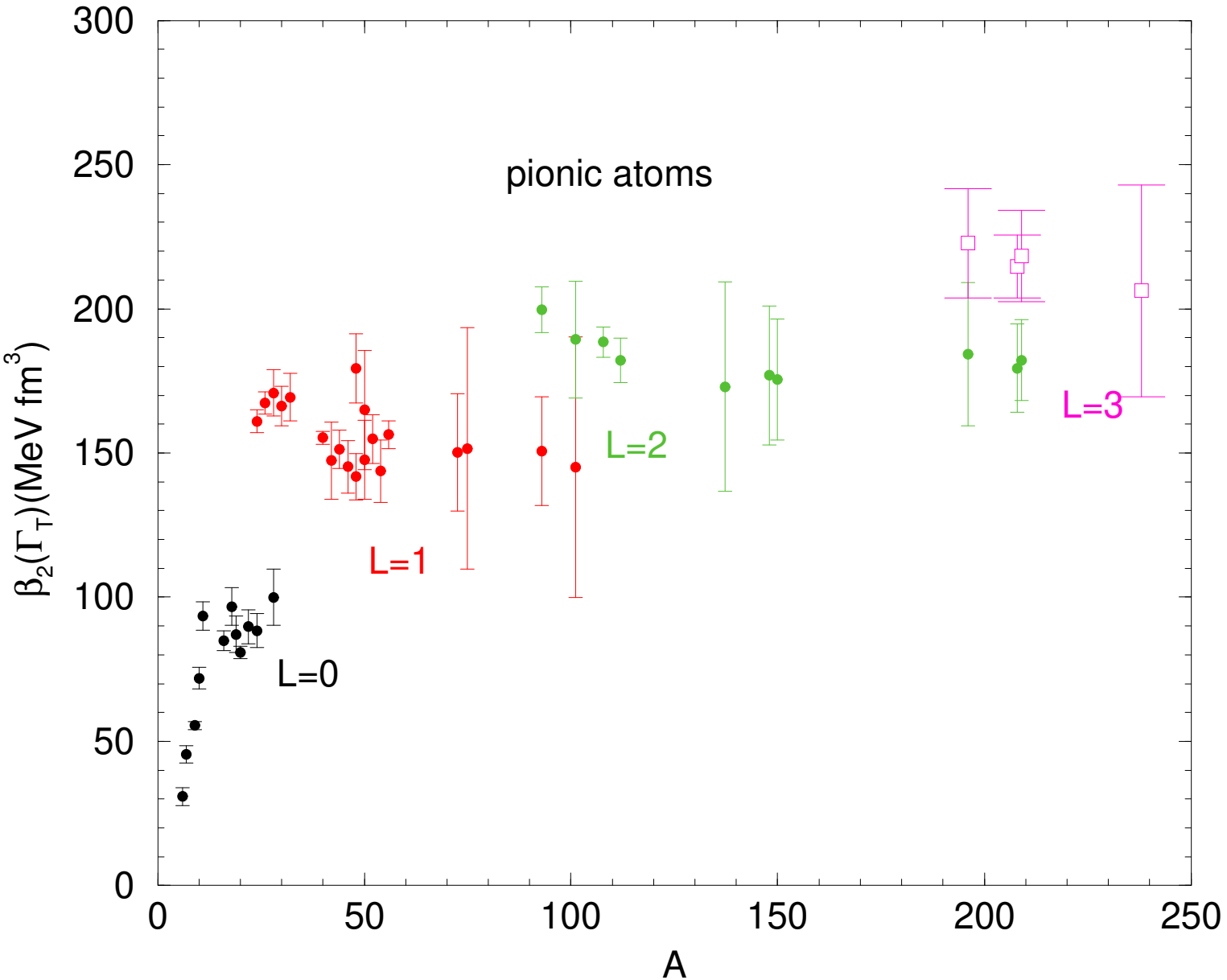
Comparing kaonic and pionic atoms

type	ImV	No. data points	No. species	L values
K^-	$1N$+$2N$	65	24	1-6(7)
π^-	$2N$ s+p waves	116	50	0-3

The s-wave term in the pionic potential is an analog of the $2N$ term in the kaonic potential. Easy to separate the s-wave term from the full potential. Experimental errors are generally smaller than the kaonic atom errors. Similar qualities of fits.


pionic atoms
experiment
best fit
Γ_{exp}(keV)
A
1e+02
1e+01
1e+00
1e−01
1e−02
0
5
10
15
20
25
30


pionic atoms
$\beta_2(\Gamma_s)$(MeV fm^3)
A
L=0
L=1
L=2
L=3
0
20
40
60
80
100
120
140
0
50
100
150
200
250


pionic atoms
$\beta_2(\Gamma_T)$(MeV fm^3)
A
L=0
L=1
L=2
L=3
0
50
100
150
200
250
300

With

$$\beta_2 \;=\; \Gamma_{NN}\;\frac{\int \rho^2\; d\vec{r}}{\mathrm{A}\int \rho^2|\psi|^2\; d\vec{r}} \approx \textit{constant}??$$

we note that for a K^- in an atomic s-state and Z close to 1, $|\psi|^2$ may be replaced by $|\psi(0)|^2$ and then

$$\beta_2 \;=\; \Gamma_{NN}/A\;|\psi(0)|^2.$$

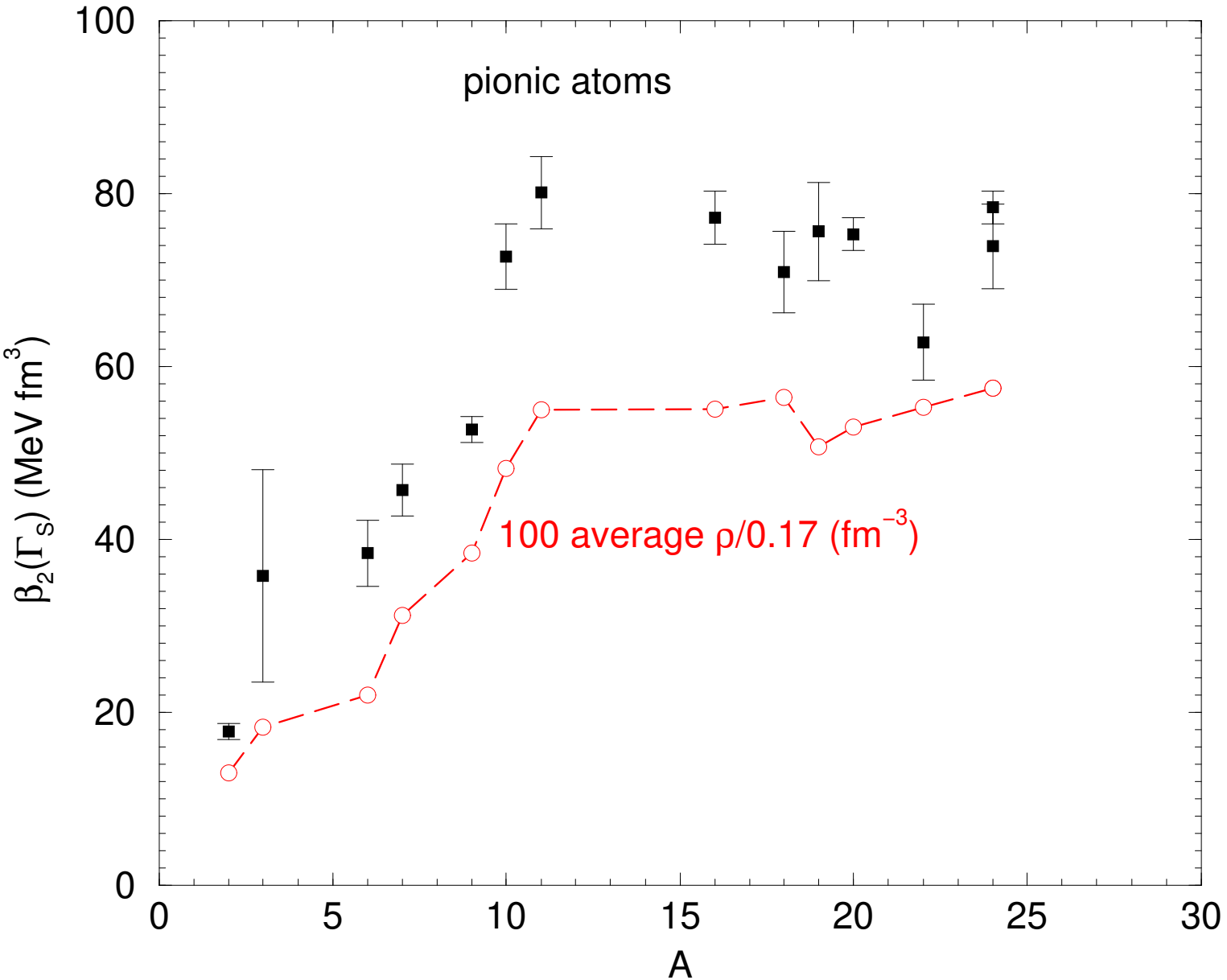
For the more general case and noting that

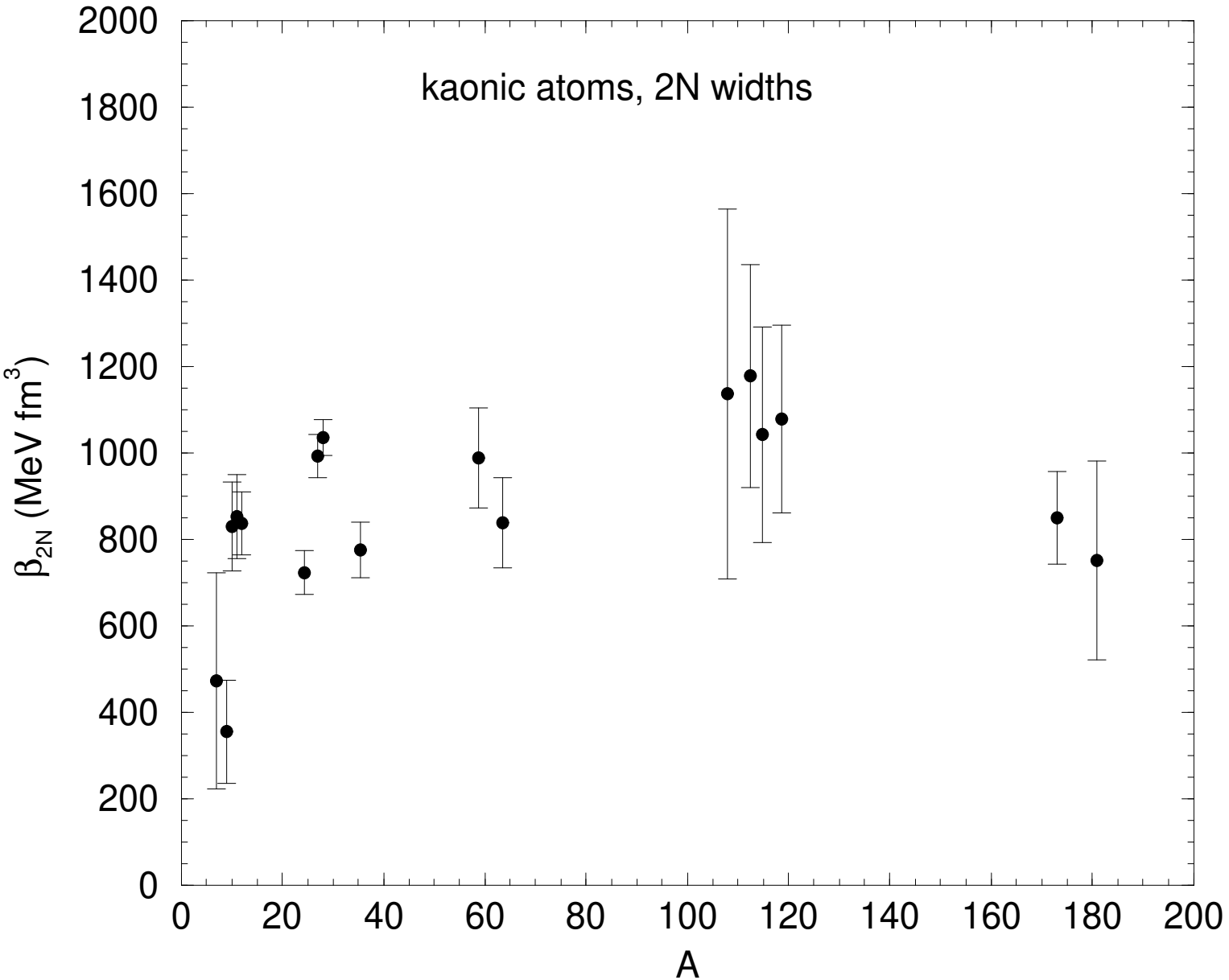
$$\int \rho^2 \, d\vec{r} \; = \; A \, \bar{\rho}$$

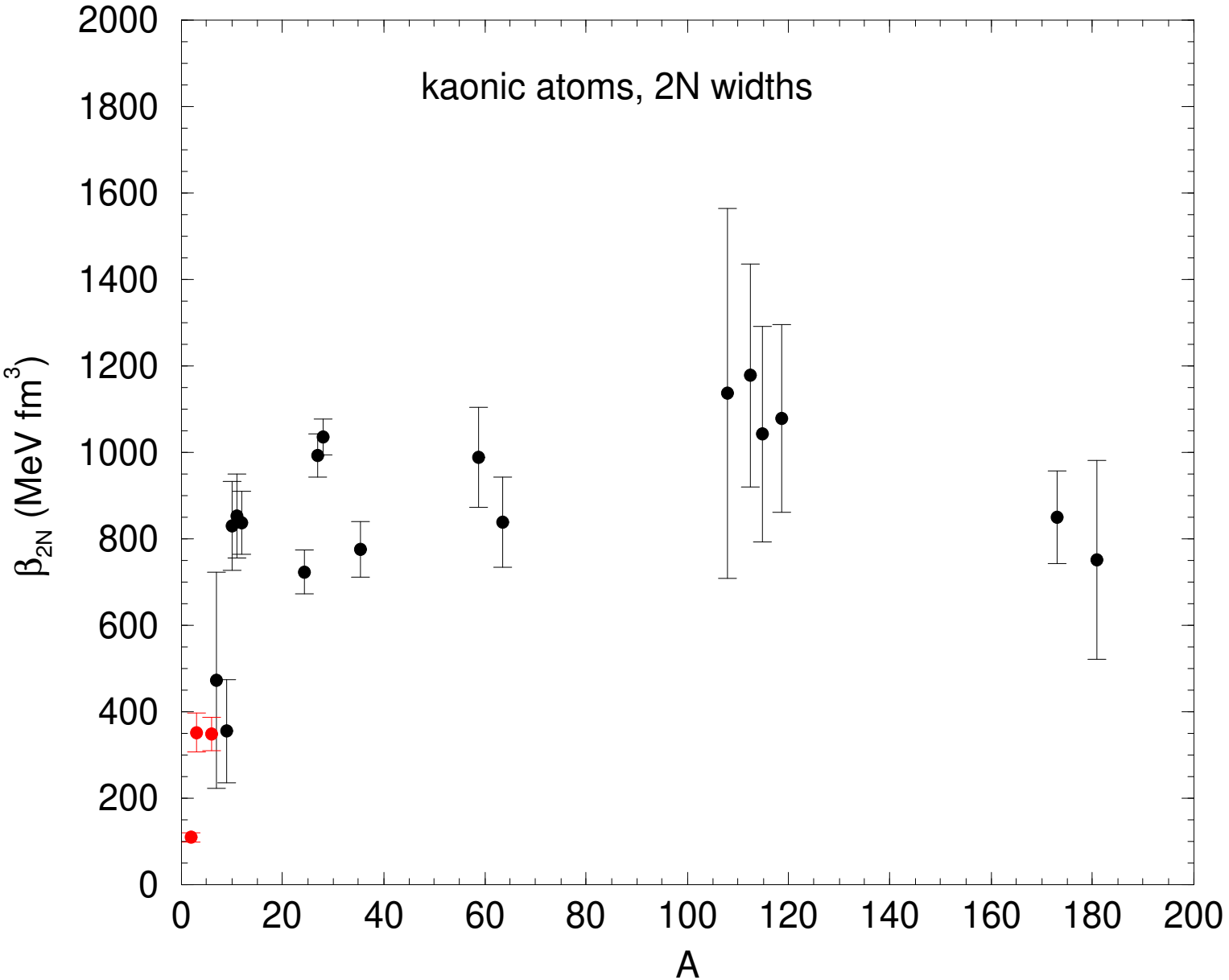
with $\bar{\rho}$ the average nuclear density, we end up with

$$\beta_2 \; = \; \frac{\bar{\rho} \, \Gamma_{NN}}{\int \rho^2 |\psi|^2 \, d\vec{r}} \, .$$

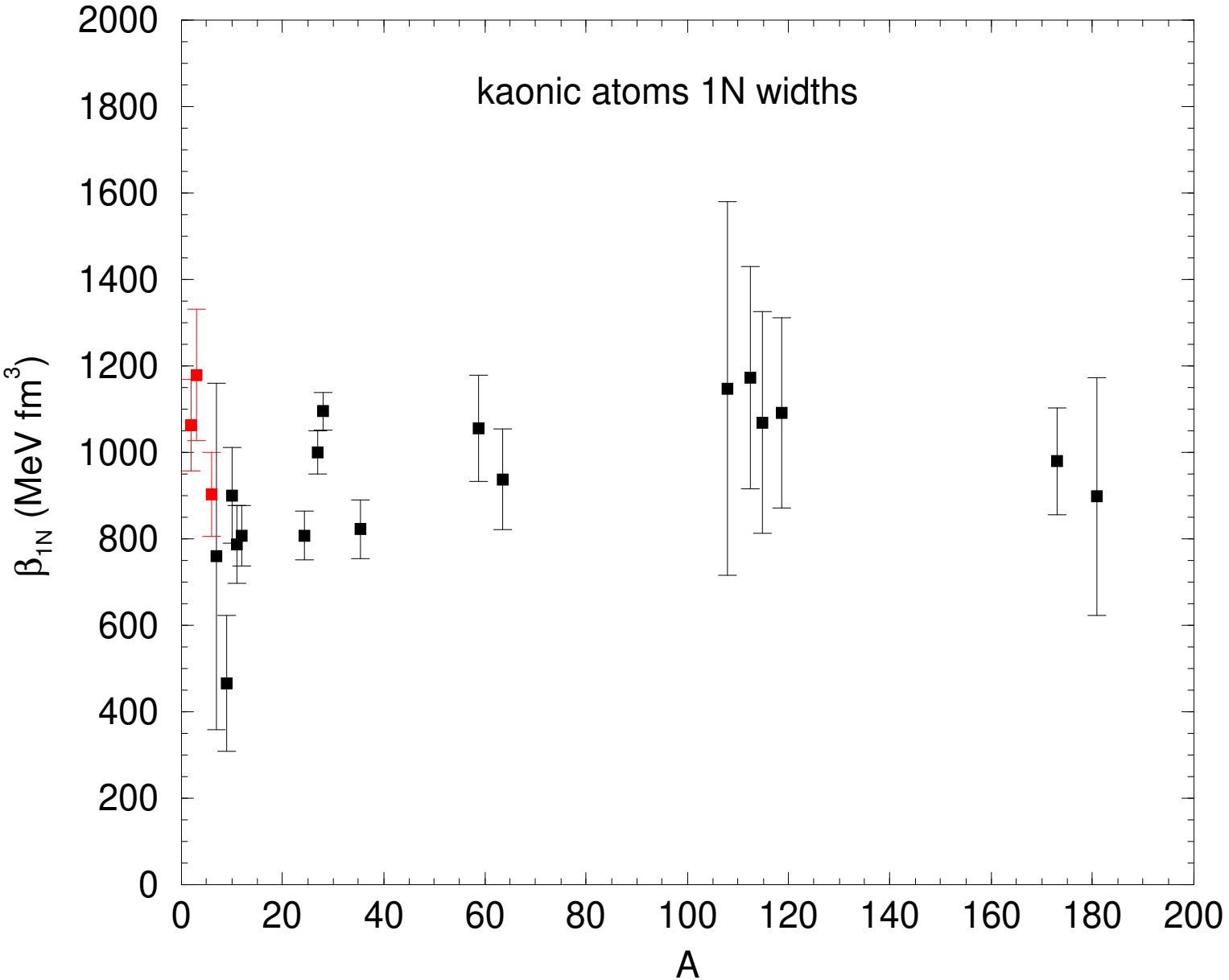
Since Γ_{NN} is approximately proportional to $\int \rho^2 |\psi|^2 \, d\vec{r}$ it is expected that β_2 will be proportional to the average nuclear density that increases sharply from ^{3}He to ^{12}C, and then assumes a rather constant value. A notable exception is ^{4}He with a density typical of a medium-weight nucleus.


pionic atoms
100 average ρ/0.17 (fm^{-3})
$\beta_2(\Gamma_s)$ (MeV fm^3)
A
0
20
40
60
80
100
0
5
10
15
20
25
30

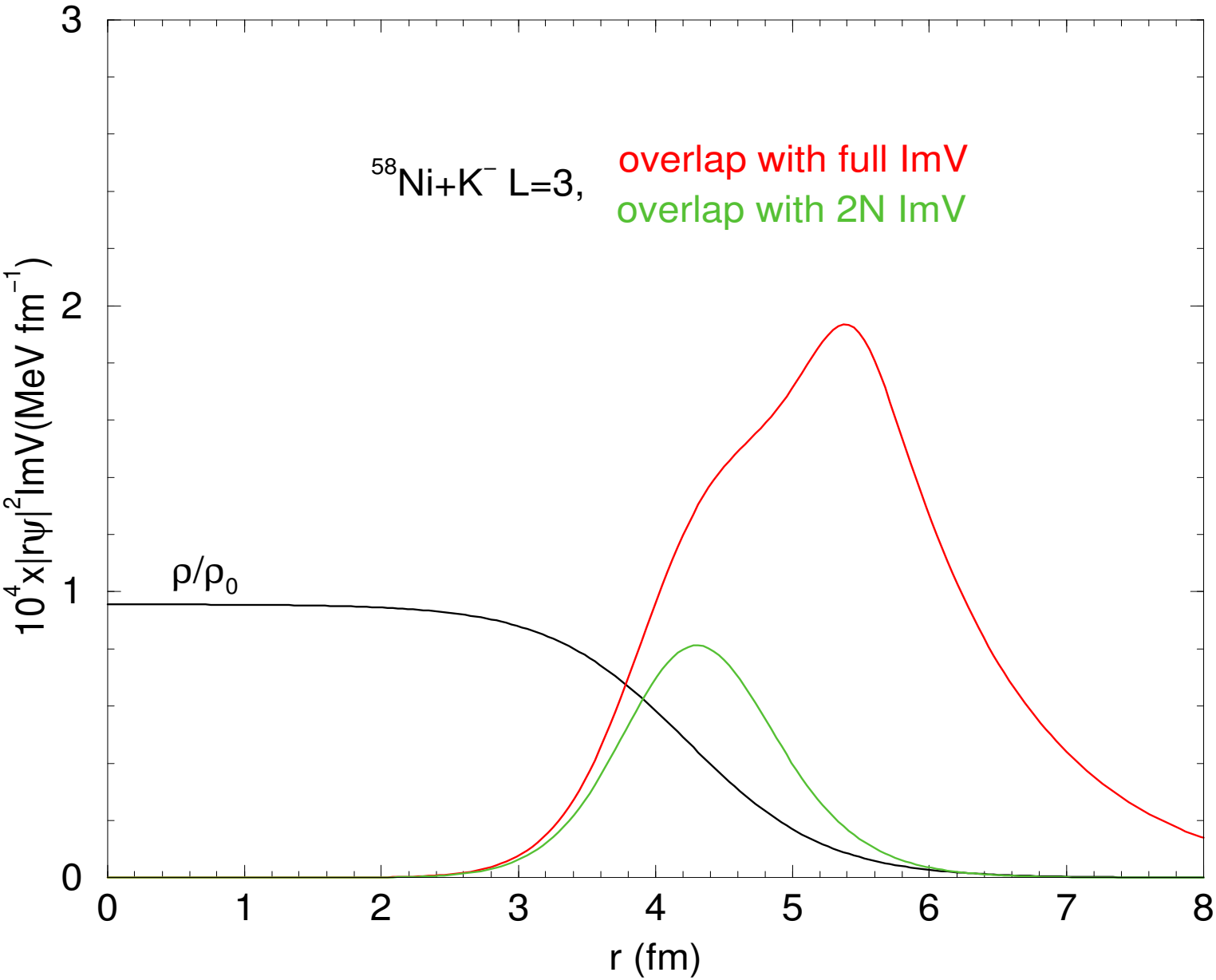

kaonic atoms, 2N widths
β_{2N} (MeV fm^3)
A
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
20
40
60
80
100
120
140
160
180
200



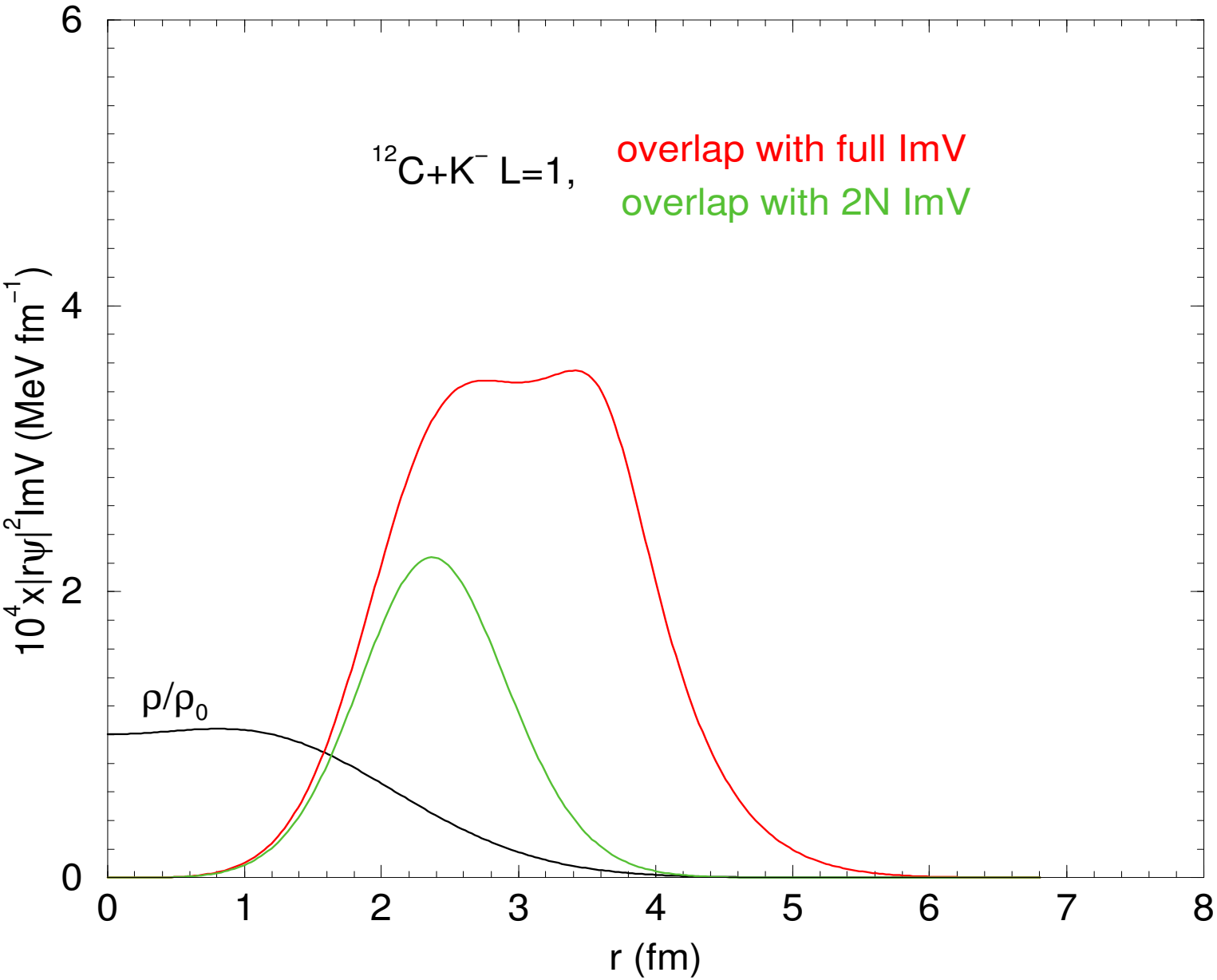
points in red are predictions of a best-fit potential



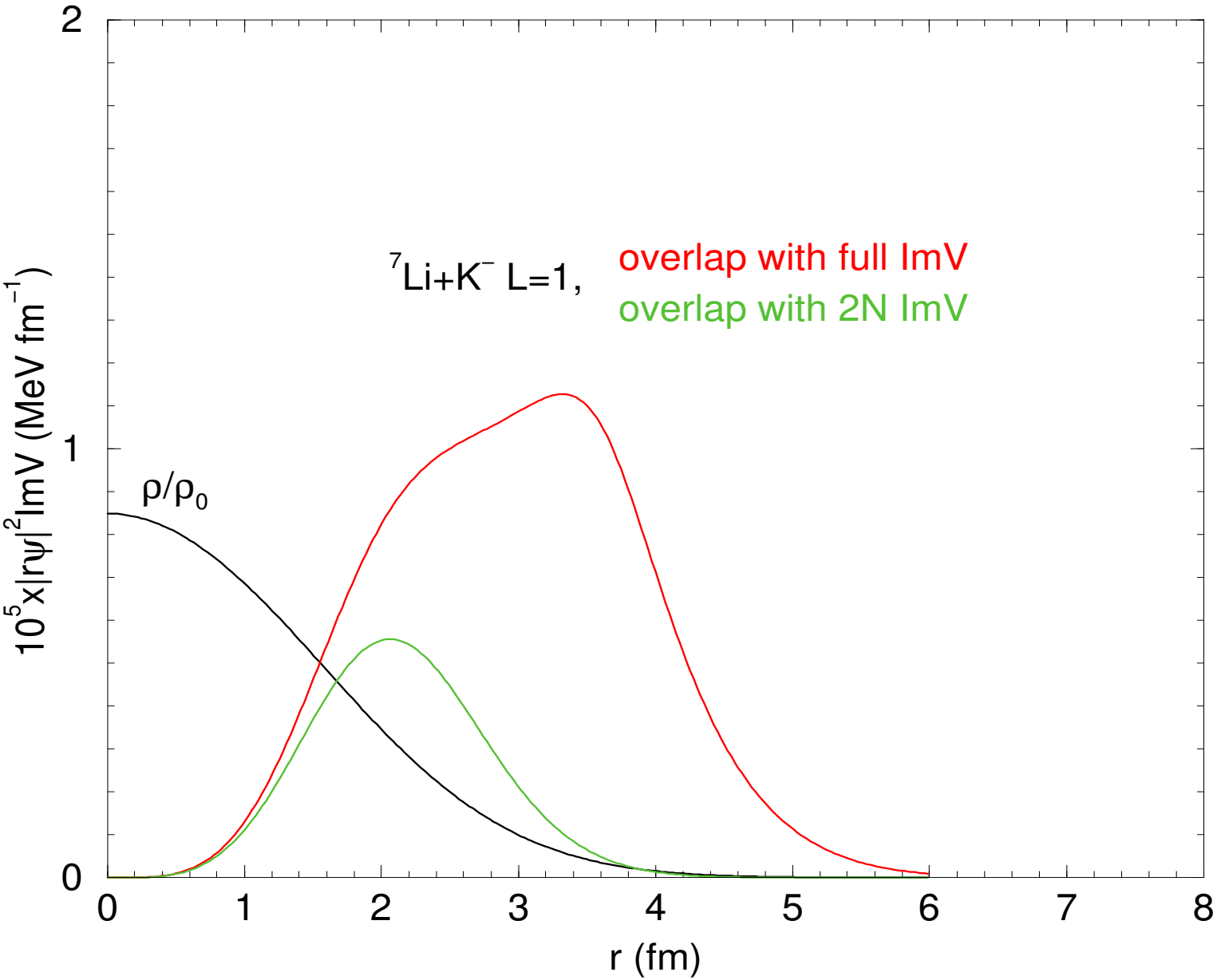
points in red are predictions of a best-fit potential



$\rho_0 = 0.17\ \mathrm{fm}^{-1}$


^{12}C+K$^-$ L=1,
overlap with full ImV
overlap with 2N ImV
$10^4 x|r\psi|^2$ImV (MeV fm^{-1})
ρ/ρ$_0$
r (fm)
0
1
2
3
4
5
6
7
8

$\rho_0 = 0.17$ fm^{-1}


^{7}Li+K$^-$ L=1,
overlap with full ImV
overlap with 2N ImV
ρ/ρ$_0$
10^5x|rψ|^{2}ImV (MeV fm^{-1})
r (fm)
0
1
2
3
4
5
6
7
8

$\rho_0 = 0.17$ fm^{-1}

Summary

- Significant progress in understanding kaonic atoms, converging on multinucleon interaction with the nucleus.
- 35-40 years old data have yielded beyond expectations.
- High quality measurements for L=1 kaonic states in ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B and ^{12}C could allow for few-body approaches, connecting to the density dependence in heavier kaonic atoms.
- It is high time for new experiments.

I wish to thank Avraham Gal and Nir Barnea for meetings and discussions.

This work is supported by the European Union Horizon 2020 research and innovation programme under grant agreement No. 824093.