X-ray spectroscopy of heavy kaonic atoms

T. Ishiwatari

SMI, Vienna

LNF/Italy, 19-21.6.2013

Our recent focus on kaonic atoms

- Precise measurement of kaonic hydrogen 1s state (done by SIDDHARTA)
- Shifts and widths of kaonic ^{3,4}He 2p states (done by E570, SIDDHARTA, to be done by J-PARC E17)
- First observation of kaonic deuterium 1s state (to be done by SIDDHARTA-2)

Targets with Z=1 and 2 have been used recently.

Targets with Z>2 are FULLY understood? No interest?

Heavy kaonic atoms
-- Again, kaonic atom puzzle!!--

Heavy kaonic atoms

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Puzzle of kaonic atoms with Z>2

THE KAONIC ATOMS 'PUZZLE': WHAT NEXT?

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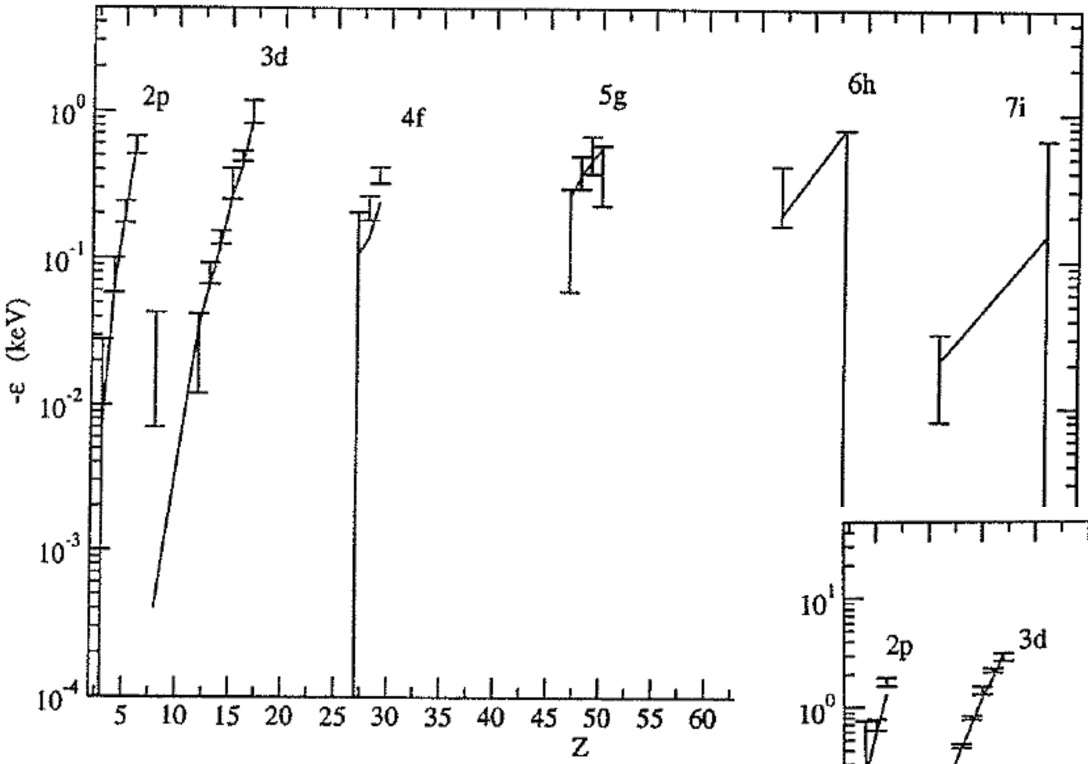
Messages to Experimentalists

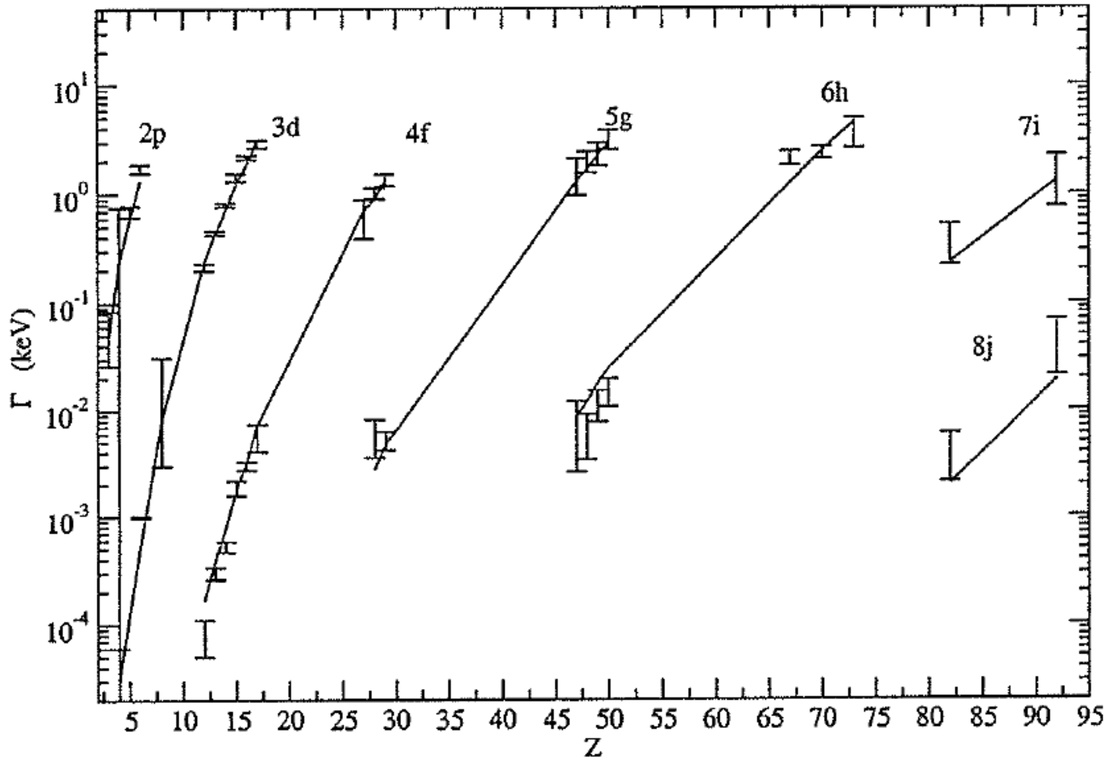
See also, Friedman, Gal: arXiv:1108.2156v1, updated version of Proc. INPC2010

Kaonic atom data (Z>2)

Shift



Width



Shifts and widths were measured with targets from Li to U.

Theoretical works have been progressed.

Kaonic hydrogen puzzle

Deser Formula

$$\varepsilon + i\frac{1}{2}\Gamma = 2\alpha^3\mu^2 a_{K^-p}$$

$$a(K^-p) = \frac{1}{2}(a_0 + a_1)$$

Scattering data (by Martin) gave

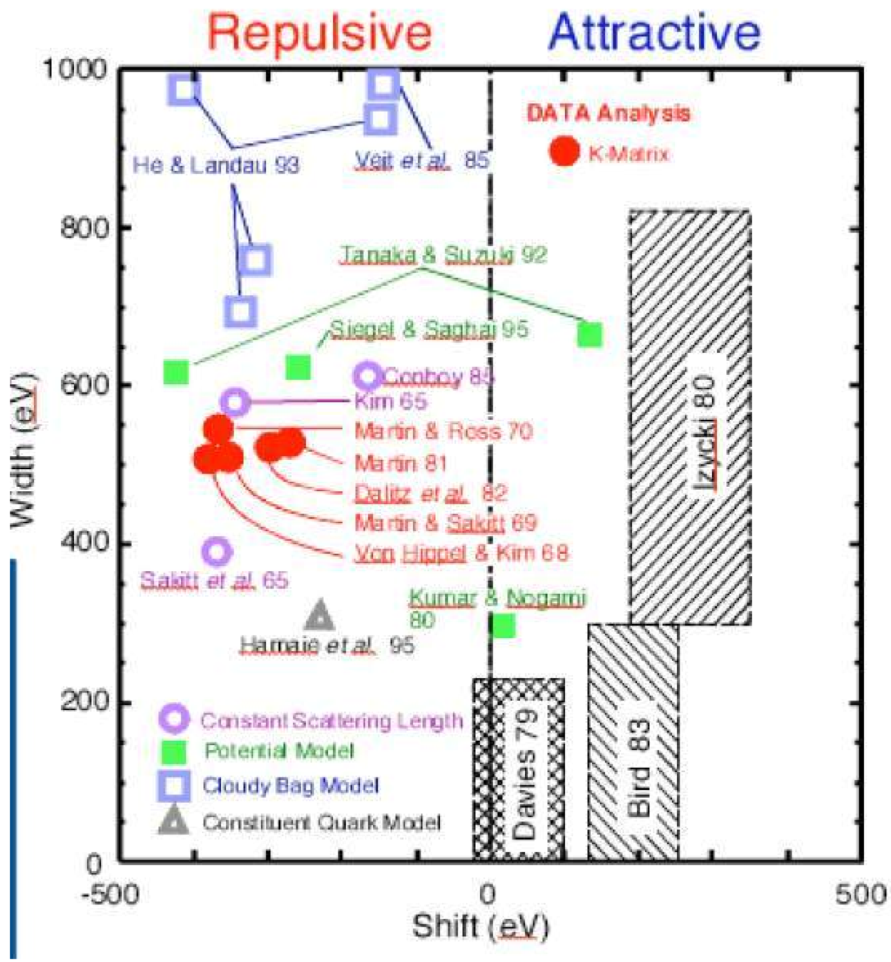
$$a_0 = -1.70 + i0.68\,\mathrm{fm}$$

$$a_1 = +0.37 + i0.60\,\mathrm{fm}$$

$$a(K^-p) = -0.66 + i0.64\,\mathrm{fm}$$

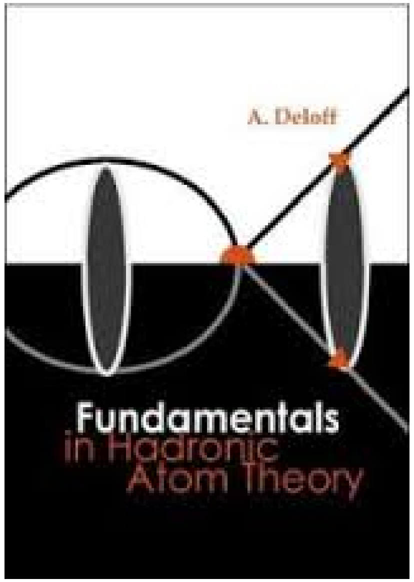
Negative shift!

Experiments: positive shift!



KpX, DEAR, SIDDHARTA measured negative shifts, solving the puzzle…

Kaonic atom data (Z>2)



Text book of exotic atoms by A. Deloff (2003)

Early calculations revealed two facts:

- A simple optical potential proportional to the nuclear density reproduces quite well the data
- The best fit depth of the optical potential violates the low-density limit.

A simple potential:

$$2\mu V(r) = -4\pi A\left(1+\frac{\mu}{M}\right)b_0 \rho(r)$$

Solving Klein-Gordon eq. (Schroedinger eq.), Energy shifts and widths can be determined.

Compare with experimental data

$$\varepsilon, \Gamma \Leftrightarrow b_0$$

A simple potential: $2\mu V(r) = -4\pi A(1+\frac{\mu}{M})b_0\rho(r)$

$$b_0 = \frac{1}{2}[a(K^- p) + a(K^- n)]$$

$$a(K^- p) = \frac{1}{2}(a_0 + a_1), \quad a(K^- n) = a_1$$

Scattering data (by Martin) gave

$$a_0 = -1.70 + i0.68\,\text{fm}$$

$$a_1 = +0.37 + i0.60\,\text{fm}$$

⇒ $b_0 = -0.15 + i0.62\,\text{fm}$ **Negative b0**

A fit to kaonic atom data shows a big departure from the above free-space value

$b_0 = (0.35 \pm 0.03) + i(0.82 \pm 0.03)\,\text{fm}$ Earlier work by Batty

Positive b0

$b_0 = (0.62 \pm 0.05) + i(0.92 \pm 0.05)\,\text{fm}$ Recent work using refined potential

Interesting sign inversion!! See e.g. Sec.4 of Phys. Rep. 287 (97) 385

Heavy kaonic atoms

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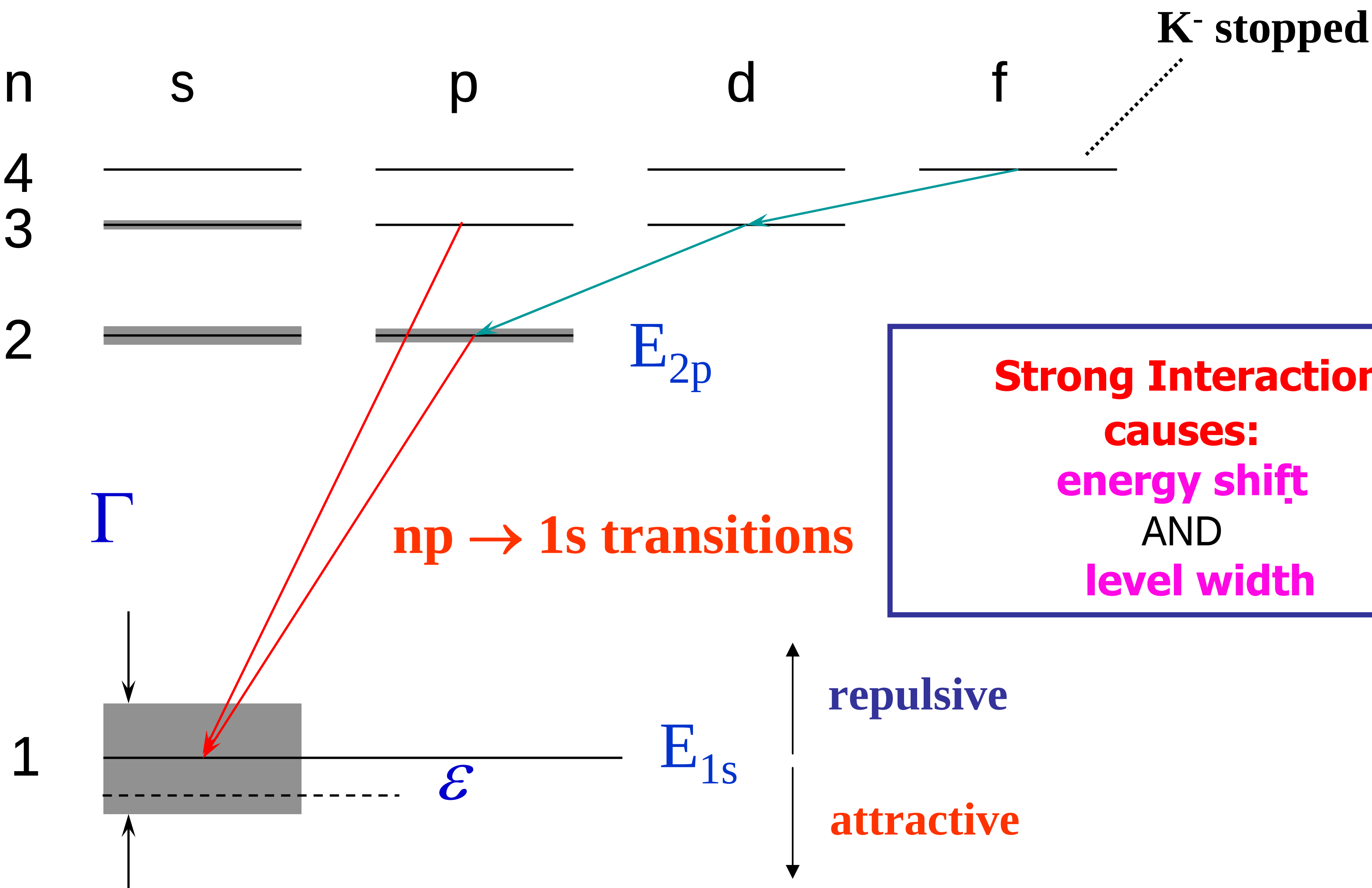
Different scenarios for different exotic atoms

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

Data of kaonic atoms = “good” data sets,
but questions for potential depths—deep or shallow?

Kaonic atoms



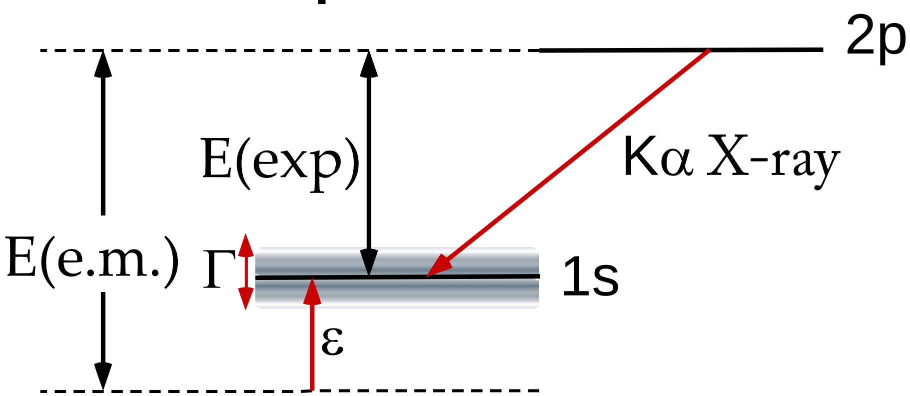
Strong Interaction causes:
energy shift
AND
level width

$$\varepsilon = E_{np \to 1s}(\text{exp}) - E_{np \to 1s}(\text{e.m.})$$

Energy shifts and widths

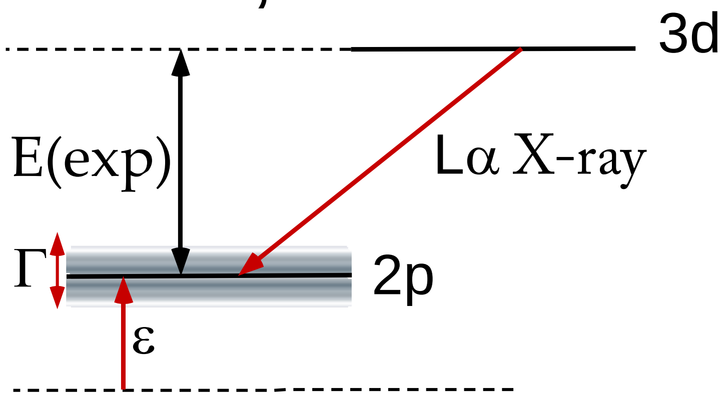
Z=1

K-p, K-d



Z=2

K-^{3}He, K-^{4}He

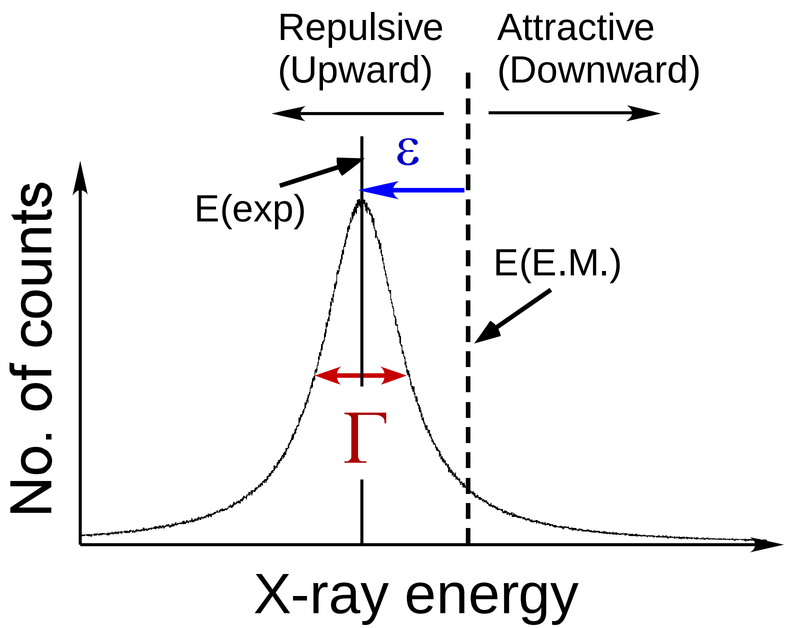


$$E(e.m.) \approx -\frac{1}{2}\mu c^2 (Z\alpha)^2 \cdot \left[\frac{1}{n_i^{\,2}} - \frac{1}{n_f^{\,2}}\right]$$

$$\varepsilon = E(\exp) - E(e.m.)$$

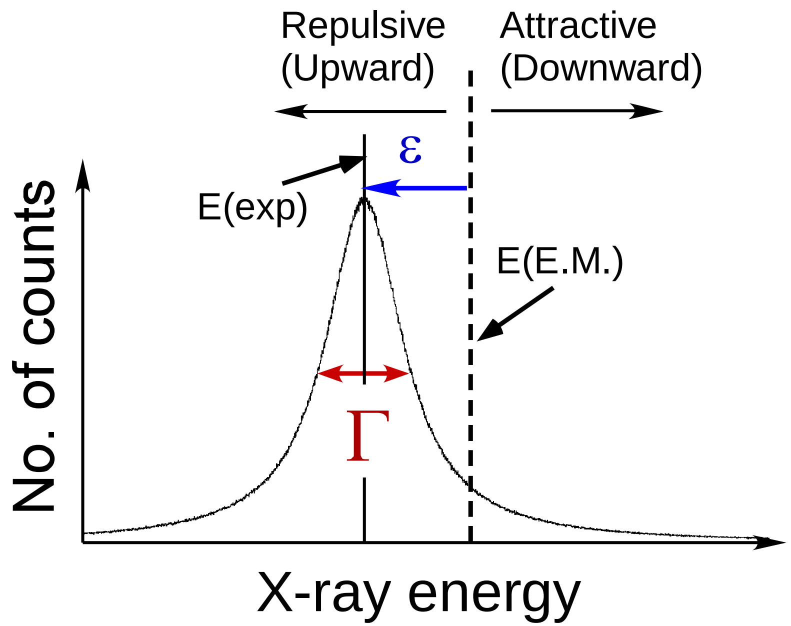
$$\varepsilon < 0\,(\text{repulsive})$$

$$\varepsilon > 0\,(\text{attractive})$$



Shifts and widths of
“Last orbits” (measured targets)

1s: Z= 1(H)
2p: Z= 2(He)~6(C)
3d: Z= 8(O)~17(Cl)
4f: Z= 27(Co)~29(Cu)
5g: Z= 47(Ag)~50(Sn)
6h: Z= 67(Ho)~73(Ta)
7i: Z= 82(Pb)~92(U)



•“Last orbits” do not mean physically really last.

K-O 2p → very large width and very small yield
K-C 3d → very small shift and very small width

No data for Nitrogen → 2p: Large width, 3d: small shift

Shifts and widths of
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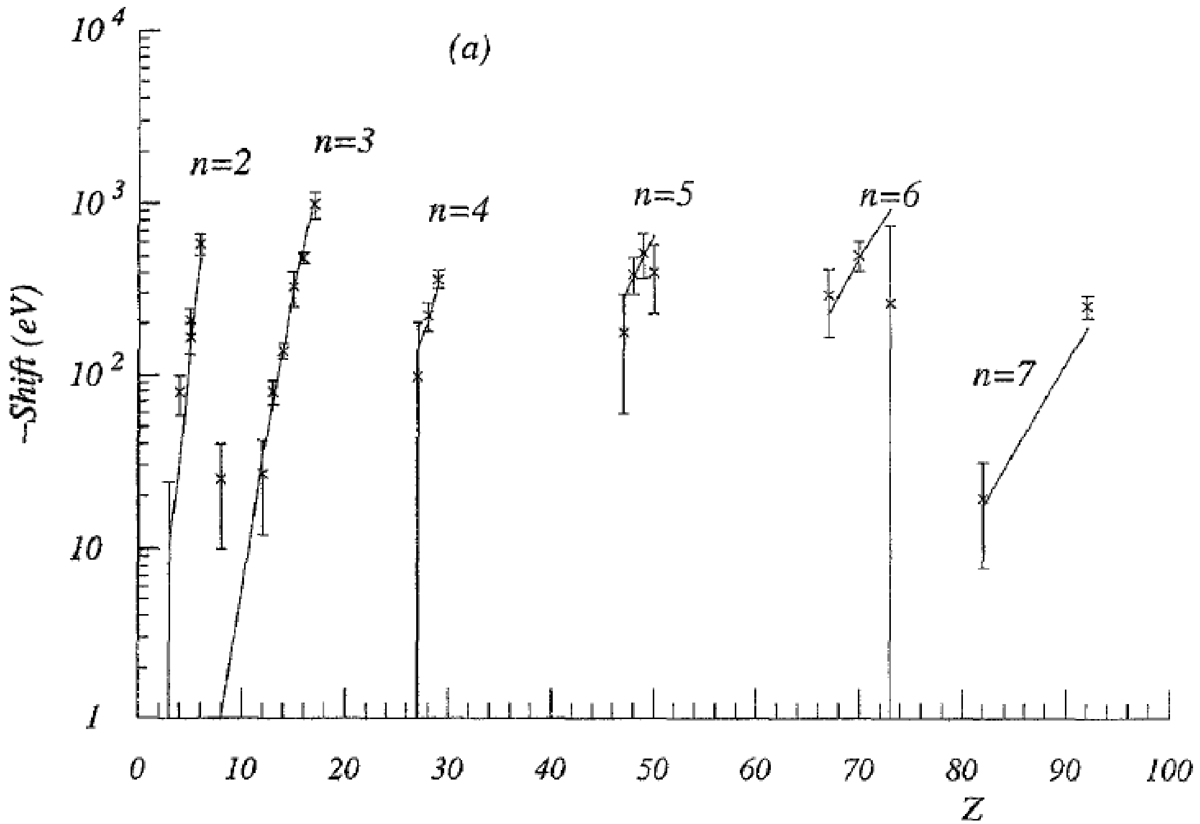
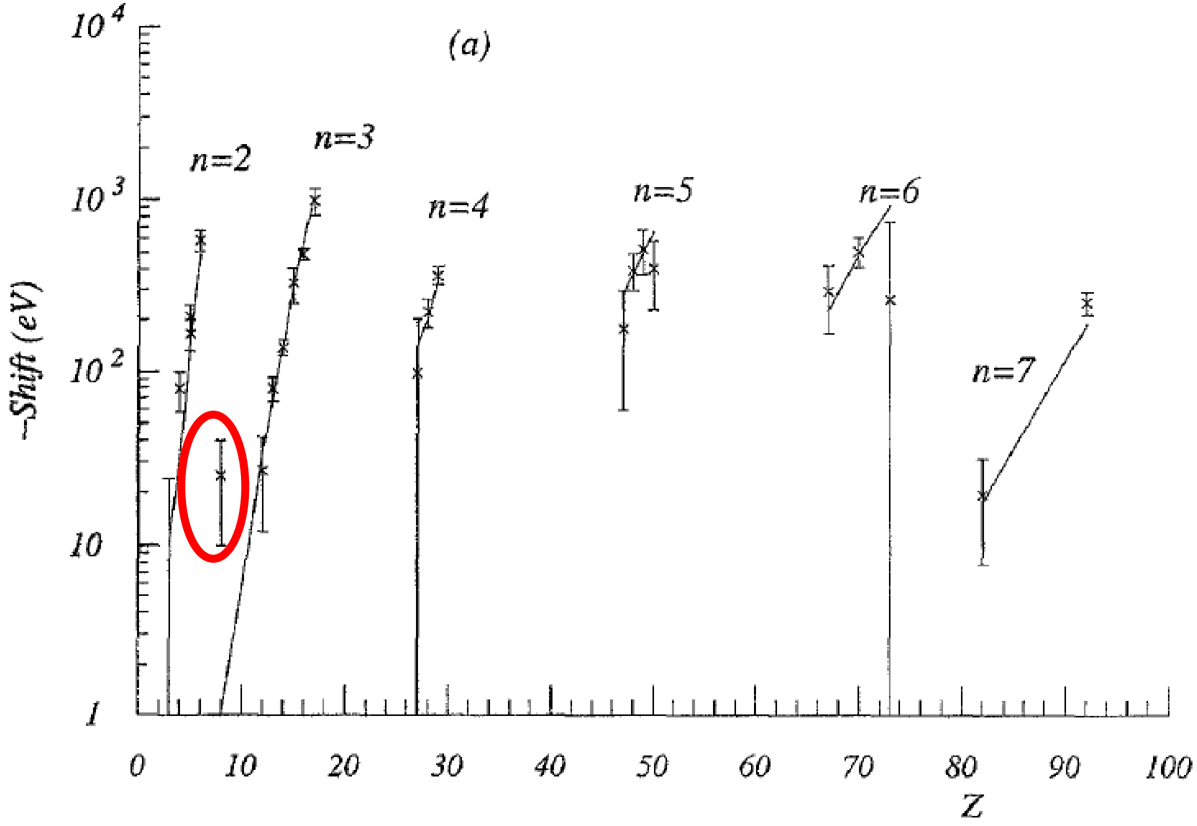


One target→ One shift and One width

It is interesting : One target→ more than one shifts and widths

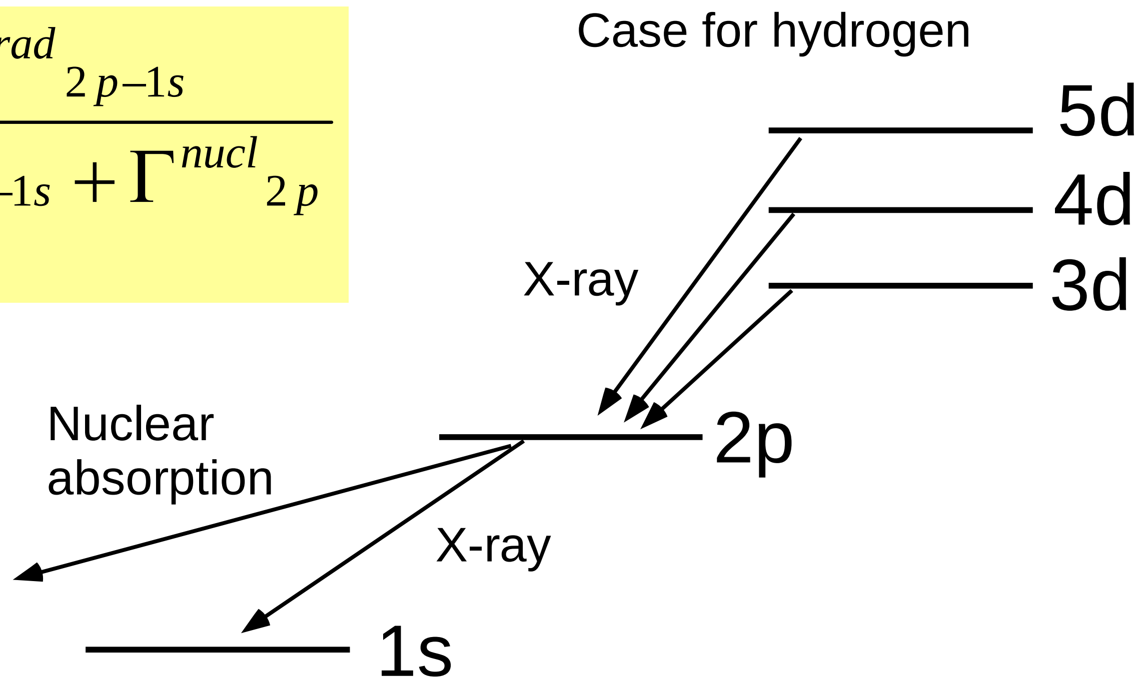


K-O 4-3:
Exp: -25±18 eV [NPA329 (79) 407]
Theory: 0.1~1 eV [NPA 673 (2000) 335]

Alternative way to determine "upper" level width

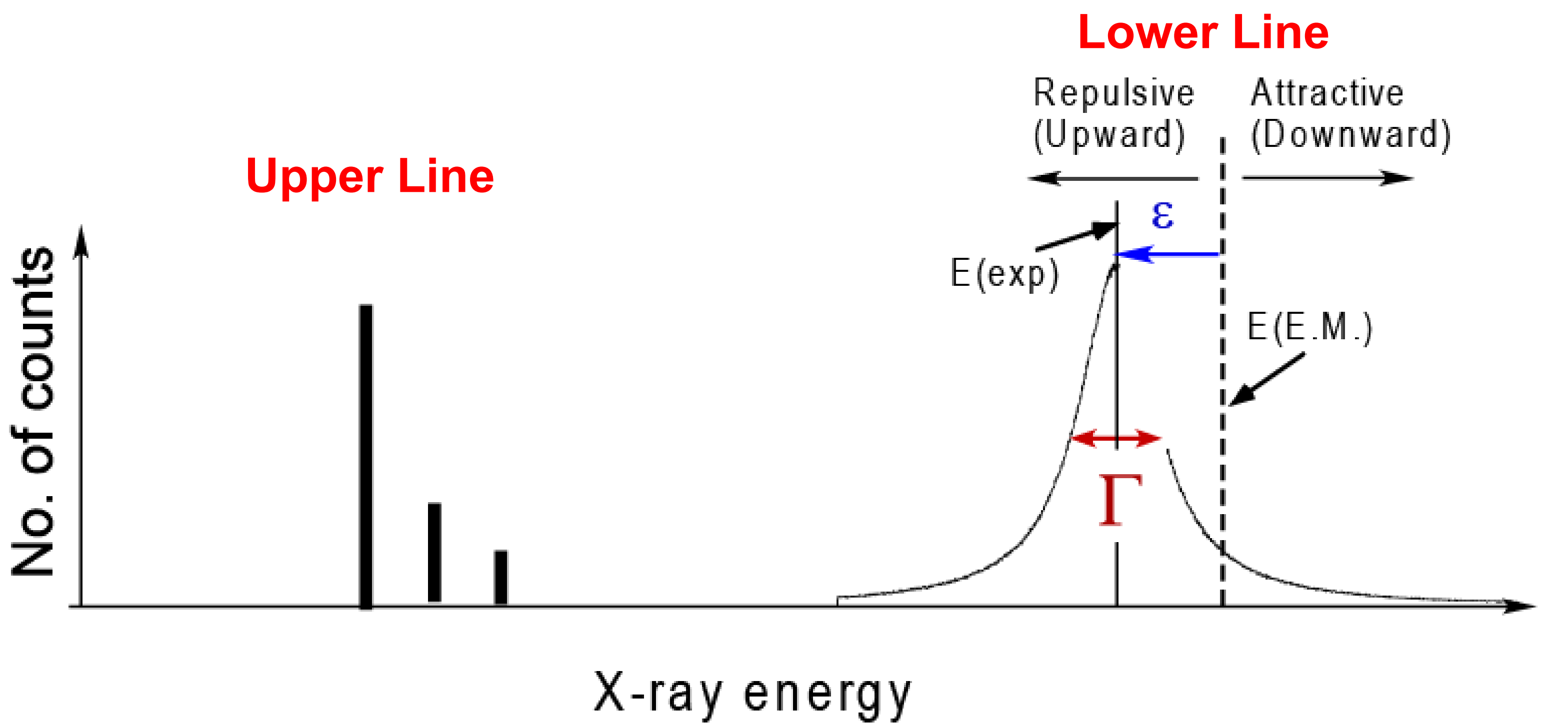
Missing X-rays → related to "upper" level width

$$Y = \frac{Y_{K\alpha}}{\sum_{i=\alpha,\beta,\ldots} Y_{Li}} = \frac{\Gamma^{rad}{}_{2p-1s}}{\Gamma^{rad}{}_{2p-1s} + \Gamma^{nucl}{}_{2p}}$$



Measurements of Ka yield and L-total yields give 2p width
Similar for other transitions

More precisely, need rates of Auger transitions, electron refilling, kaon decay, etc.
(from Cascade calculations)

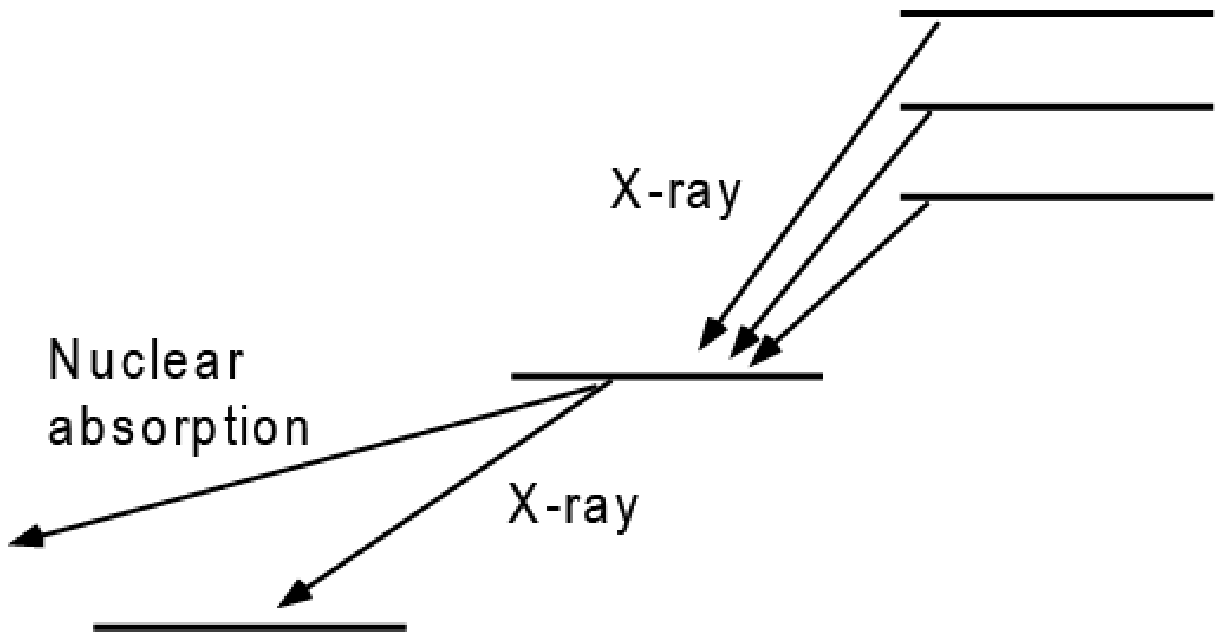


Measurements:

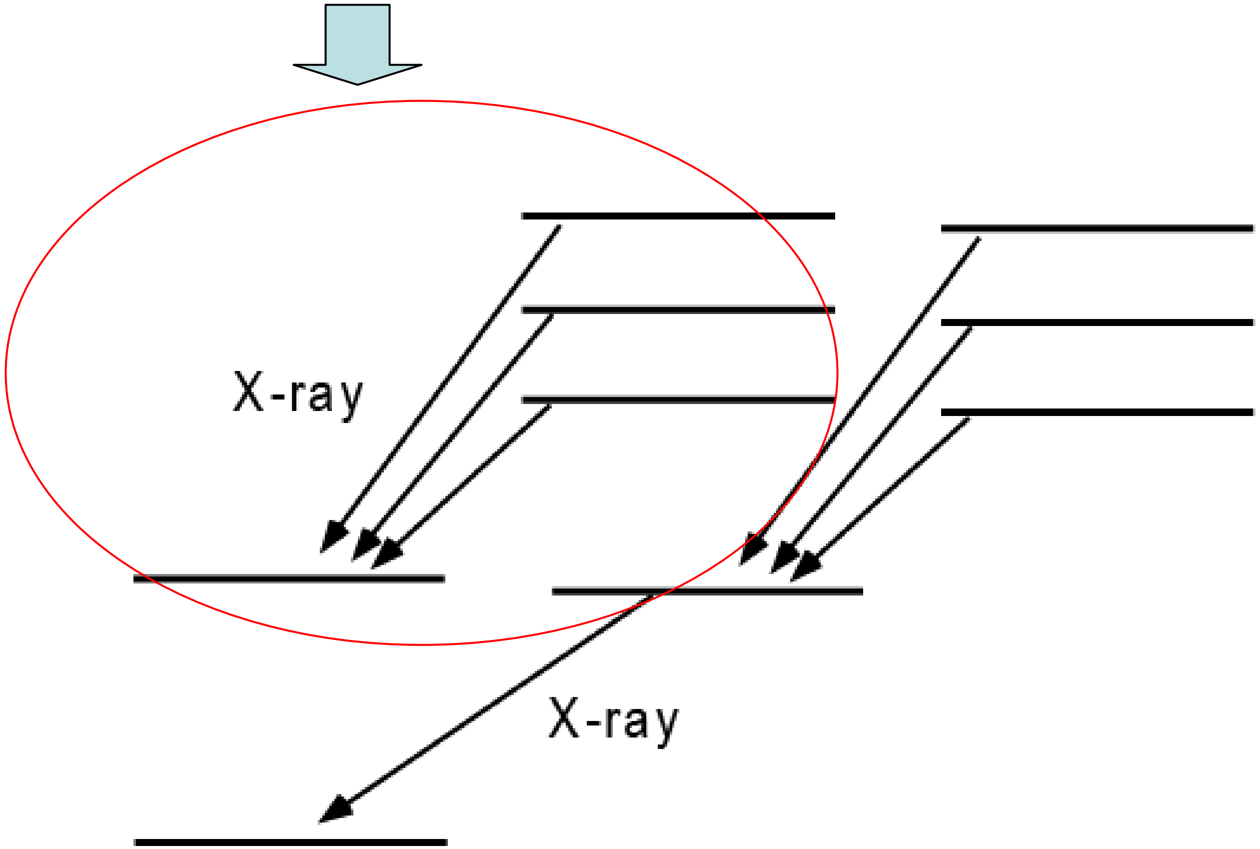
1. **shift and width for Lower**
2. **Relative yield of Lower and Upper**

•Energy dependence of
X-ray detection efficiency and X-ray attenuation in target

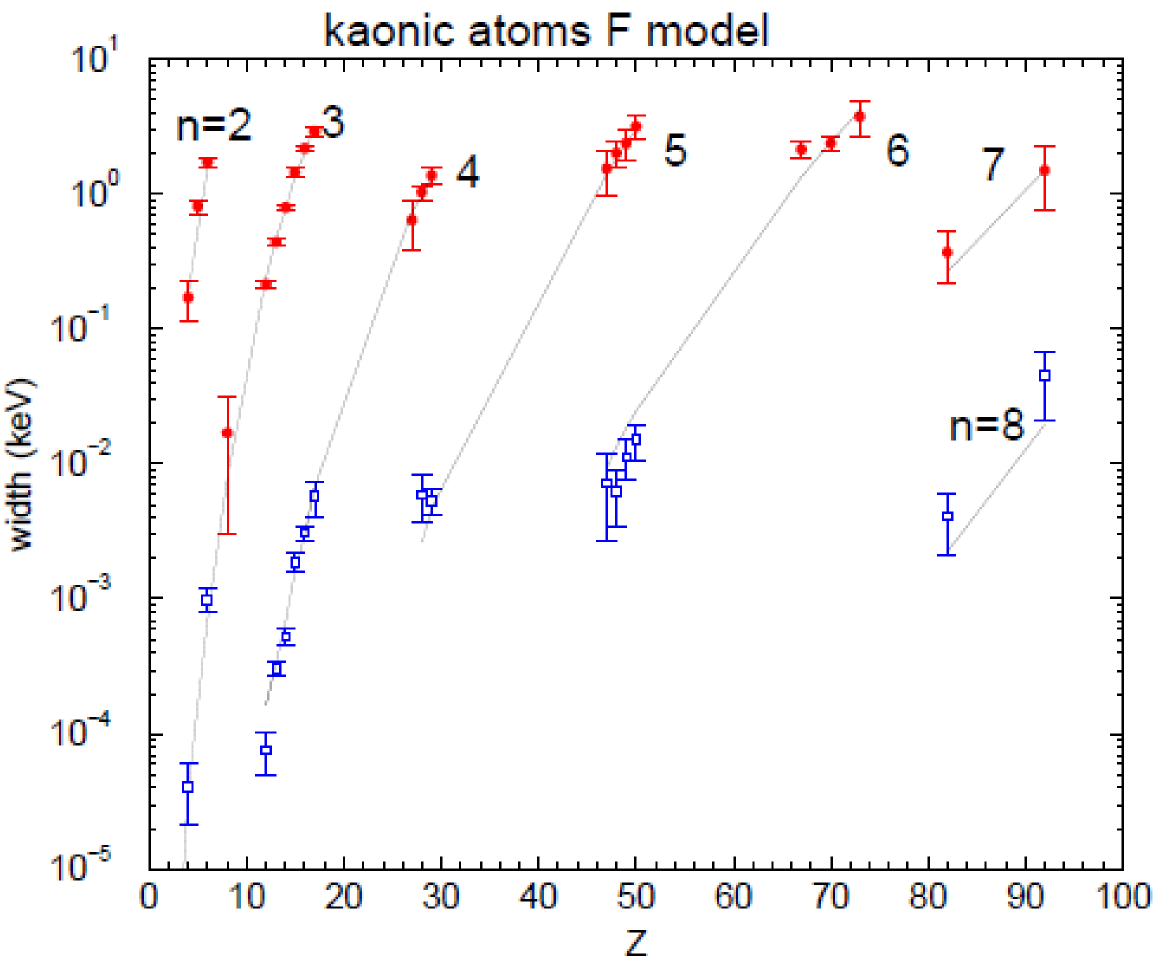
Thin targets OR Low momentum spread and low energy kaons preferred


X-ray
Nuclear
absorption
X-ray

X-rays from parallel transitions



Need subtraction of X-rays from parallel transitions.
However, the energy differences are smaller than detector resolution.
Estimation by cascade calculations is needed.
Same for kaon mass measurements (unless using high resolution detector)



Red points = direct measurements

Blue points = upper level widths (determined from yield balance)

One target has data of 2 widths
→Important for constrains

Quality fits over five orders of magnitude.

Results of global fits apply to average behaviour.

Deep or Shallow?

Table 1. Global fits to kaonic atom 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

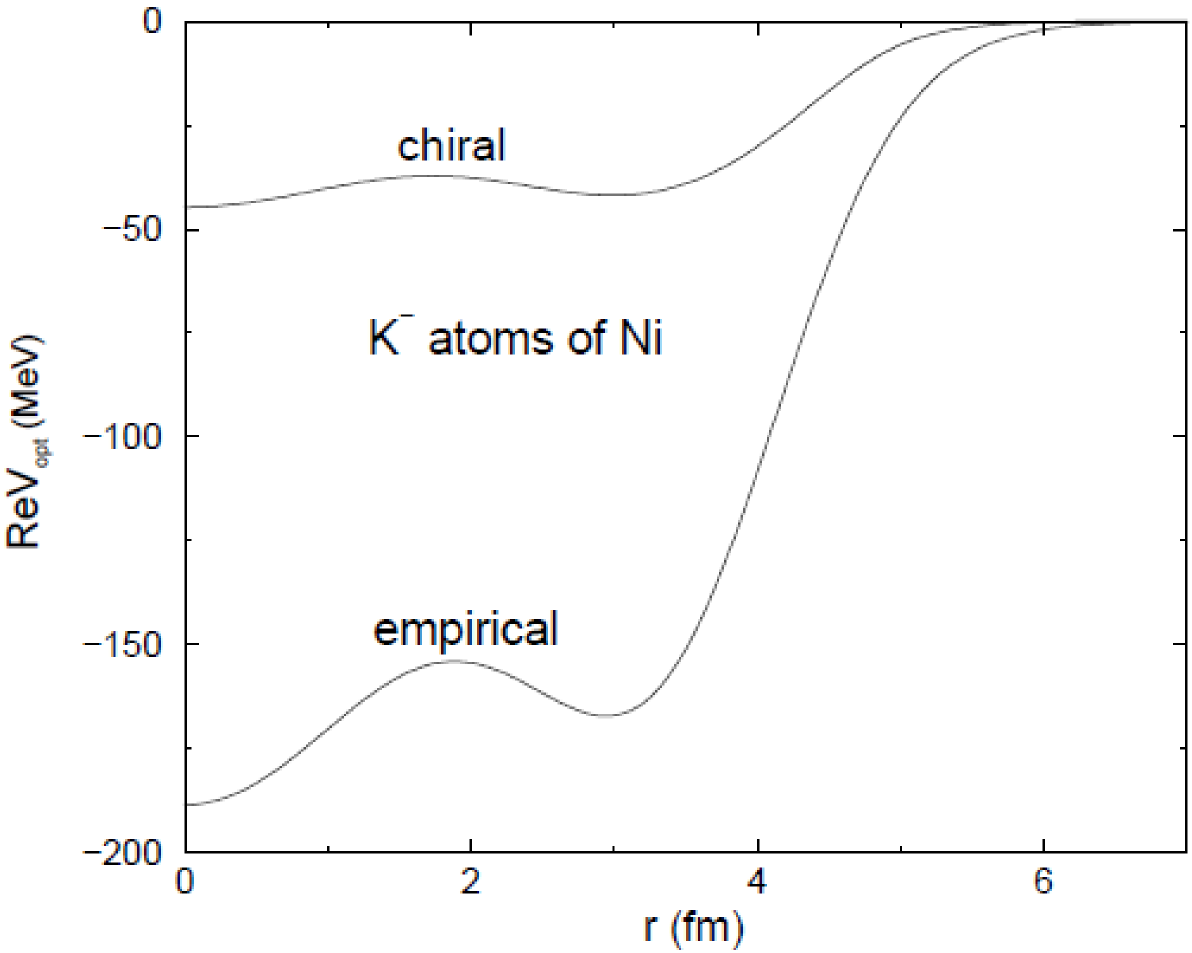
Phenomenological optical potential: tρ (fixed t effective amplitude)
t(ρ)ρ (empirical density-dependent (DD))

Chiral-based t(ρ): potentials constructed from more fundamental approaches

Phenomenological approaches gave better chi2-fit!

Selection of 65 points
(=24 shifts, 24 widths, 17 upper widths; some data excluded)
See 2.2.2 Physics Reports 287 (1997) 385

Real K-Ni potential from chiral and empirical DD potentials



Chi2-analysis prefers deep potential by empirical DD

→ Related to kaonic nuclei and **kaon condensation in neutron stars,**

Existence of a K- strong-interaction l=3 quasibound state

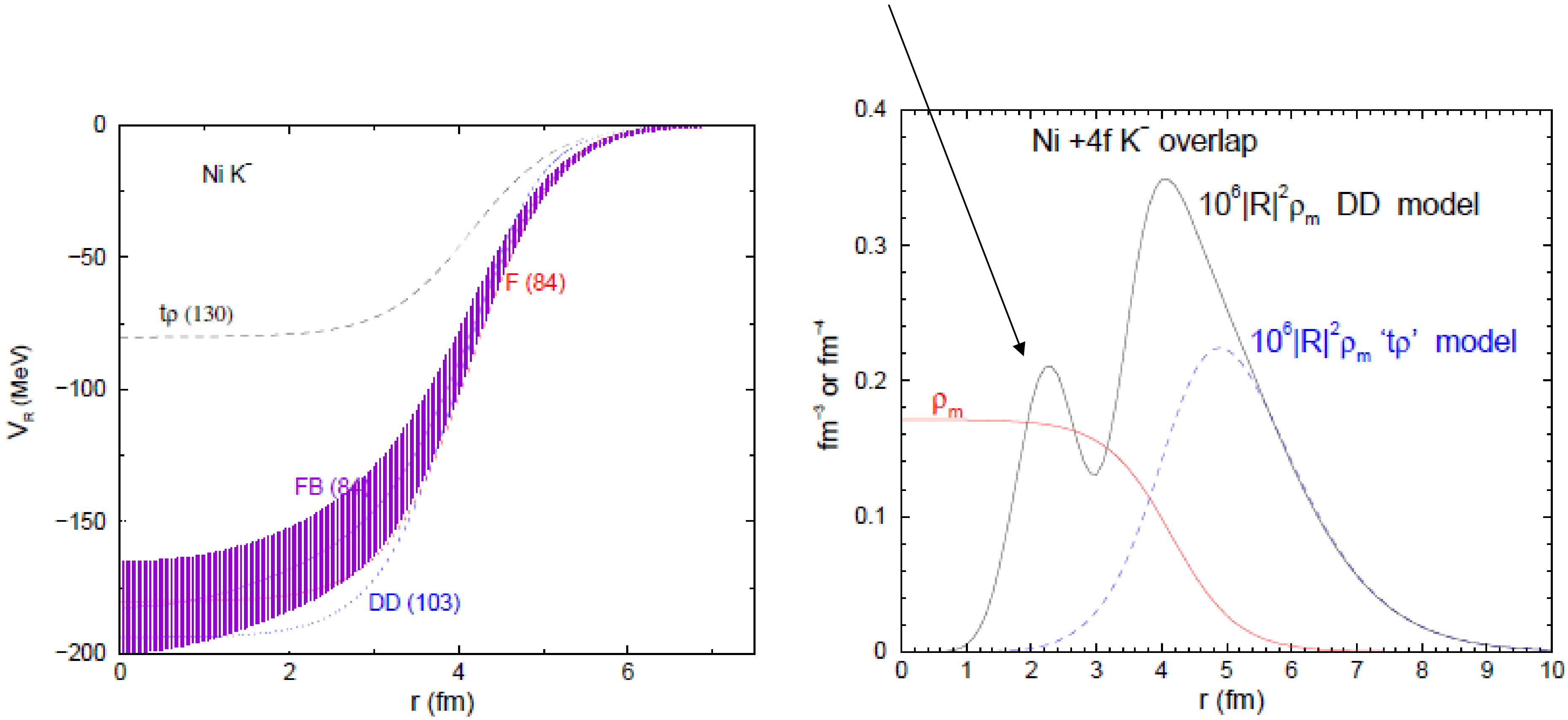
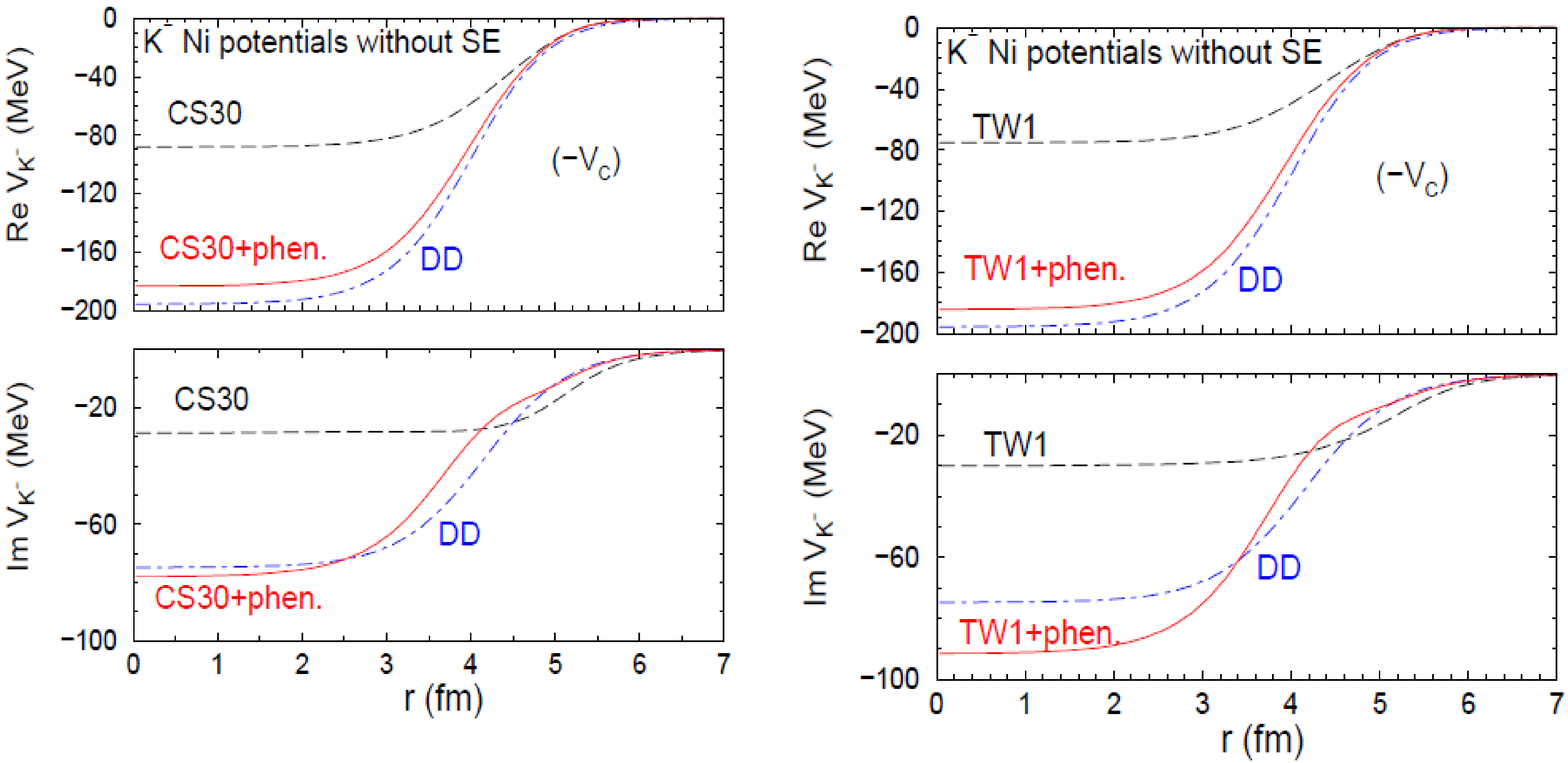


Figure 6. Left: $V_R^{\bar{K}}$ in Ni from global fits to 65 K^- atom data points, with χ^2 values in parentheses [2]. The shaded area approximates the uncertainty in the Fourier-Bessel fit. Right: Overlap of K^- atomic $4f$ radial wavefunctions R squared with Ni matter density ρ_m.



Phys.Rev.C 84, 045206 (2011)
NPA 881 (2012) 150; 899 (2013) 60

Question of data quality/selection

- Phenomenological potentials gave better chi2 than chiral potentials
- Is it general tendency, even if we exclude some data?
- Remove 3 nuclear species, which introduced lager chi2 values (i.e. “bad” data)

Table 2. Comparing full and 'less' data.

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 [tρ (fixed t)] **Deep [t(ρ)ρ (DD)]**

Removing C, Mg, Si data, chi2 are better,
and the results are still same

Table 4. Comparing full and reduced data.

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

Only data of C, Si, Ni, Sn, Pb, the results does not change so much

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

Even more reduced data set, the results do not change so much
Always deep potentials give better chi2.

What's next?

- Even if reduced data set were used, the fit with the deep real potential is again significantly better than the fit with the shallow potential. Thus, it appears to be an inherent property of the kaonic atom data.
- An obvious line of action to resolve the puzzle of the depth of the kaonic atom real potential is to repeat some of the 30-40 years old measurements with the presently available techniques.

What's next?

- Unrealistic to repeat experiments on all the 23 targets. Select a small number of targets that are representative of the full set. 5 targets cover the whole range of the original data. The widths are not too large and the relative yields of the upper levels are of the order of 10% or more.

target	C	Si	Ni	Sn	Pb
ref	12	13	13,14	13	15
(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
relative 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→n energy (keV)	63.3	123.7	231.6	403.9	426.2

New results give still deep potential?? Indeed so??

4. Summary

possible existence of antikaon-nucleon clusters. Global fits of optical potentials to the world's data on kaonic atoms lead to good agreement with data for a shallow type of real potential and to very good agreement for a deep type of real potential.

Although deep potentials favors in terms of chi2,
but available data cannot exclude shallow potentials.

New precise measurements:

1. **check old data**
2. **Improvement of data can provide further chi2-descrepancy between shallow and deep potentials.**
3. **Can we confirm that the exclusion of shallow potential??**

The depth of the antikaon-nucleus real potential has received renewed attention in the last decade because of its relevance to recent theoretical speculations[8] and experimental indications[9,10] for the existence of bound clusters of nucleons and an antikaon with binding energies of the order of 100 MeV. If confirmed they will exclude the shallow potentials, assuming that the depth does not vary strongly with the binding energy.

Last but not least, if the empirical deep potentials are indeed confirmed, then there will remain the question of why they differ so much from potentials constructed using more fundamental approaches.

by E. Friedman

Fitting to such a data set with improved accuracy could resolve the issue of deep vs. shallow potentials and determine how deep is 'deep'

by A. Gal

Under this classification E. Friedman has performed a survey of nuclear targets that could be used in new kaonic atom experiments.
The aim is to be able to determine strong interaction widths of TWO levels in the same atom, referred to as 'lower' and 'upper' level. The interest in this topic arises from our recent work (Nucl. Phys. A 899 (2013) 60-75) where we showed that such measurement could help to disentangle one-nucleon absorptions from multi-nucleon processes.

The accuracy of upper level widths in old measurements leaves much to be desired. The present work has identified 6-8 suitable targets.
A paper is being written up for publication.

LEANNIS report by A. Gal

Minimum data sets (by Friedman)

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
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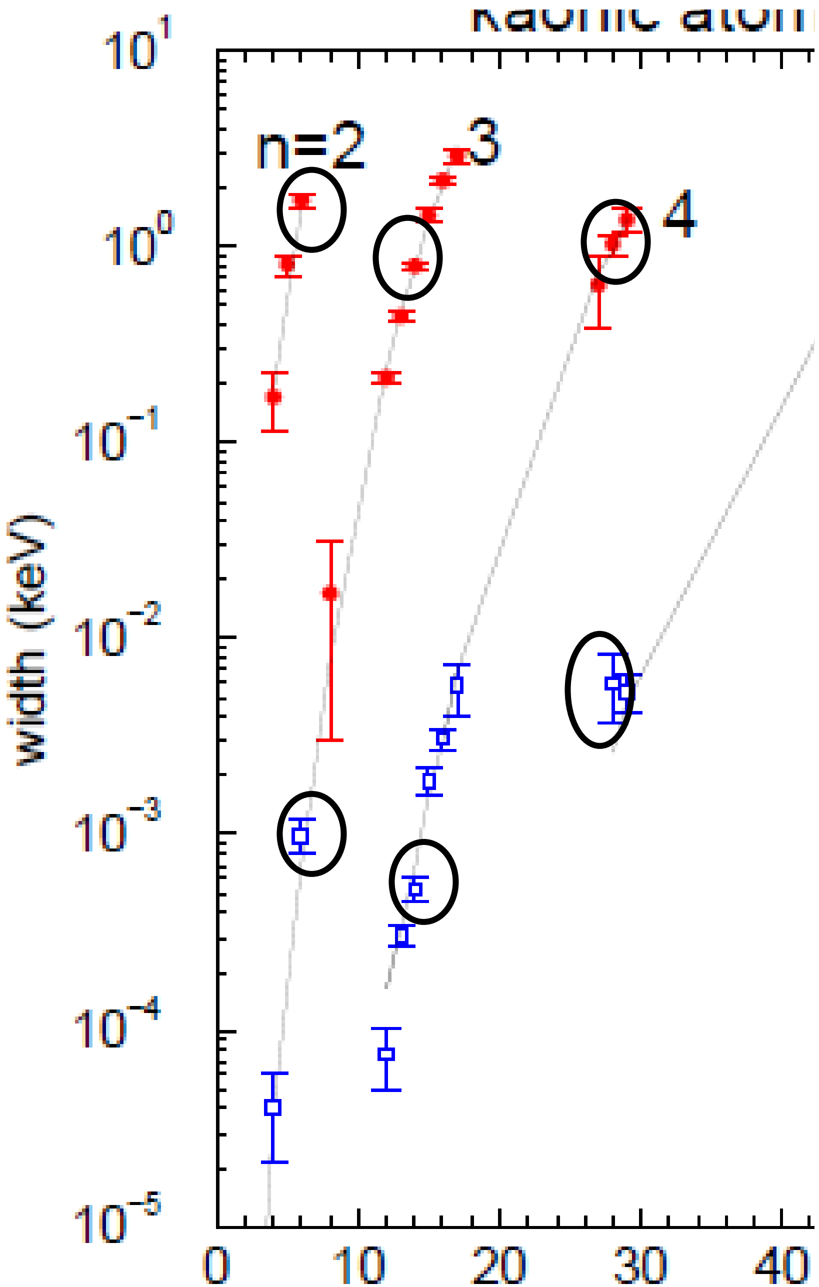
Meson2010, Friedman

Let's look existing data carefully



Suggestion:
C,Si,Ni,Sn,Pb

Old method:
Error reduction using "averaging"

Average of Be,B,C→ n=2
Average of Be-Cl → n=3
…

New method:
Error reduction using "Precision"

Precise C → n=2
Precise C,Si → n=3
Precise Si,Ni → n=4
…

Minimum data sets (by Friedman)

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Meson2010, Friedman

Yield per stopped kaon

	C(3-2)	Si(4-3)	Ni(5-4)	Sn(6-5)	Pb(8-7)
X-ray per stopped K	**0.028**	**0.13**	**0.045**	**0.076**	**0.27**

Friedman, NPA579(1994)518
Wiegand, PRA9 (1974) 2282

target	C	Si	Ni	Sn	Pb
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A very simple optical model calculation

K-Pb	Exp		Calc.	
	Shift	Width	Shift	width
9-8	--	4.1+/-2.0 eV	0.08 eV	2 eV
8-7	-20+/-12 eV	370+/-150 eV	-16 eV	220 eV
7-6 (650 keV)	--	--	**-2.8 keV**	**10.5 keV**

Detector resolution~1.5 keV

Calculated absolute Yield at 7-6~0.1%

Minimum data sets (by Friedman)

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ref	(a)	(b)	(b),(c)	(b)	(d)
(n,l)	2p	3d	4f	5g	7i
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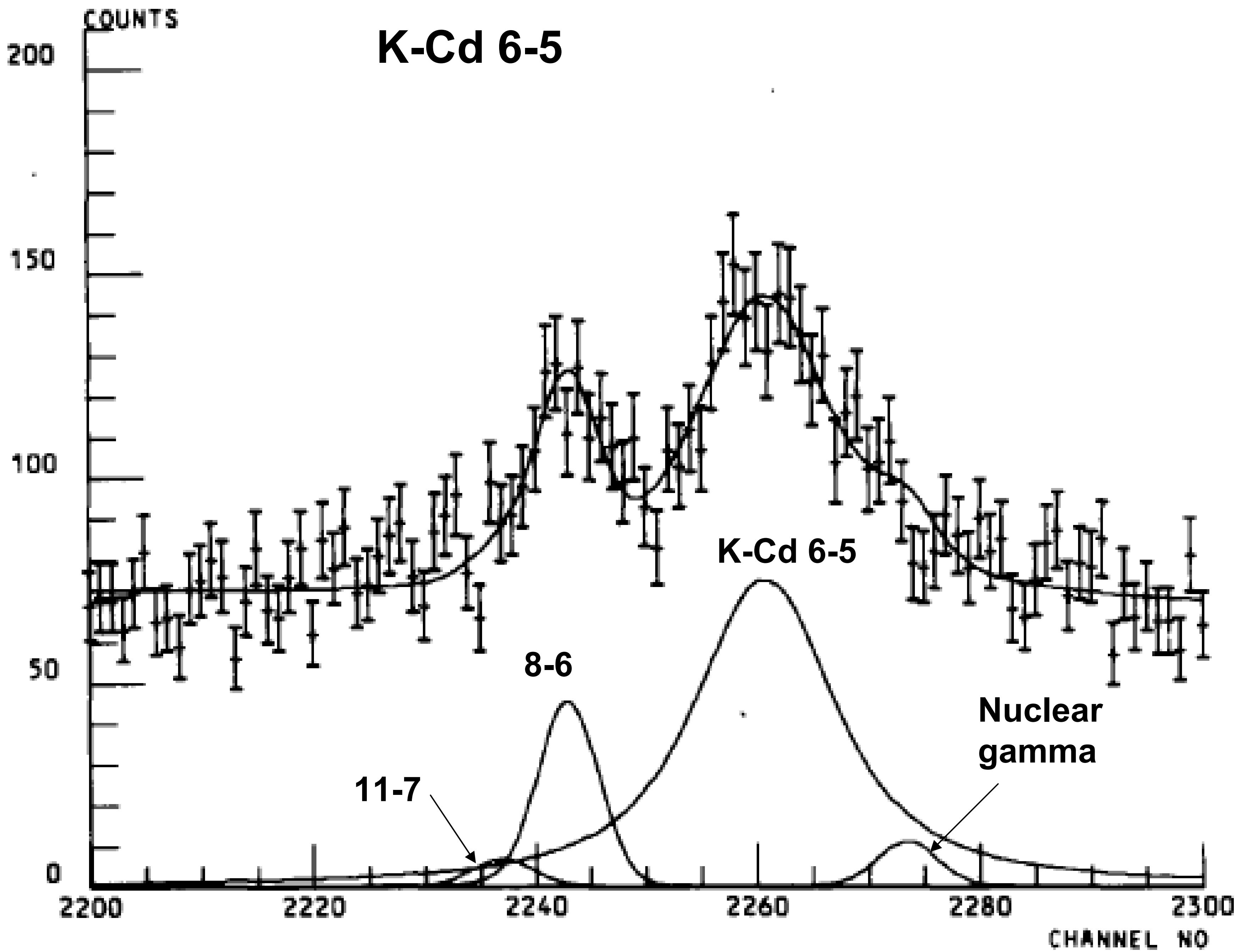
Meson2010, Friedman

Sn 6-5: be care for overlap of 6-5 and 8-6

Energy difference of E(6-5) and E(8-6) is smaller
In addition E(11-7)..
Not easy to extract 6-5 contamination.

Same for Ξ-atoms (J-PARC E03)



K-Cd 6-5
COUNTS
200
150
100
50
0
8-6
K-Cd 6-5
11-7
Nuclear gamma
2200
2220
2240
2260
2280
2300
CHANNEL NO

target	C	Si	Ni	Sn	Pb
ref	12	13	13,14	13	15
(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
relative 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

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Si	-240±50	810±120	-- (due to thick target)	NPA 231 (74) 477
Si	-130±15	800±33	$0.54^{+0.07}_{-0.06}$	NPA 329 (79) 407
Ni	-180±70	590±210	6.0±2.3	NPA 231 (74) 477
Ni	-246±52	1230±140	--	NPA 329 (79) 407
Pb	-20±12	--	**--**	NPA254(75)381
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154

***Ni widths are small compared to calculations [NPA 231 (74) 477]**

•Pb data: several problems…

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Ni	**-180±70**	**590±210**	**6.0±2.3**	**NPA 231 (74) 477**
Ni	-246±52	1230±140	--	NPA 329 (79) 407

NPA 231 (74) 477

Element	Transition $n_i, l_i \rightarrow n_f, l_f$	Width of level Γ_{n_f} (eV)		Shift of level ΔE_{n_f} (eV)		$\bar{A}^{\text{fit}}$ (fm) (does not include yield)
		meas.	calc (3)	meas.	calc (3)	
$_{13}$Al	4, 3 → 3, 2	490±160	545	−130±50	−63	$0.3^{+0.6}_{-0.5}+i(1.1\pm0.5)$
$_{14}$Si	4, 3 → 3, 2	810±120	895	−240±50	−120	$0.25^{+0.30}_{-0.25}+i(1.15^{+0.25}_{-0.20})$
$_{28}$Ni	5, 4 → 4, 3	590±210	1031	−180±70	−97	$-0.1^{+0.3}_{-0.2}+i(0.6^{+0.3}_{-0.2})$
$_{29}$Cu	5, 4 → 4, 3	1650±720	1504	−240±220	−181	$0.7^{+1.0}_{-0.7}+i(0.9^{+0.6}_{-0.8})$

Ni width disagreement is serous! Also, it related to upper width.
[Wycheck told me that the upper width of Ni is strange.]

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Ni	-180±70	590±210	6.0±2.3	NPA 231 (74) 477
Ni	**-246±52**	**1230±140**	**--**	**NPA 329 (79) 407**

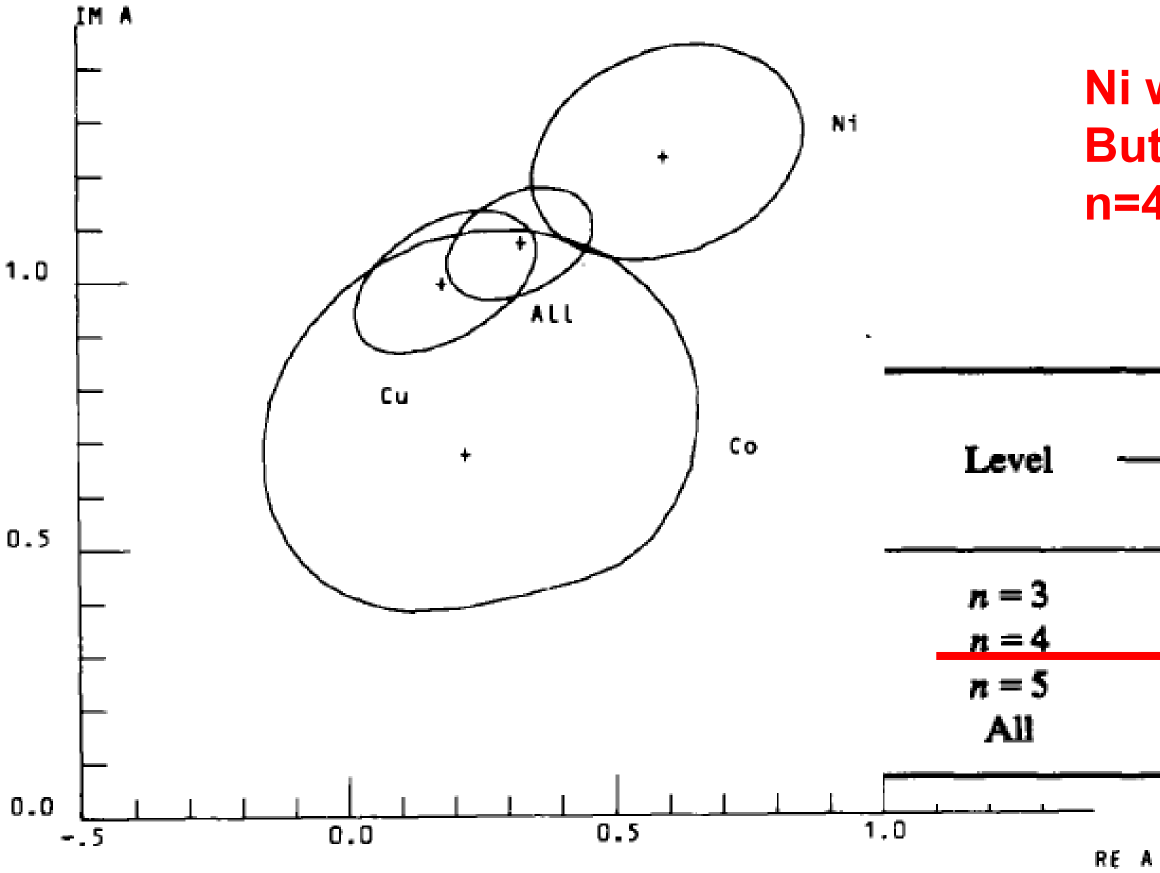
NPA 329 (79) 407

Calibration problem

The data for Co and Ni were obtained prior to the introduction of the stabiliser and simultaneous collection of calibration data. In both cases there appears to be a small energy shift between the data and the calibration runs. This was observed by looking at unshifted X-ray lines and identified γ-lines in the data. These led to an additional error of ±30 eV being introduced.

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Ni	-180±70	590±210	6.0±2.3	NPA 231 (74) 477
Ni	**-246±52**	**1230±140**	**--**	**NPA 329 (79) 407**

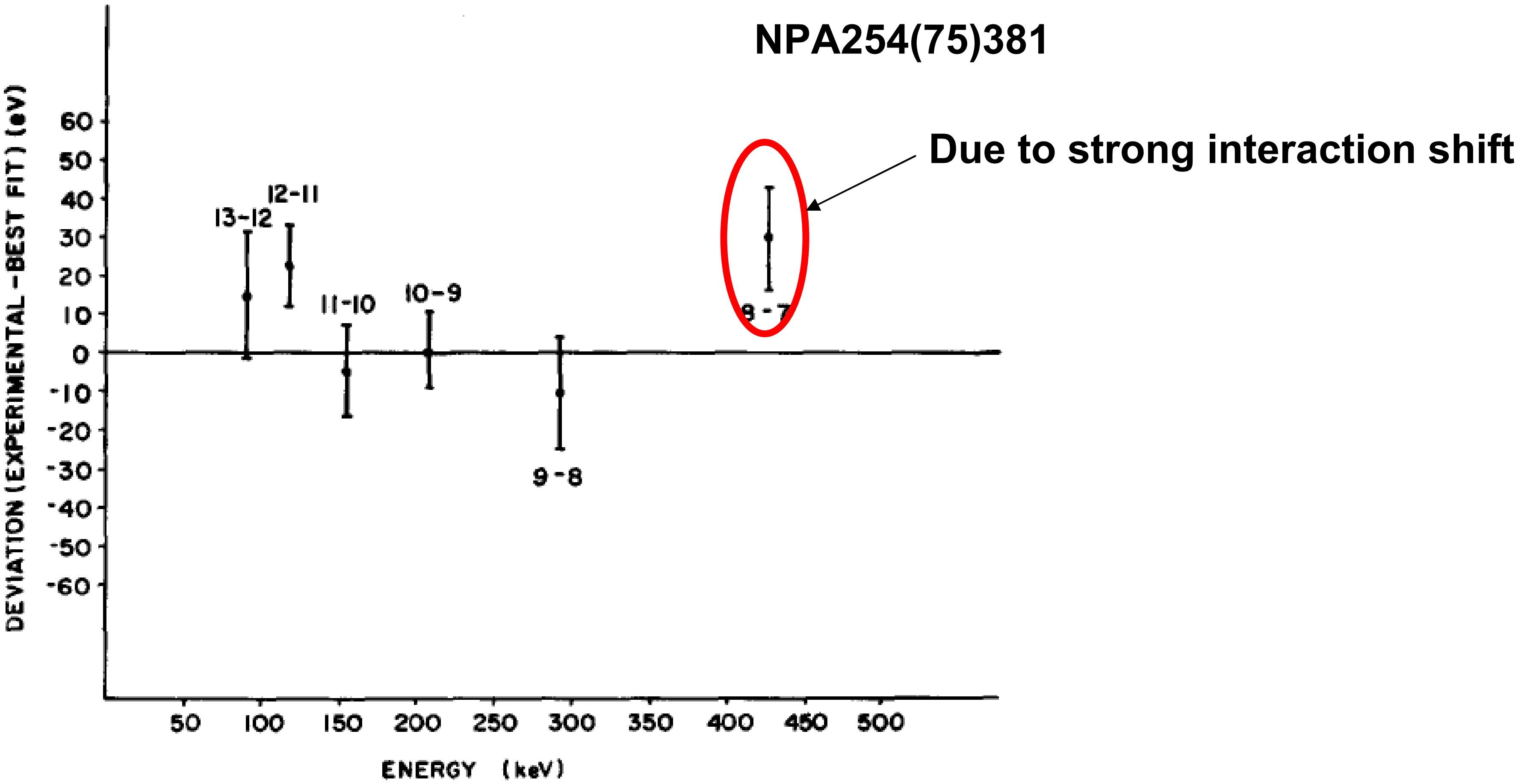
NPA 329 (79) 407



Ni width was too large??
But it seems unclear whether
n=4 level problem.

Level	$\bar{a}$		χ^2/N
	a_R(fm)	a_I(fm)	
$n=3$	0.33±0.04	0.78±0.03	0.6
$n=4$	0.33±0.14	1.07±0.11	0.8
$n=5$	0.57±0.21	0.84±0.11	0.4
All	0.34±0.03	0.81±0.03	1.0

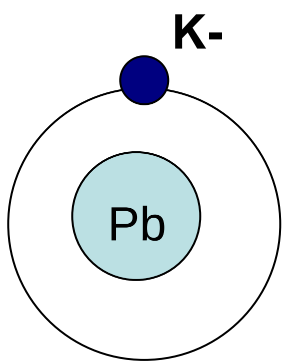
	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	**-20±12**	**--**	**--**	**NPA254(75)381**
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154



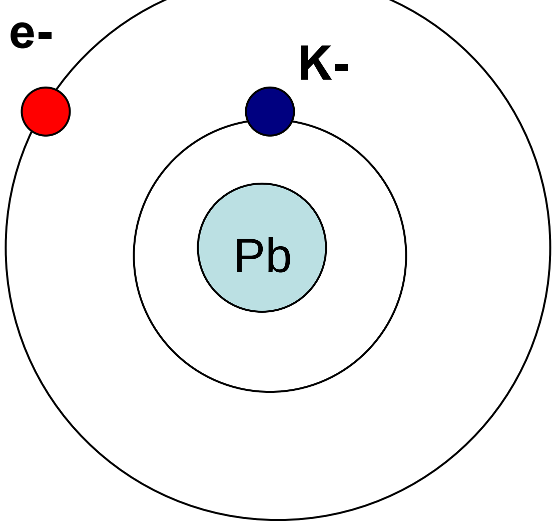
	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	**-20±12**	**--**	**--**	**NPA254(75)381**
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154

	Energy [keV]	Shift [eV]	Kaon mass [MeV]
Measurement	426.181±0.012		
Calculated	426.201	-20±12	493.715 (used)
[Optical model]		[-23]	
Measurement			493.657±0.020 (determined)
Cal,+**V(α^2(Zα^2))** (but not sure)	426.173±0.012	(+8±17)	493.696±0.025 (determined)
Calculated **[PRC 40(89) 2154]**	426.149	+32±12	493.6364 (used)
Calculated **[PRA 71 (2005) 032501]**	426.180	(+1±12)	493.677 (used) [current PDG value]

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	**-20±12**	**--**	**--**	**NPA254(75)381**
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154



Z(Pb)=82, so total charge=+81 (=+82(Pb)-1(K-))
very highly ionized.



Target=solid
electron refilling from surrounding atoms
(+Auger e- emission)

Electron screening causes energy shifts,
depending on the number of electrons in kaonic Pb

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	**-20±12**	**--**	**--**	**NPA254(75)381**
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154

TABLE 8

Calculated theoretical K^-Pb transition energies

Transition	Zeroth order (keV)	$\alpha(Z\alpha)$ (eV)	$\alpha(Z\alpha)$ iter. (eV)	$\alpha(Z\alpha)$ finite size (eV)	$\alpha^2(Z\alpha)$ (eV)	$\alpha(Z\alpha)^3$ (eV)	$\alpha(Z\alpha)^{5,7}$ (eV)	Finite size high order (eV)	Electron screen (eV)	Nuclear pol. (eV)	E_{calc} (keV)
13 → 12	90.697	284.0	0.5	0.4	2.0	−7.7	−1.1	0.5	−51.8	0	90.924
12 → 11	116.575	419.5	0.8	0.8	2.9	−10.6	−1.5	0.8	−44.9	0	116.943
11 → 10	153.328	632.8	1.4	1.5	4.3	−14.7	−2.1	1.2	−38.2	1	153.916
10 → 9	207.340	980.0	2.3	3.1	6.7	−20.7	−3.0	2.1	−31.9	2	208.280
9 → 8	290.081	1569.5	3.9	7.1	10.9	−29.8	−4.3	3.6	−25.9	5	291.621
8 → 7	423.579	2625.5	7.2	18.2	18.6	−44.5	−6.4	5.9	−20.4	18	426.201

NPA254(75)381 assumed two 1S electrons (but how evaluated?)

Electron screening = 20 eV at 8-7 transition

Electron screening effects

PRA 71 (2005) 032501

Nucleus	Transition $n_i \to n_f$	Shift [eV] $E_m - E$						ΔE_m	
		No Elect.	[H]	[He]	[Li]	[Be]	[Ar]		
Be	$4 \to 3$	0.5	0.5	0.5	0.5			1	
Al	$9 \to 8$	−1.0	−0.4	0	0.1			1	
Pb	$8 \to 7$	−9	0	8	10	11	12	12	[
	$9 \to 8$	−49	−37	−26	−25	−23	−22	13	[
	$10 \to 9$	−41	−26	−12	−10	−8	−7	8	[
	$11 \to 10$	−50	−33	−16	−13	−10	−9	11	[
	$12 \to 11$	−27	−6	14	17	20	22	10	[
	$13 \to 12$	−40	−10	8	12	15	17	15	[

M_K=493.677 (current PDG value); [H]=1 1S electron, [He]=2 1S electrons, etc.

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	**-20±12**	**--**	**--**	**NPA254(75)381**
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	+72+(+27-57)	284±14	Y=82±4%	PRC 40 (89) 2154

	Energy [keV]	Shift [eV]	Kaon mass [MeV]
Measurement			493.657±0.020 (determined)

Calibration done by 75Se and 198Au gamma-rays

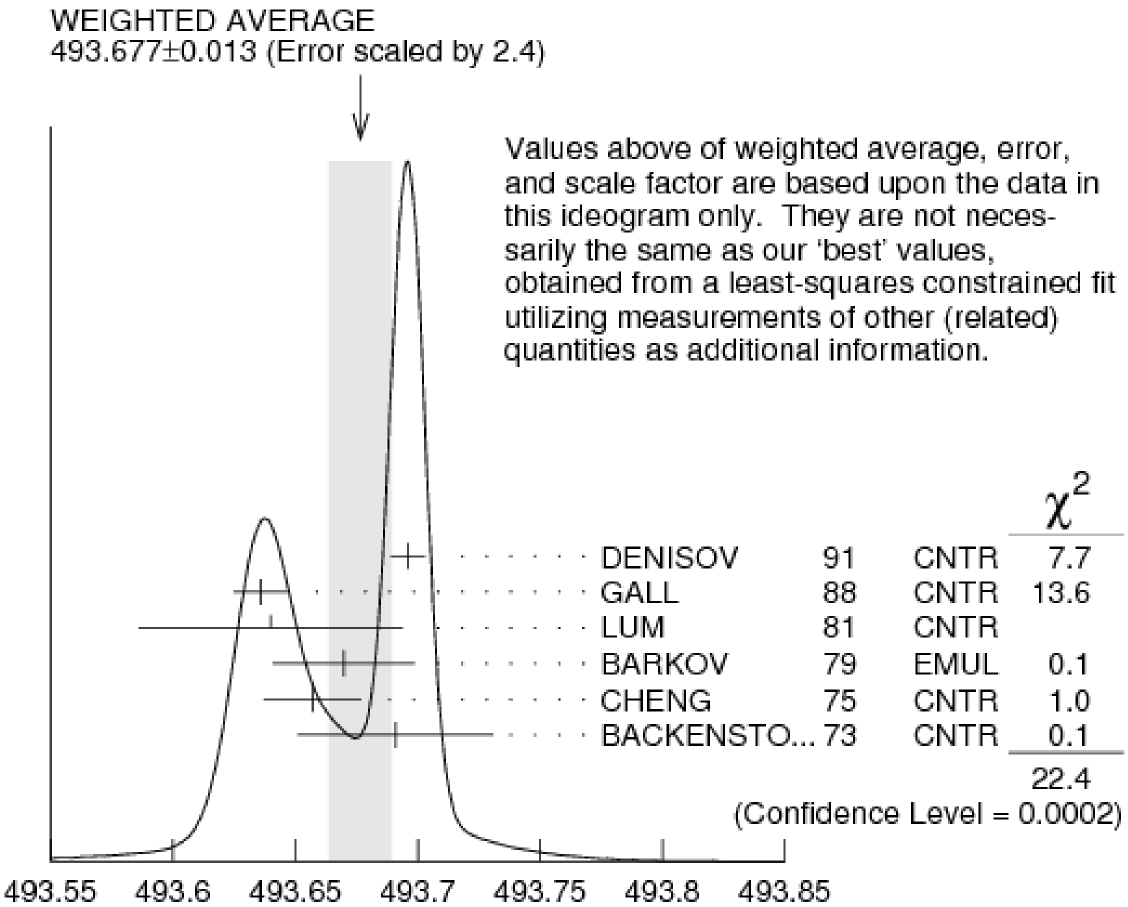
Yu.M. Ivanov, representing DENISOV 91, has estimated corrections needed for the older experiments because of improved 192Ir and 198Au calibration γ-ray energies. He estimates that CHENG 75 and BACKENSTOSS 73 mK± values could be raised by about 15 keV and 22 keV, respectively

PDG

⇨ **If so, need recalculation of shift**

In addition, Nuclear gamma-ray contaminations??
(K-Pb X-rays + gamma-rays in a peak area)

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	-20±12	--	--	NPA254(75)381
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	**+72+(+27-57)**	**284±14**	**Y=82±4%**	**PRC 40 (89) 2154**



Group of PRC is same as Gall PRL60(88)186
M_K=493.636±0.011 MeV

Shift was evaluated using this value.

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	-20±12	--	--	NPA254(75)381
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	**+72+(+27-57)**	**284±14**	**Y=82±4%**	**PRC 40 (89) 2154**

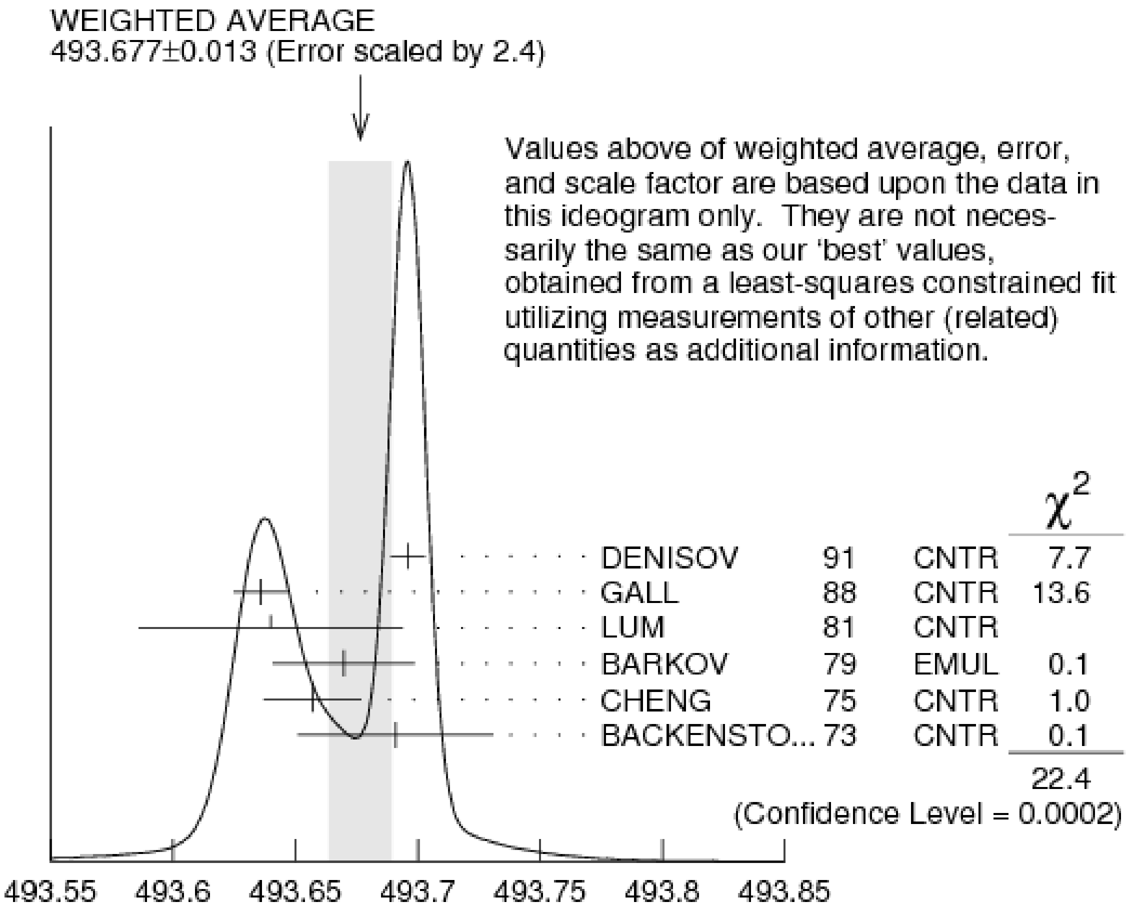
Calibration problem?
511 keV line is not reliable for energy calibration?

These uncertainties resulted in part because **the e+e- 511 keV annihilation line does not provide a reliable energy calibration**. The energy may be shifted by an amount which depends on the specific material in which the positron annihilates.

Depending on possible calibration methods, the error was increased.

However, positive shift is inconsistent with other lighter nuclei.

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	-20±12	--	--	NPA254(75)381
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	**+72+(+27-57)**	**284±14**	**Y=82±4%**	**PRC 40 (89) 2154**



Gall PRL60(88)186
M_K=493.636±0.011 MeV

Denisov JETPL 54(91)558
[with new error estimation*]
M_K=493.696±0.007 MeV
*Method unpublished
[Only thesis]

Reconsideration of Pb

NPA585(95)229c

	Shift [eV]	Width [eV]	Upper Width [eV]	Ref
Pb	-20±12	--	--	NPA254(75)381
Pb	--	370±140	4.1±2. (Y=79±8%)	J.P. Miller, Ph.D (75)
Pb	**+72+(+27-57)**	**284±14**	**Y=82±4%**	**PRC 40 (89) 2154**

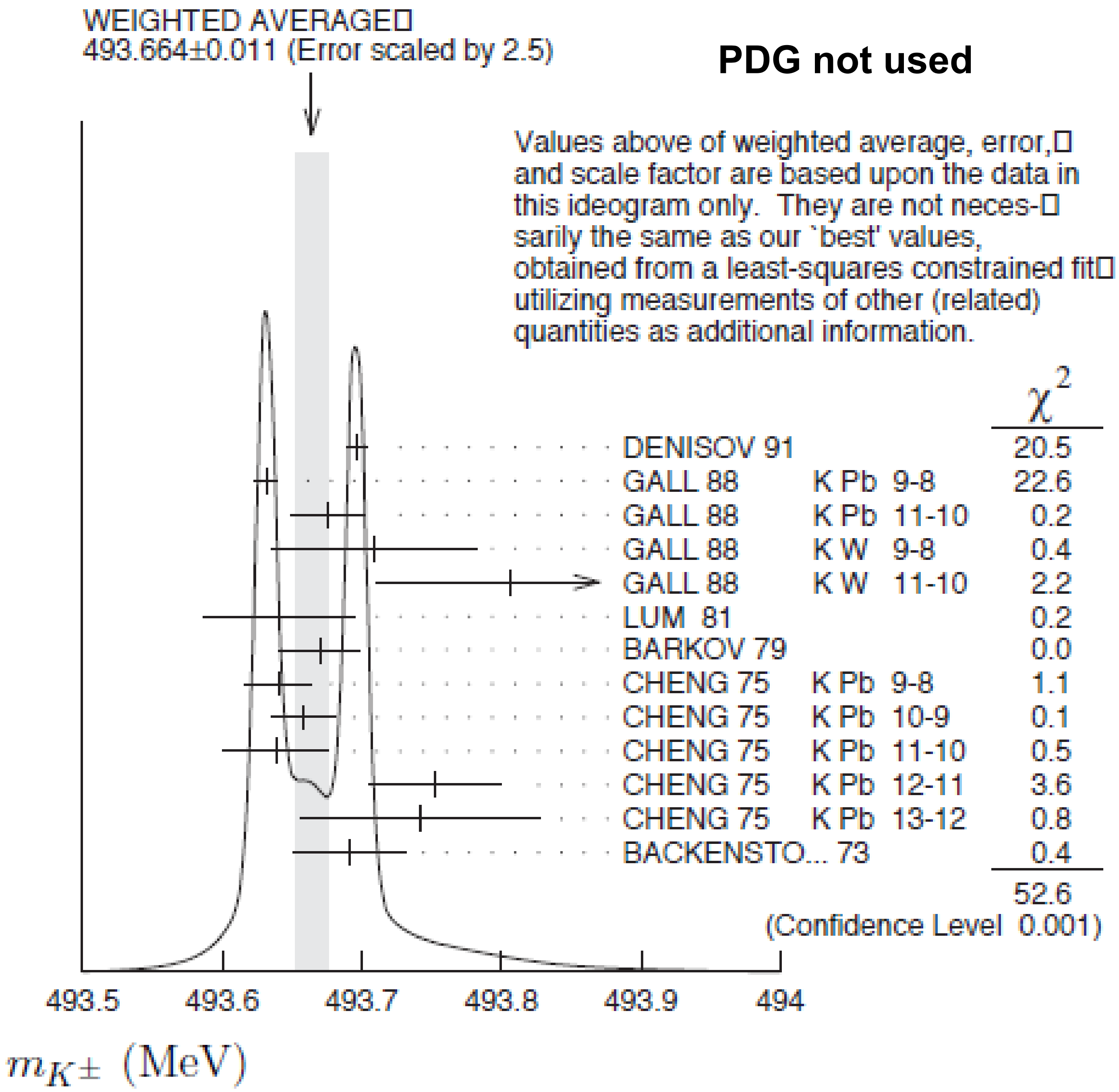
NPA585(95)229c

Transition	ε_{meas}	(1) ε_{calc}	(2) ε_{corr}	(3) ε_{corr}
W (8 → 7)	0.079±0.025	-0.003	0.024±0.025	-0.020±0.025
W (7 → 6)	-0.353±0.092	-0.967	-0.744±0.092	-0.811±0.092
Pb (8 → 7)	0.072±0.057	-0.023	0.072±0.057	0.018±0.057
U (8 → 7)	-0.40±0.17	-0.189	-0.40±0.17	-0.47±0.17
	$\chi^2 = 66$		17	12

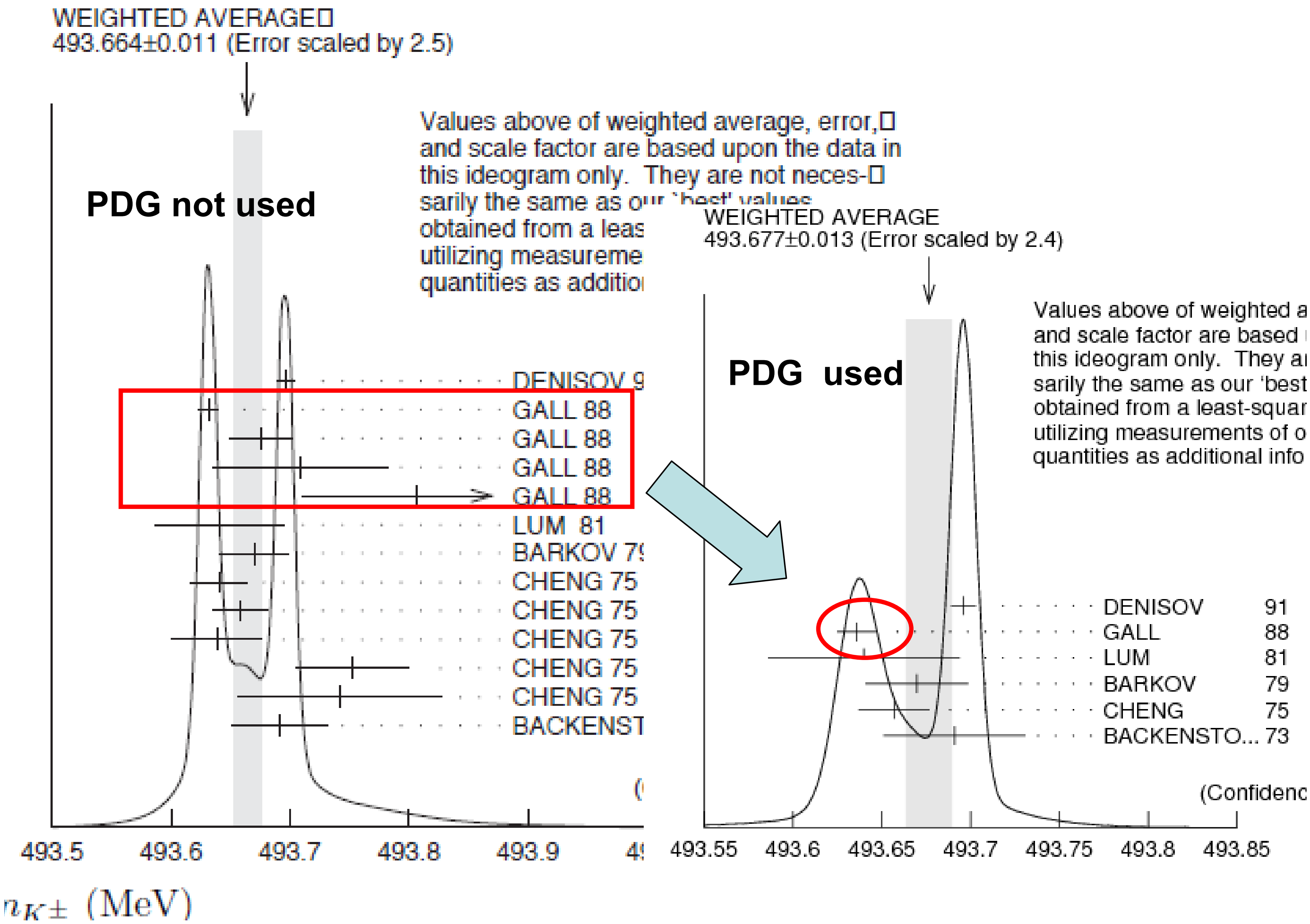
All values are in keV.

(1) Optical model prediction
(2) Including E2 mixing effects
(3) Using Kmass by Denisov

Anyway, PRC data are not used for optical model calculations! Even now..



WEIGHTED AVERAGE
493.664±0.011 (Error scaled by 2.5)
PDG not used
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our `best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.
χ2
DENISOV 91 20.5
GALL 88 K Pb 9-8 22.6
GALL 88 K Pb 11-10 0.2
GALL 88 K W 9-8 0.4
GALL 88 K W 11-10 2.2
LUM 81 0.2
BARKOV 79 0.0
CHENG 75 K Pb 9-8 1.1
CHENG 75 K Pb 10-9 0.1
CHENG 75 K Pb 11-10 0.5
CHENG 75 K Pb 12-11 3.6
CHENG 75 K Pb 13-12 0.8
BACKENSTO... 73 0.4
52.6
(Confidence Level 0.001)
493.5
493.6
493.7
493.8
493.9
494
m_{K±} (MeV)


WEIGHTED AVERAGE
493.664±0.011 (Error scaled by 2.5)
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not neces-sarily the same as our 'best' values obtained from a leas utilizing measureme quantities as additio
PDG not used
DENISOV 9
GALL 88
GALL 88
GALL 88
GALL 88
LUM 81
BARKOV 7
CHENG 75
CHENG 75
CHENG 75
CHENG 75
CHENG 75
BACKENST
493.5
493.6
493.7
493.8
493.9
$m_{K^\pm}$ (MeV)
WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)
Values above of weighted a and scale factor are based this ideogram only. They a sarily the same as our 'best obtained from a least-squar utilizing measurements of o quantities as additional info
PDG used
DENISOV 91
GALL 88
LUM 81
BARKOV 79
CHENG 75
BACKENSTO... 73
(Confidenc
493.55
493.6
493.65
493.7
493.75
493.8
493.85

Best way for K-Pb

- High resolution
  better than 200 eV upto 400 keV energy
  to avoid parallel & nuclear-gamma
- Gaseous Pb target
  to avoid electron screening

However, it is unrealistic!?

How to estimate possible higher order radiative corrections..

Kaon Mass used for determination of shifs

	Kaon Mass [MeV]	Ref
C	493.73	PLB 38 (72) 181
Si,Ni	493.715±0.037	NPA 231 (74) 477
Pb	493.715	NPA 254 (75) 381
Si,Ni,Sn	493.707	NPA 329 (79) 407
Pb	493.6364	PRC 40 (89) 2154
PDG	493.677±0.016 [our fit]	PRD86(12)821
C (4f-3d)	493.696±0.007	JETPL 54(91)558
Pb (9-8)	493.631±0.007	PRL 60 (88) 186

Need corrections for shift evaluation!

To do lists

- We need new measurements
- How accurately & precisely?

  -- Theoretical requirements: errors of xx eV for KC,, xx eV for KPb
- What physics we can get?
  - **Potential can be determined with xxx MeV accuracy**
  - **Exclude deep potential with xxx sigma**
  - **Information for kaonic nuclei**

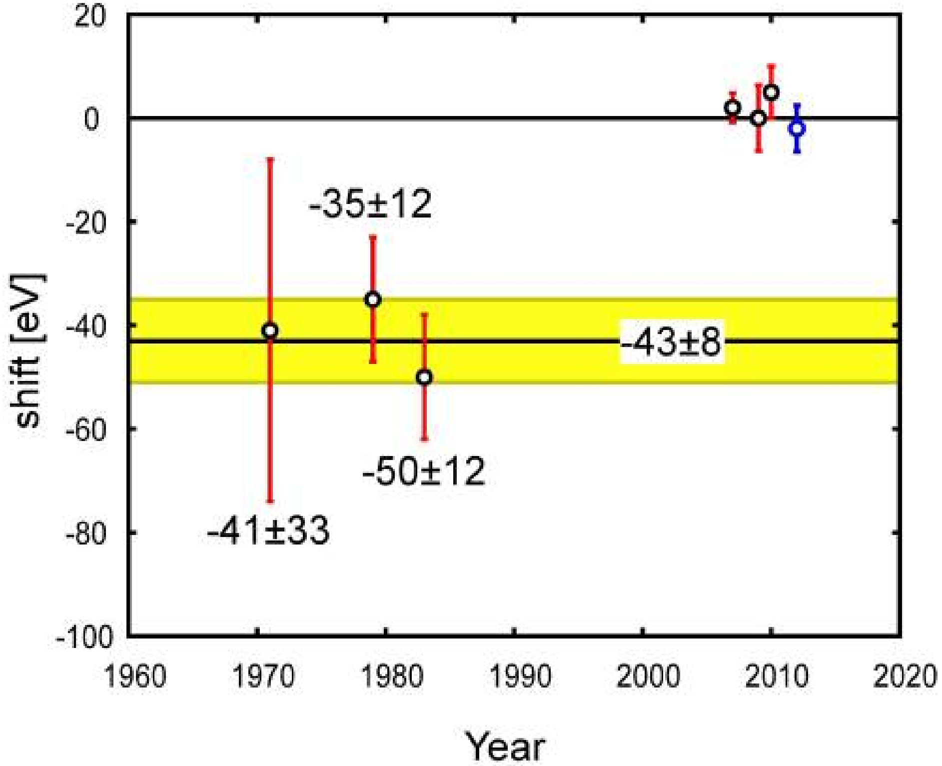
- Above important for making goal of experiments
- Selection of detector (Ge, CdZnTe,…)
  - Need Compton suppressors (NaI, BGO,..)?
  - Detector performance (stability, energy resolution, linearity, etc)
  - Calibration methods (some radioactive sources)
- DAFNE or J-PARC?
- Need Monte Carlo studies and Detector tests
- Request for beam time (How long?)

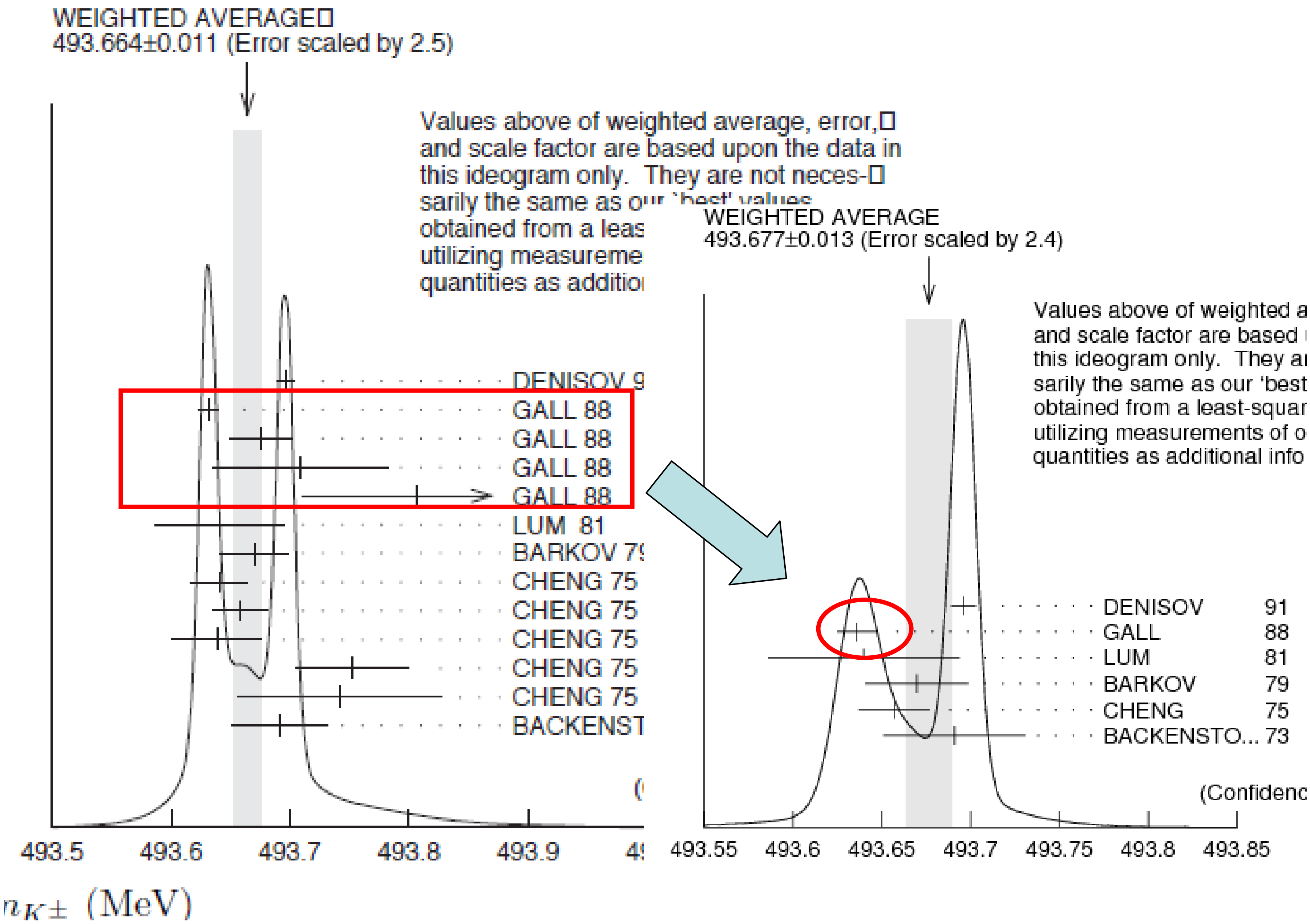
5 shifts and 10 widths determined from C,Si,Ni,Sn,Pb

→Determine parameters

→Be careful for determination of
accurate central values & systematic errors
which can be used for "averaging" results of C,Si,Ni,Sn,Pb

KHe 2p shift



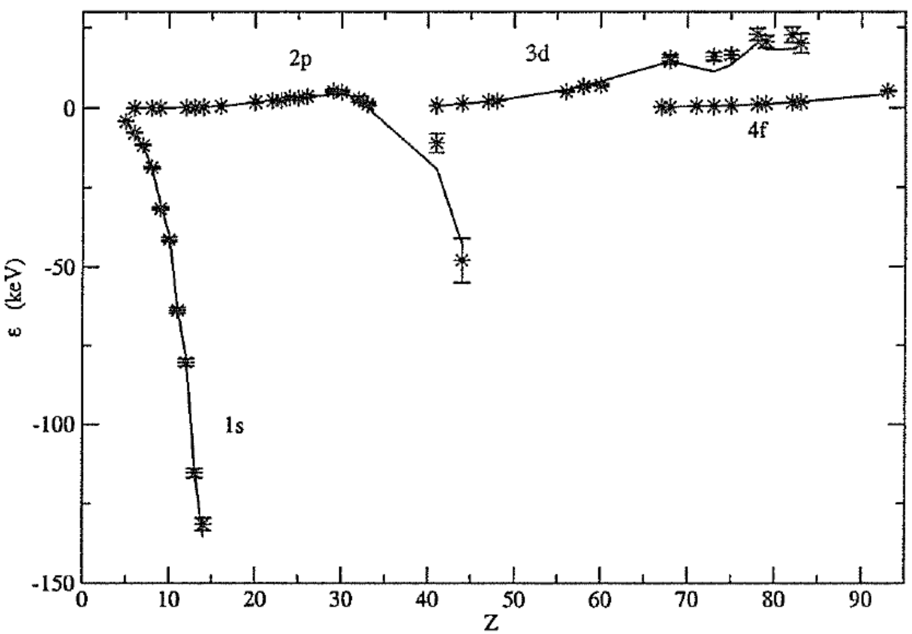


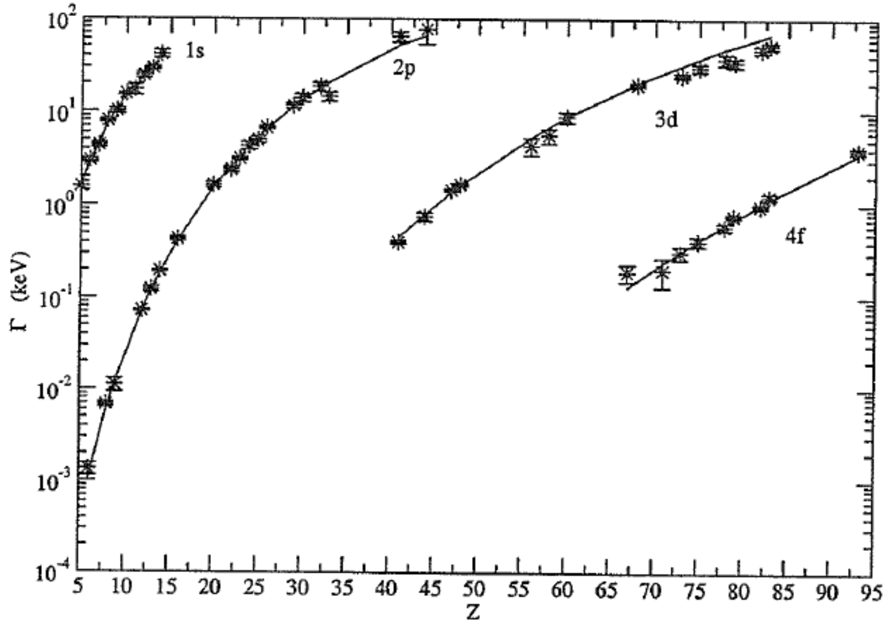
WEIGHTED AVERAGE
493.664±0.011 (Error scaled by 2.5)
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not neces-sarily the same as our 'best' values obtained from a leas utilizing measureme quantities as additio
DENISOV 9
GALL 88
GALL 88
GALL 88
GALL 88
LUM 81
BARKOV 7
CHENG 75
CHENG 75
CHENG 75
CHENG 75
CHENG 75
BACKENST
493.5
493.6
493.7
493.8
493.9
$m_{K^\pm}$ (MeV)
WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)
Values above of weighted a and scale factor are based this ideogram only. They a sarily the same as our 'best obtained from a least-squar utilizing measurements of o quantities as additional info
DENISOV 91
GALL 88
LUM 81
BARKOV 79
CHENG 75
BACKENSTO... 73
(Confidenc
493.55
493.6
493.65
493.7
493.75
493.8
493.85

Further steps

- Do we need more data set?
- Isotope differences such as 208Pb; 112Sn, 116Sn, 120Sn, 124Sn; 40Ca..48Ca (suggested by Wycheck); O istoptes (by Gal)
- According to Wycheck, the widths can be related to the subthreshold region of Λ(1405)
- Yb E2 mixing problem

- Anyway, the Kaonic atom data are still poor than the pionic atom data.





simulating absorptive effects. This "standard" optical potential takes the form

$$2\mu V(r) = -4\pi \left[q(r) - \nabla \cdot \frac{\alpha(r)}{1 + (4\pi/3)\xi\, \alpha(r)} \nabla \right], \qquad (16.62)$$

where μ is π-nucleus reduced mass and

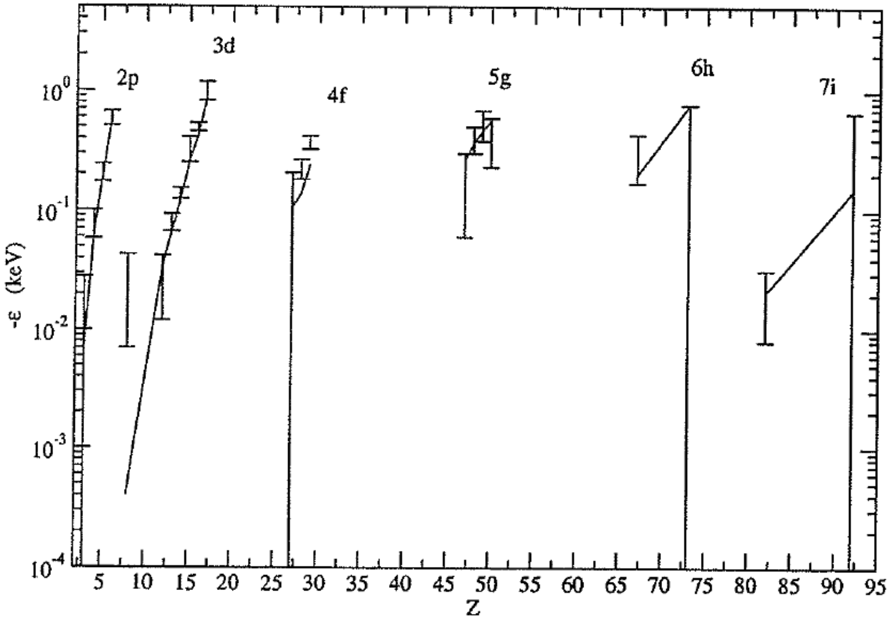
$$q(r) = (1 + \frac{m}{M})\,[b_0\, \rho(r) + b_1\, \delta\rho(r)] + (1 + \frac{m}{2M}) B_0\, \rho(r)^2; \qquad (16.63)$$

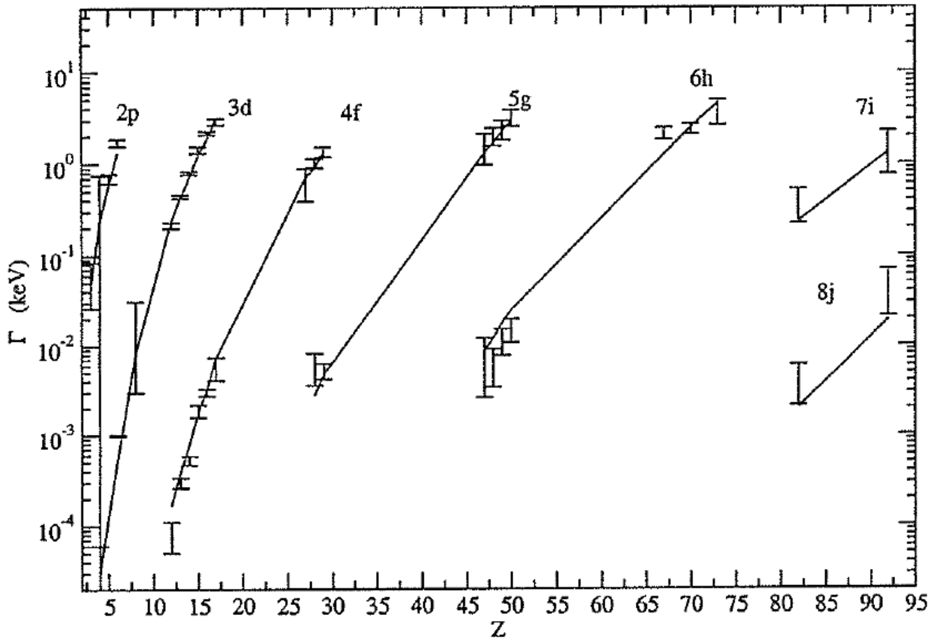
Pionic atom

$$\alpha(r) = (1 + \frac{m}{M})^{-1}\,[c_0\, \rho(r) + c_1\, \delta\rho(r)] + (1 + \frac{m}{2M})^{-1} C_0\, \rho(r)^2; \qquad (16.64)$$

where m and M denote the masses of the pion and the nucleon, respectively. We have introduced the densities

$$\rho(r) = \rho_n(r) + \rho_p(r); \qquad \delta\rho(r) = \rho_n(r) - \rho_p(r); \qquad (16.65)$$





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

Kaonic atom

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

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

Let’s think about new experiments on heavy kanic atoms