Precision spectroscopy through Dielectronic Recombination - the role of calculations

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Examples from recombination of Li-like, Na-like and Be-like ions

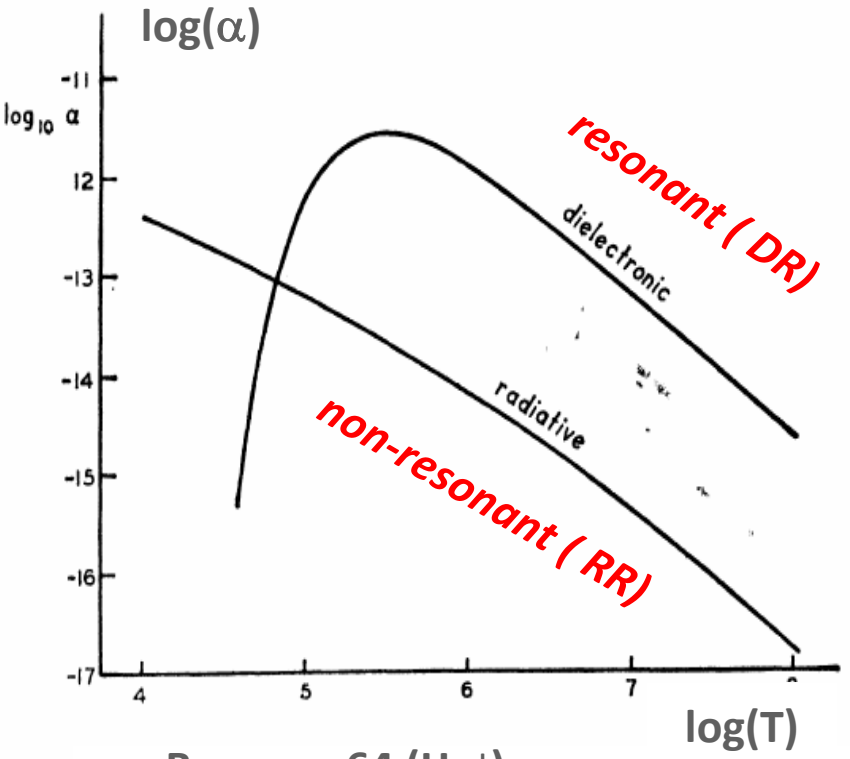
Andreas Wolf et al., MPI Heidelberg

Alfred Müller, Stefan Schippers et al, Univ. Giessen

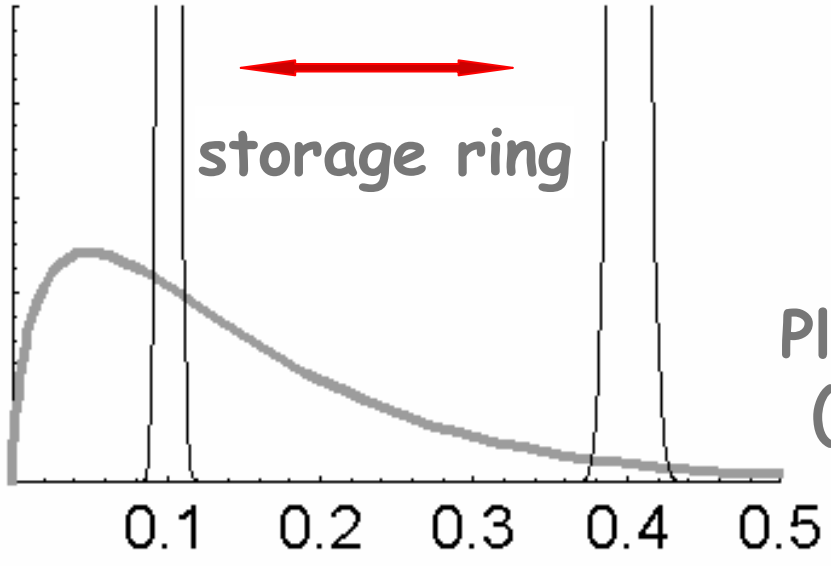
Reinhold Schuch, Istvan Orban et al, Univ. Stockholm

Electron-Ion Collisions

Spectroscopy?



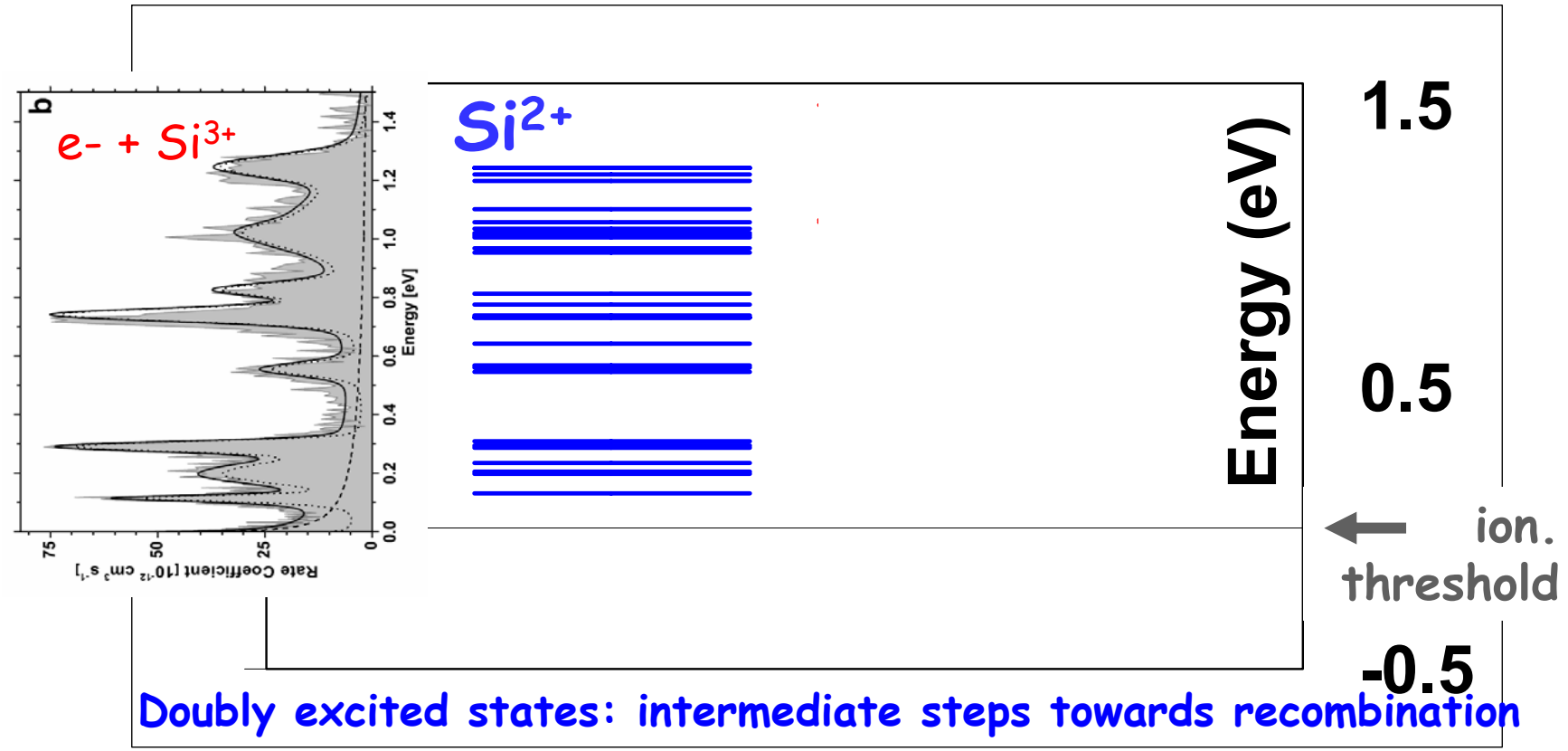
Burgess -64 (He^+)



Plasma; Maxwellian Distribution
(example with Tk_B =0.1 eV)

T=1000K $\rightarrow Tk_B$=0.1 eV

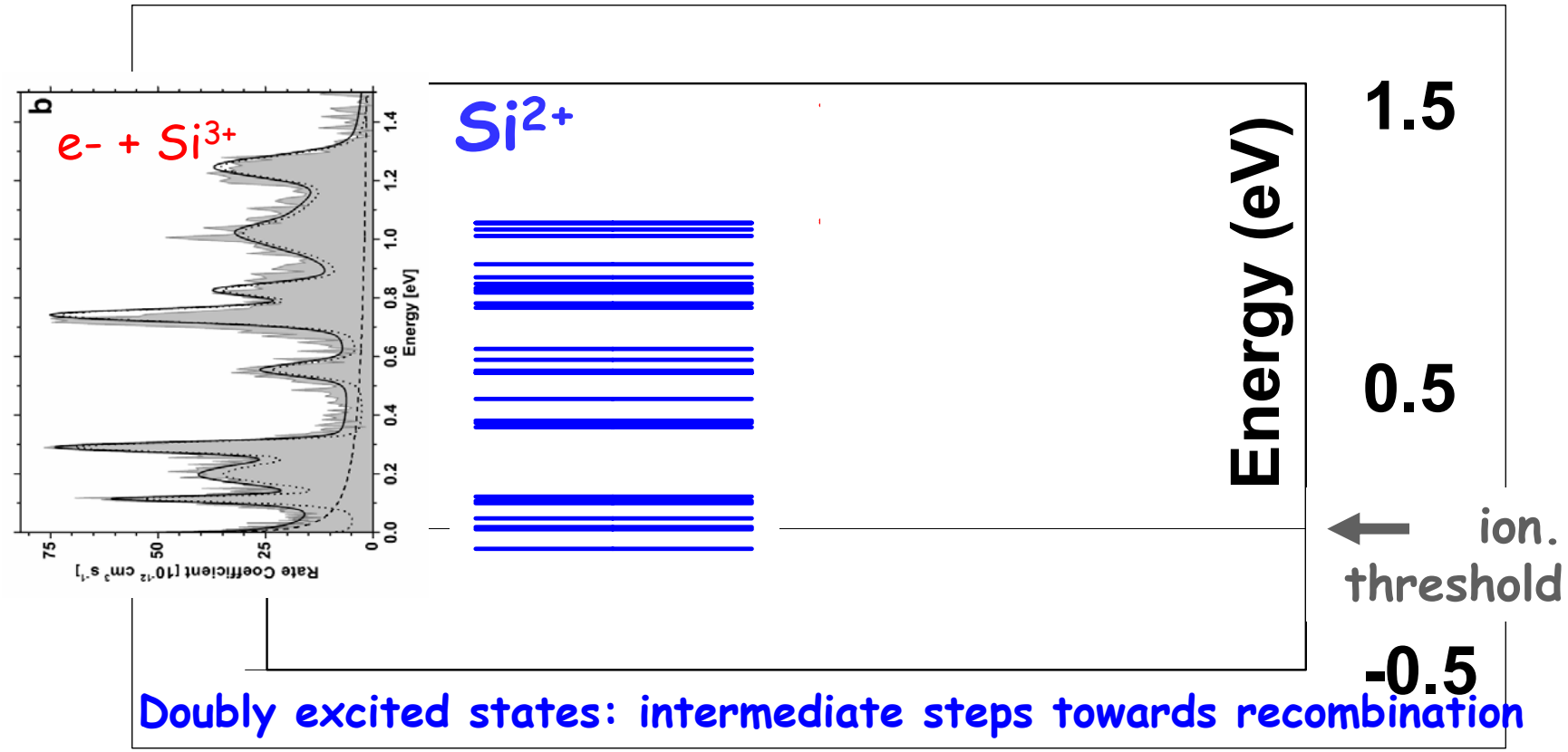
The resonance structure behind



Generally poor knowledge of doubly excited states....

Orban *et al J. Phys. B: At. Mol. Opt. Phys.* **40** 1063

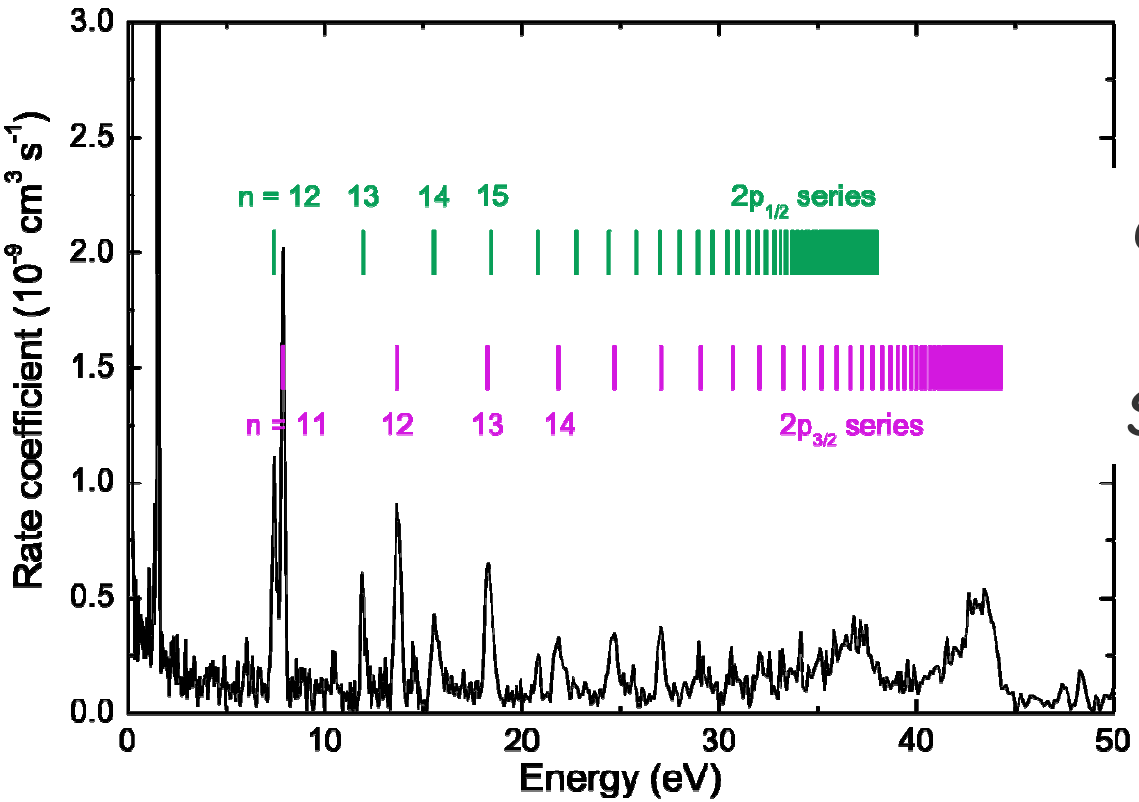
The resonance structure behind



Details in the calculation shifts resonances below or above threshold – Low energy region sensitive

relativistic effects, QED, HFS..

$^{45}Sc^{18+}$

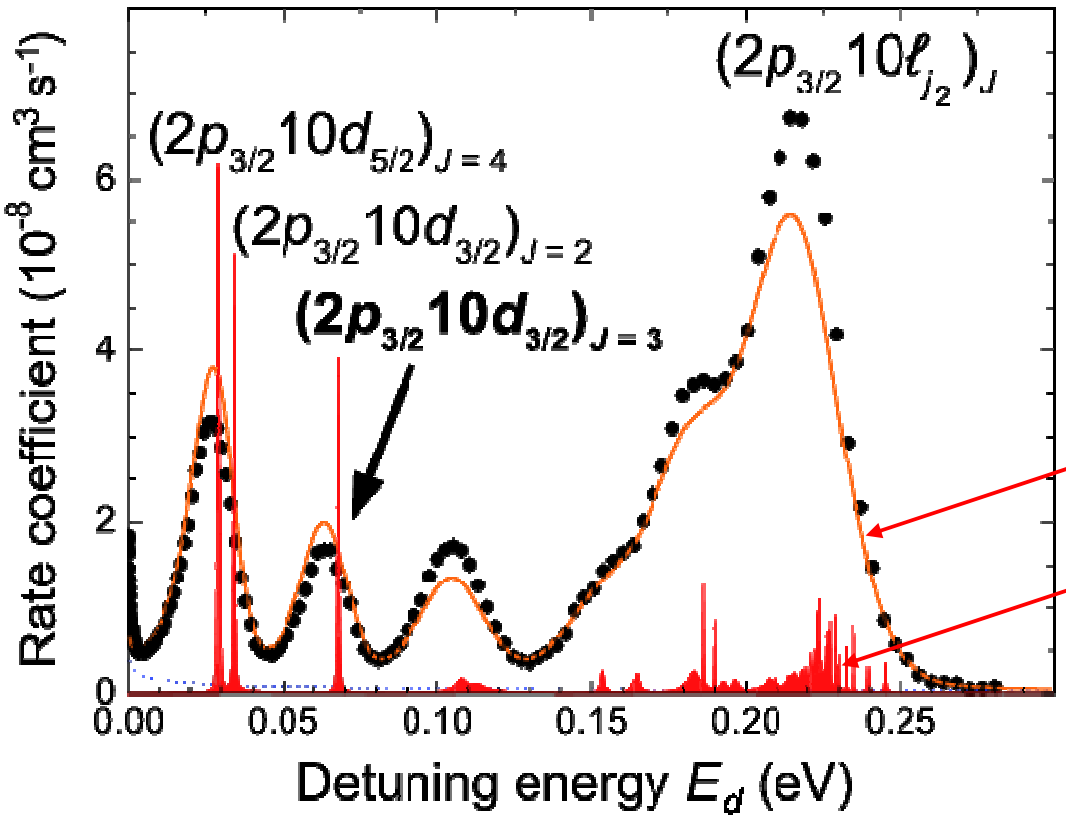


$$e^- + Sc^{18+}(1s^2 2s) \rightarrow Sc^{17+}(1s^2 2pn\ell) \rightarrow Sc^{17+}(1s^2 2sn'\ell) + h\upsilon$$

2nd type of Spectroscopical Information

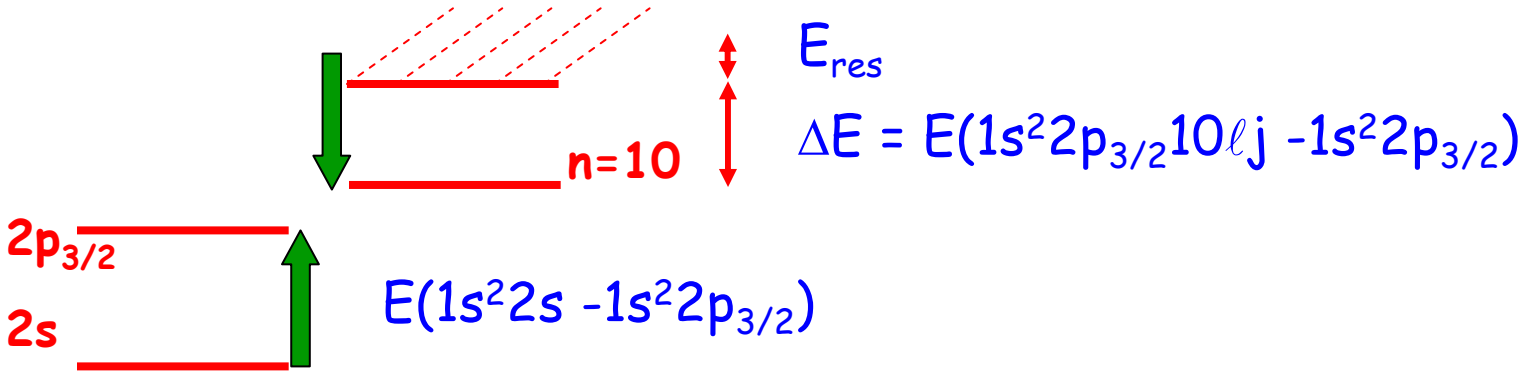
Lestinsky et al. Phys. Rev. A **70**, 042714 , Phys. Rev. Lett. **100**, 033001

$^{45}Sc^{18+}$



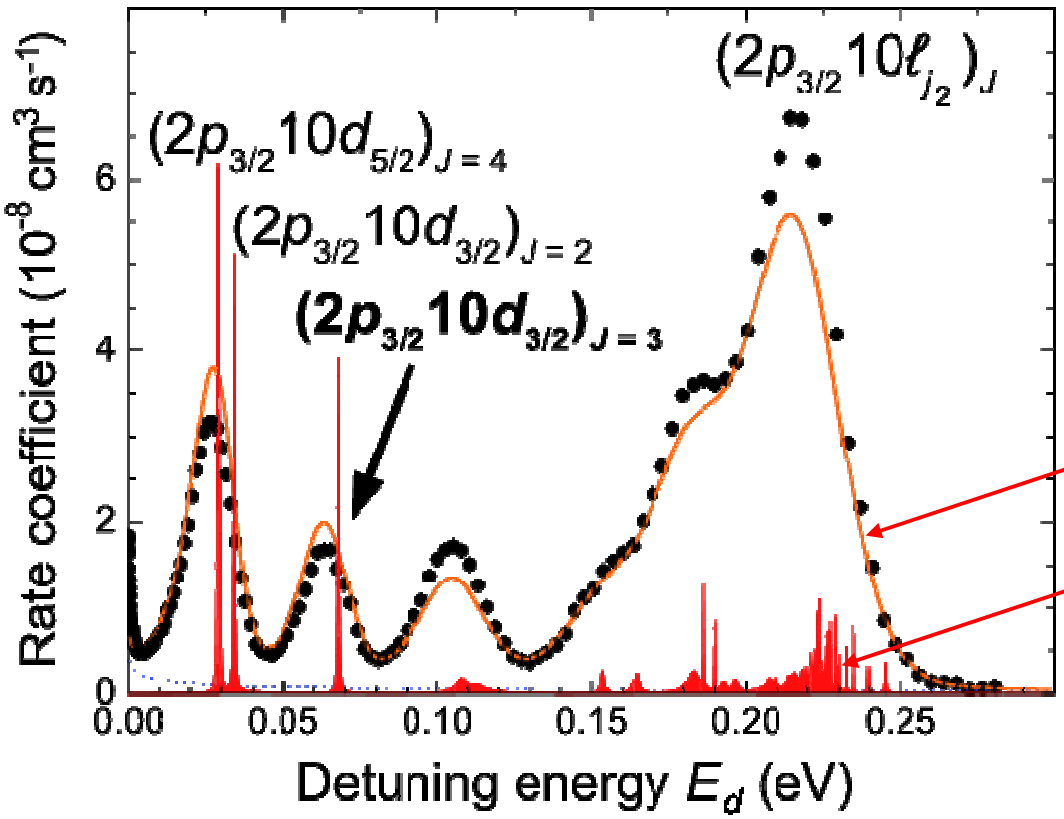
Theory folded

cross section from ~ 65 resonances



Lestinsky et al. Phys. Rev. A **70**, 042714 , Phys. Rev. Lett. **100**, 033001

$^{45}Sc^{18+}$



Theory folded

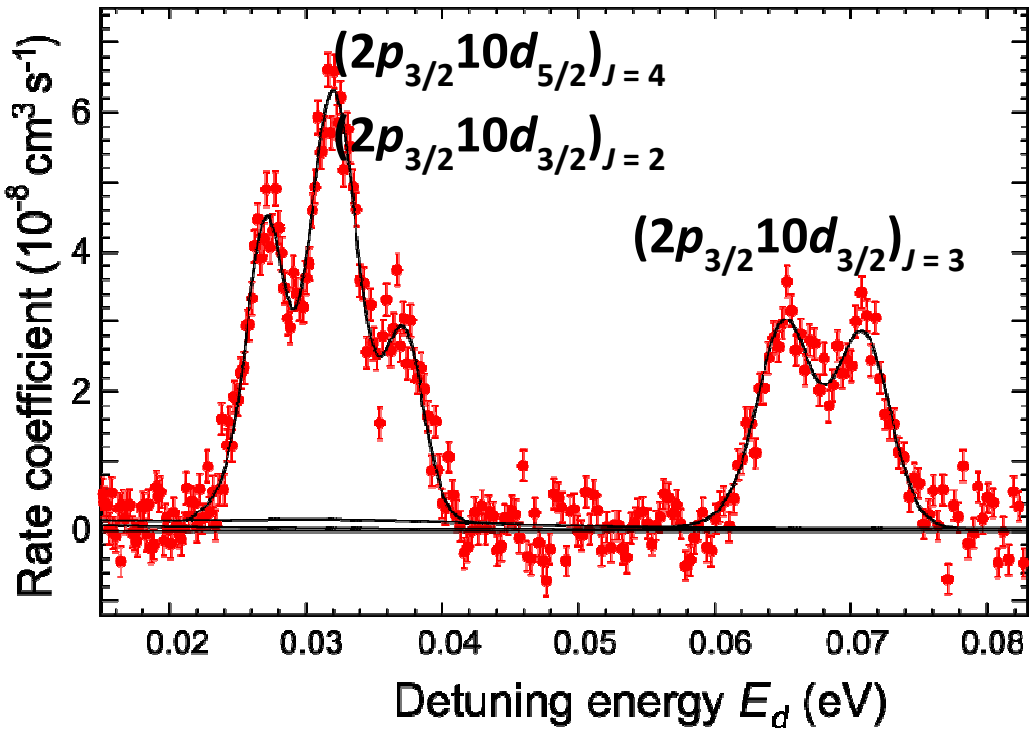
cross section from ~ 65 resonances

radiative corrections

$E(1s^2 2s - 1s^2 2p_{3/2})$

Kieslich et al. Phys. Rev. A **70**, 042714 , Lestinsky et al. Phys. Rev. Lett. **100**, 033001

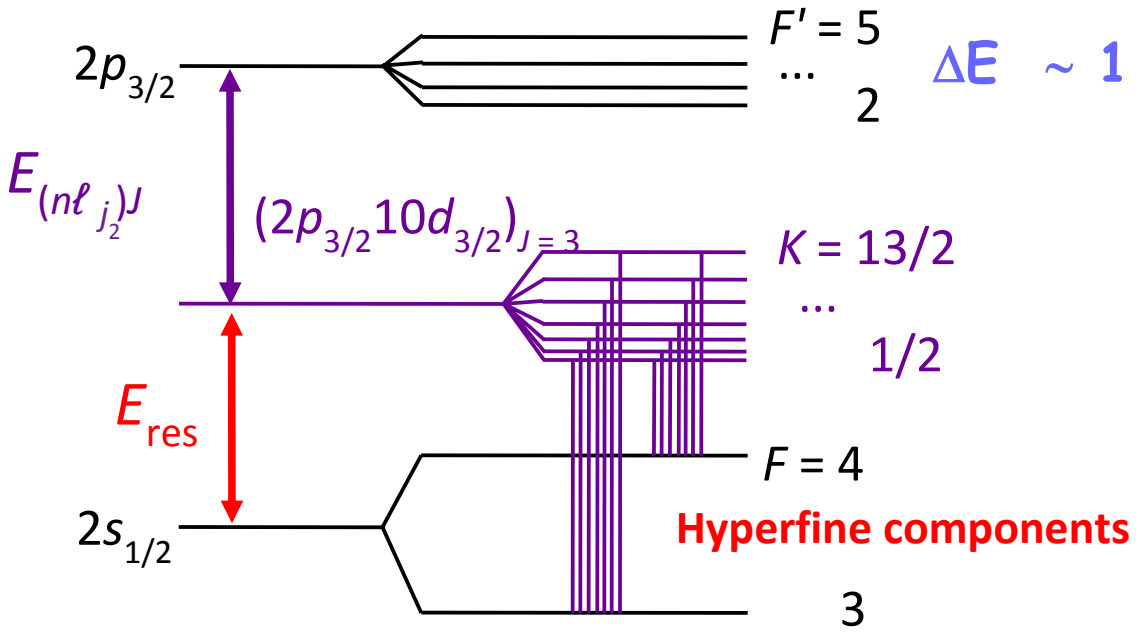
$^{45}Sc^{18+}$



$T_\perp$ = 1.0 meV

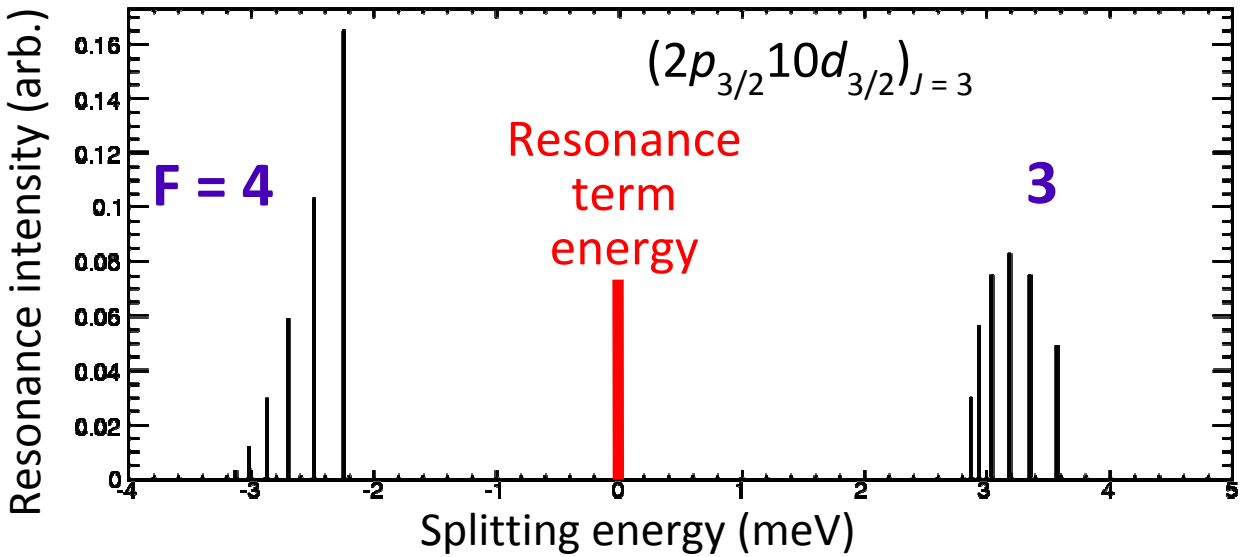
$T_\parallel$ ~ 0.02 meV

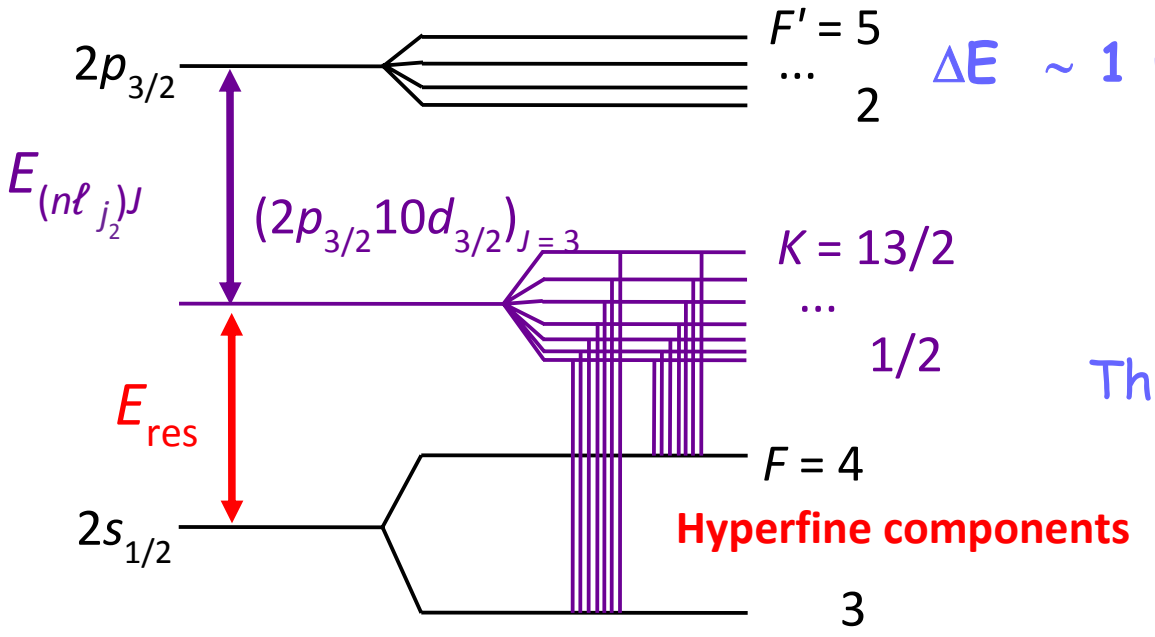
Lestinsky et al. Phys. Rev. A **70**, 042714 , Phys. Rev. Lett. **100**, 033001



^{45}Sc, I=7/2

$$| \{I\,(j_{low} j_{high})\,J\}\,K_{tot}\rangle = \sum_F c_F \,|\, \{(I j_{low})\,F\, j_{high}\}\,K_{tot}\rangle$$

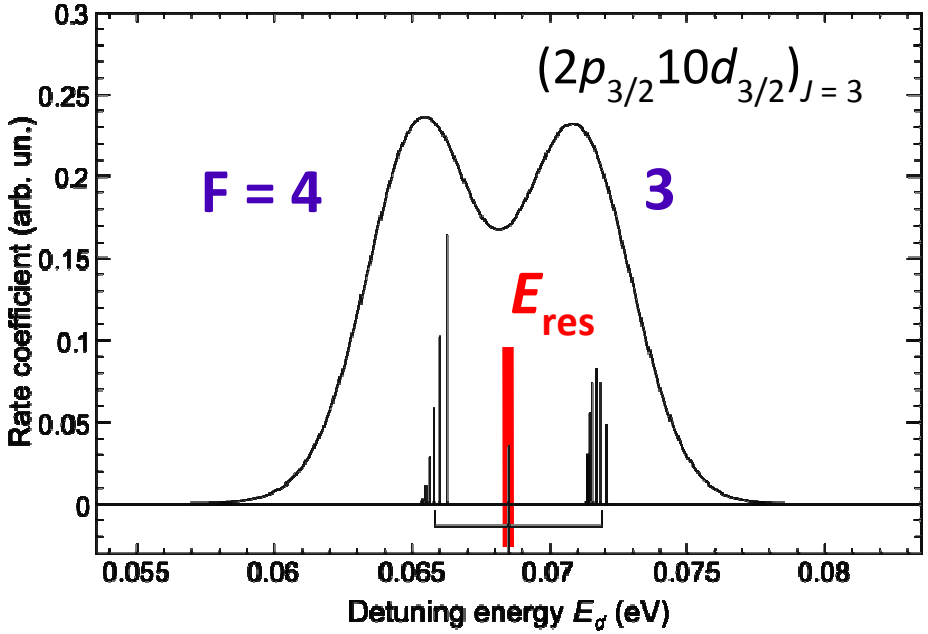




^{45}Sc, I=7/2

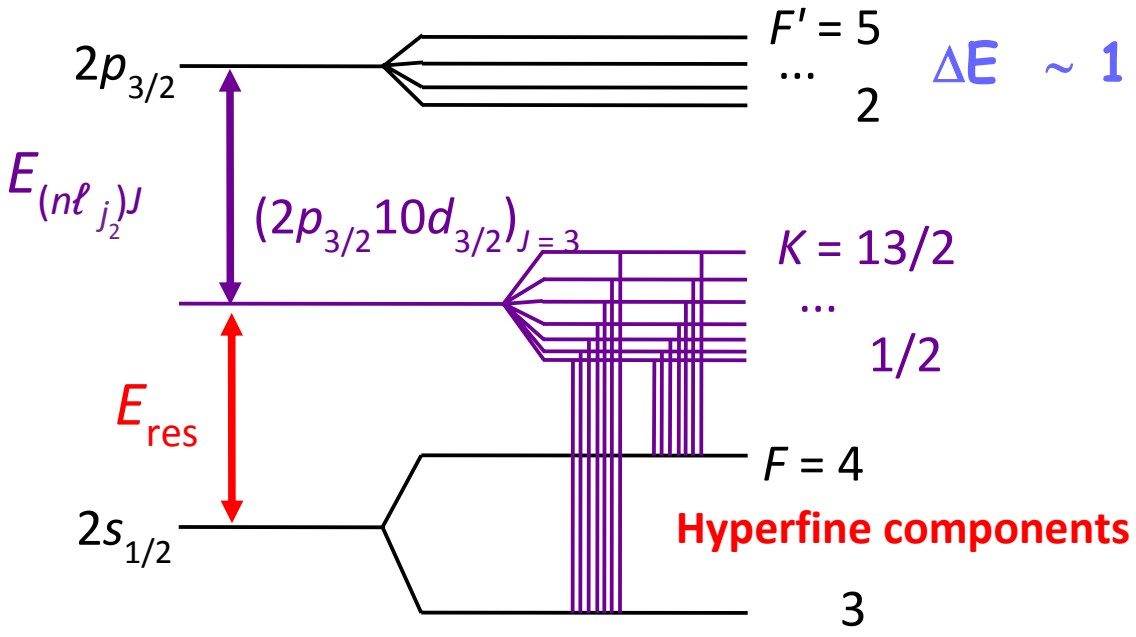
Theoretical hyperfine splitting
(Kozhedub et al 2007)

$\Delta E = 6.0633$ meV

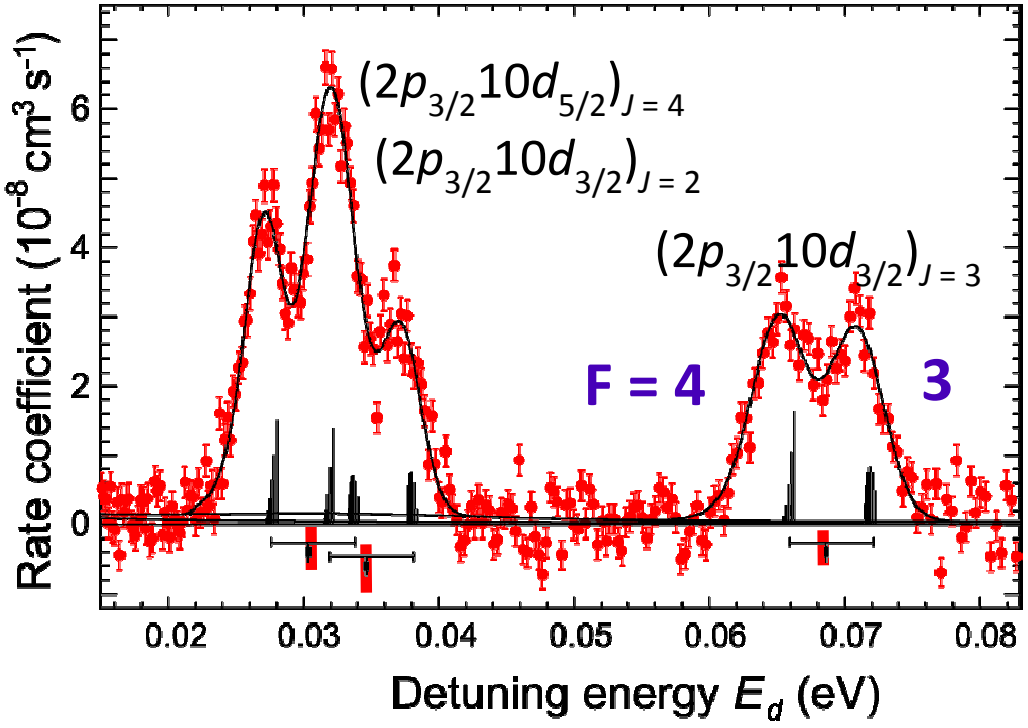


extracted 2s hfs

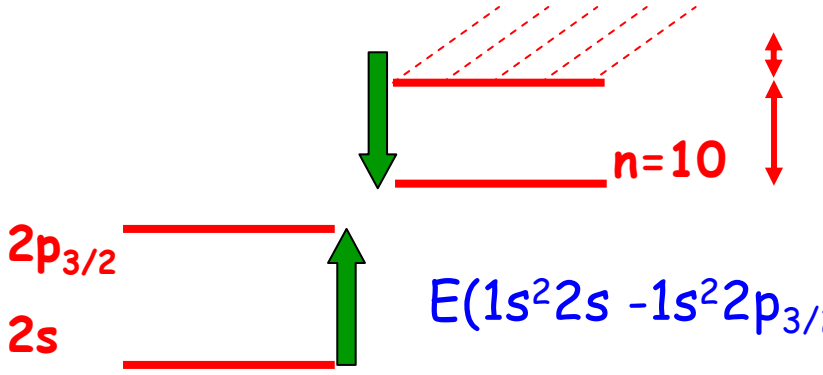
$\Delta E = 6.20(8)$ meV


$2p_{3/2}$
$F' = 5$
...
2
$\Delta E \sim 1$ meV
$E_{(n\ell\, j_2)J}$
$(2p_{3/2}10d_{3/2})_{J=3}$
$K = 13/2$
...
1/2
E_{res}
$F = 4$
Hyperfine components
$2s_{1/2}$
3

^{45}Sc, I=7/2


Rate coefficient (10^{-8} cm^3 s^{-1})
0
2
4
6
$(2p_{3/2}10d_{5/2})_{J=4}$
$(2p_{3/2}10d_{3/2})_{J=2}$
$(2p_{3/2}10d_{3/2})_{J=3}$
F = 4
3
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Detuning energy E_d (eV)

	$J = 4$	$J = 2$	$J = 3$
Exp	0.03036(10)	0.03465(10)	0.06861(10)
RMBPT +	44.27916(11)	44.27480(11)	44.24071(9)
$2p_{3/2}$-$2s$ =	44.30952(15)	44.30945(15)	44.30932(15)



E_{res}

Exp

$\Delta E = E(1s^2 2p_{3/2} 10\ell j - 1s^2 2p_{3/2})$

calculated RMBPT

$E(1s^2 2s - 1s^2 2p_{3/2})$ extracted

$2p_{3/2}$-$2s_{1/2}$ = 44.30943 (20) eV

Theory: 44.3091(21) Kozhedub et al 2007

of which screened QED 0.0331 (20) eV

The many-body Problem...

- Perturbation Theory, $H=H_0+V$
  Coupled Cluster

Systematic!

ions!

Requires a decent starting point

Li-like, Na-like etc. into Be-like, Mg-like

H_0 ?

$2p_{3/2}\ 10d_{3/2}$

$2p_{3/2}\ 10d_{5/2}$

$2p_{1/2}\ 10d_{3/2}$ ...

Many nearby configurations

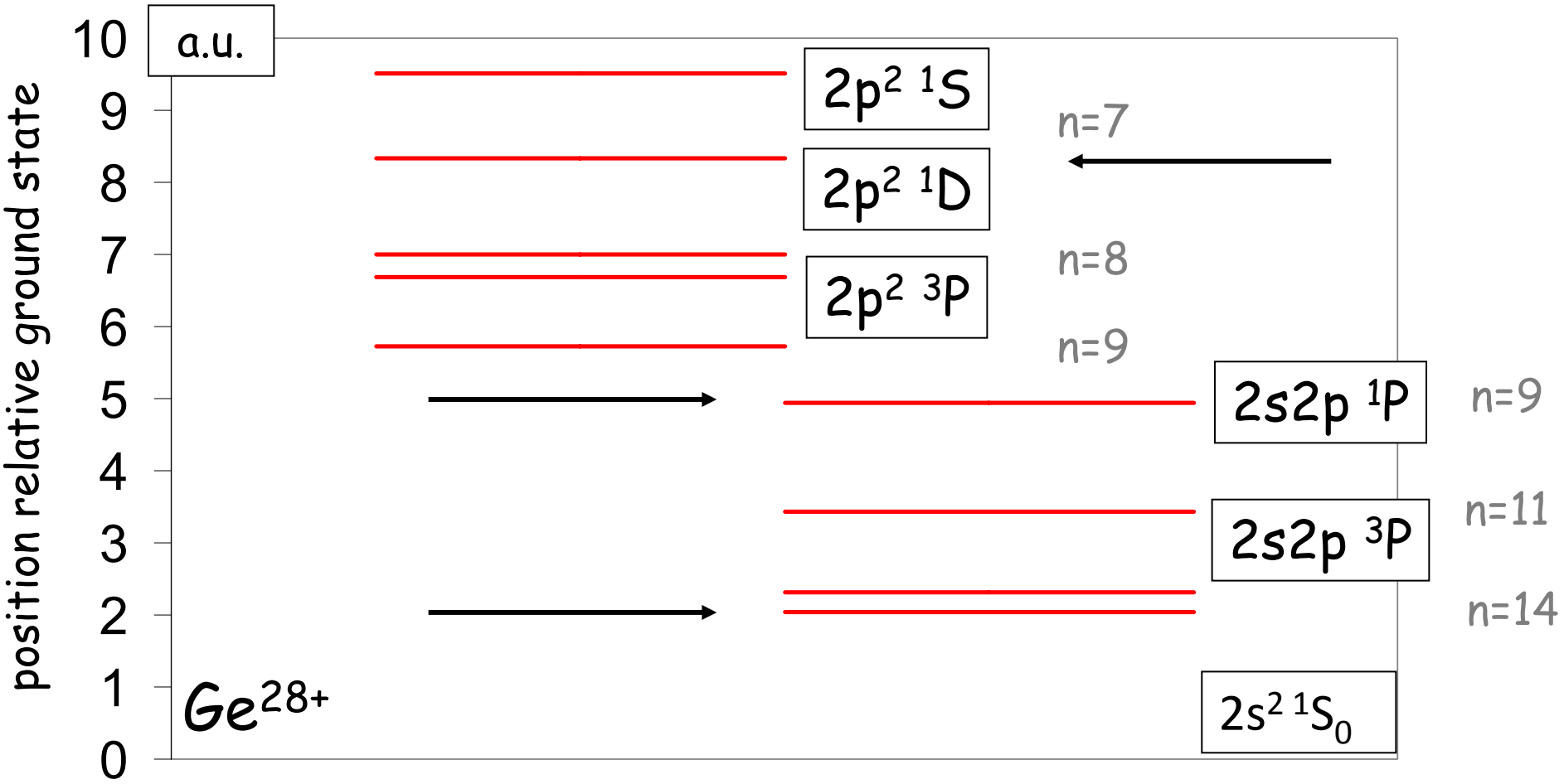
"Extended model space"

≈ small CI + MBPT

Be-like, Mg-like etc. into B-like, Al-like

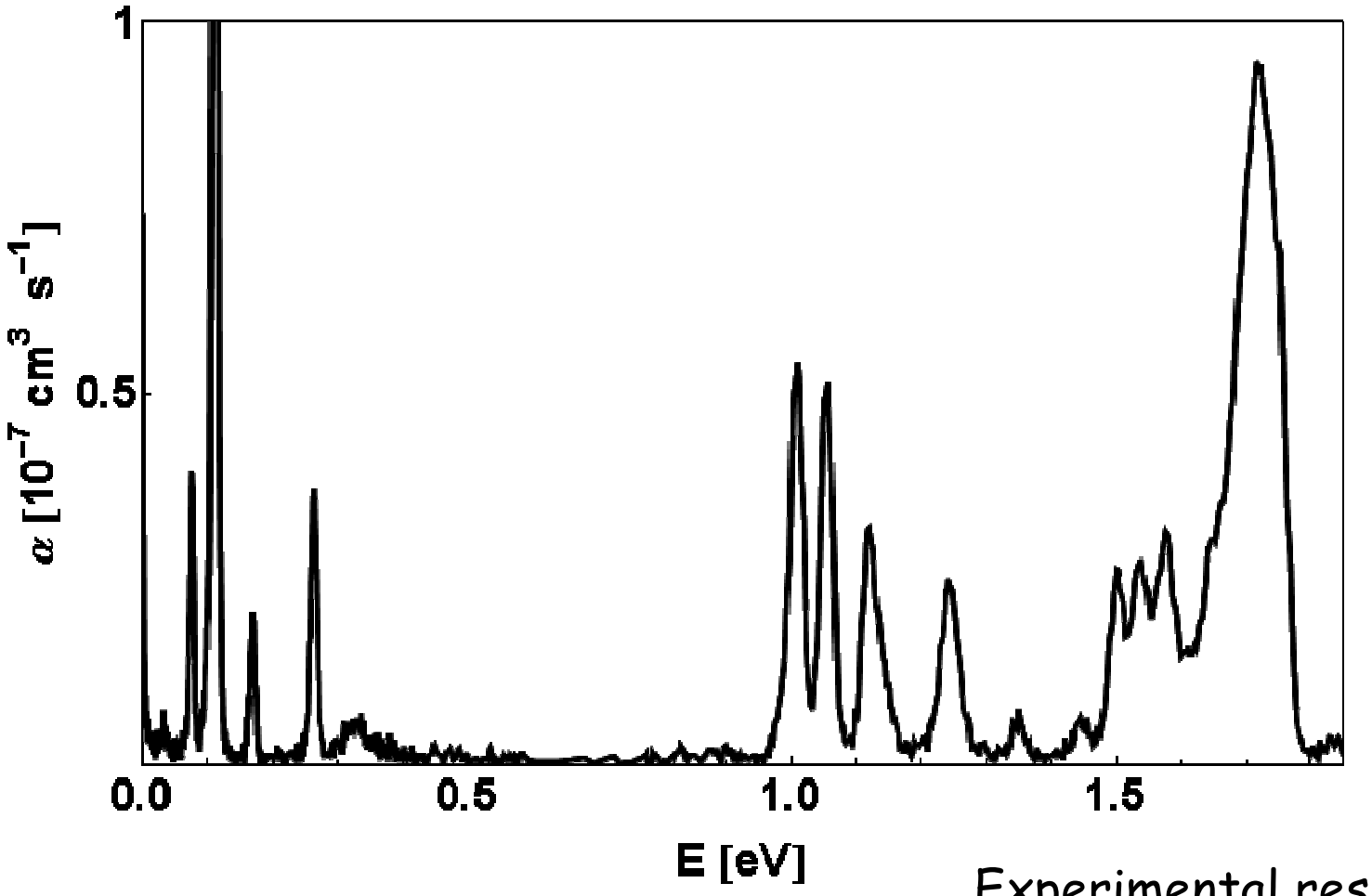
Recombination of Be-like systems?

RMPBT for 3 open shells – under construction



several different series possible...

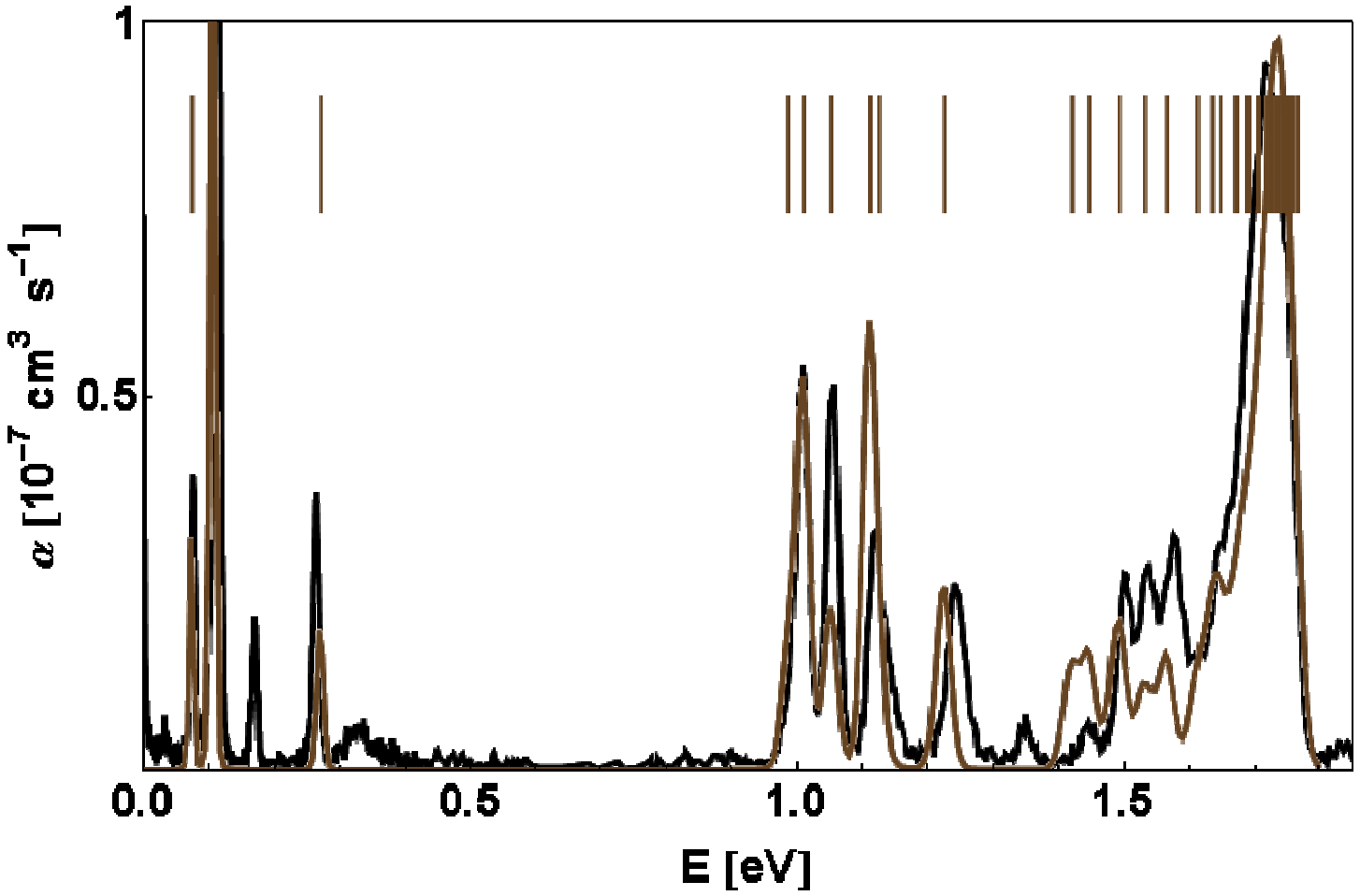
$e^- + Ge^{28+}(1s^2 2s^2) \rightarrow Ge^{27+}(1s^2\ 2\ell 2\ell'\ n\ell'')$



Experimental results

Exp: A. Wolf et al. (TSR)

$e^- + Ge^{28+}(1s^2 2s^2) \rightarrow Ge^{27+} 1s^2 \quad (2s2p)^1P_1\ 9\ell$

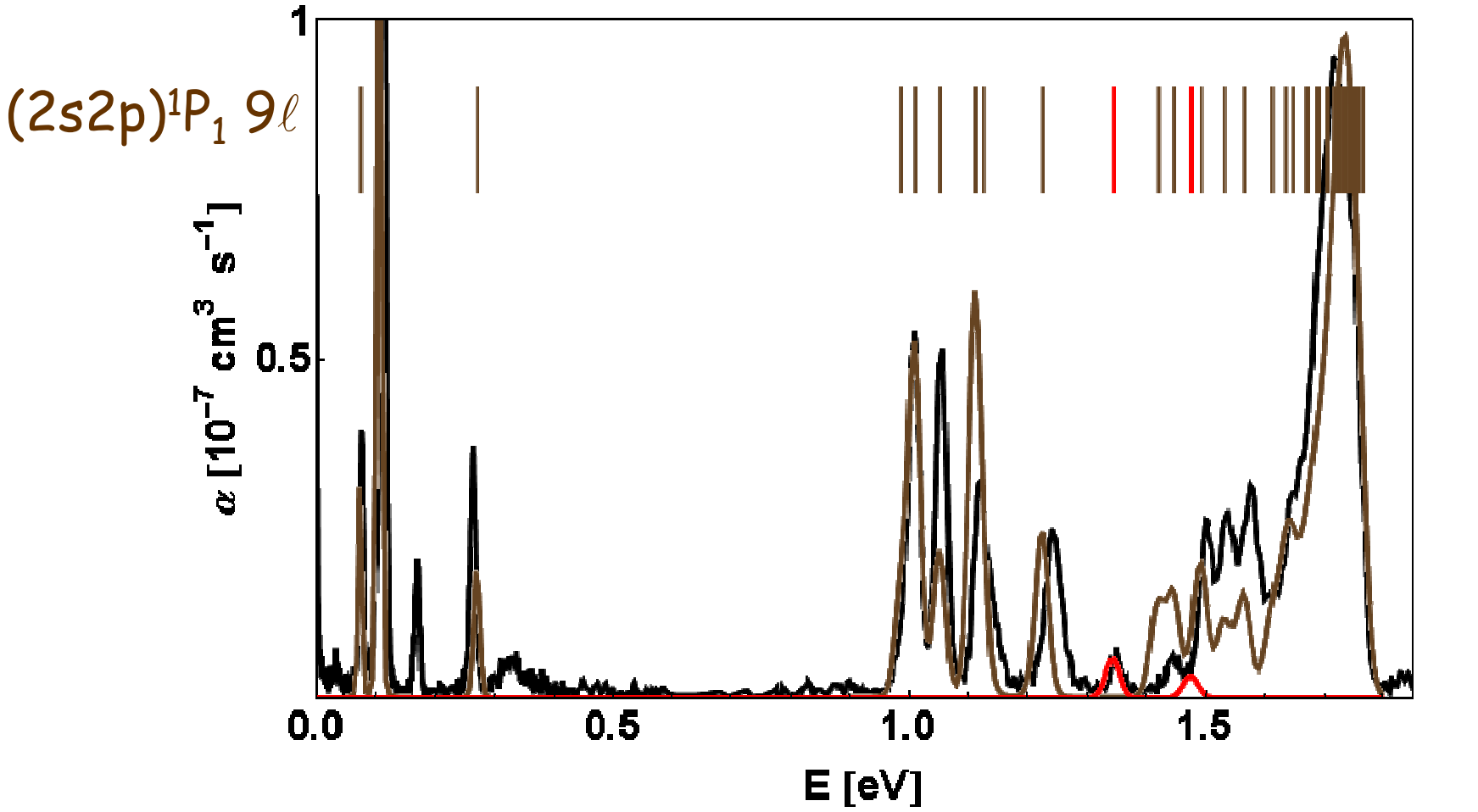


uniform shifting ~ expected size of uncalculated QED shifts - allowed

Exp: A. Wolf et al. (TSR)

$e^- + Ge^{28+}(1s^2 2s^2) \rightarrow Ge^{27+} 1s^2 \quad (2p^2)^1D_2\ 7\ell$

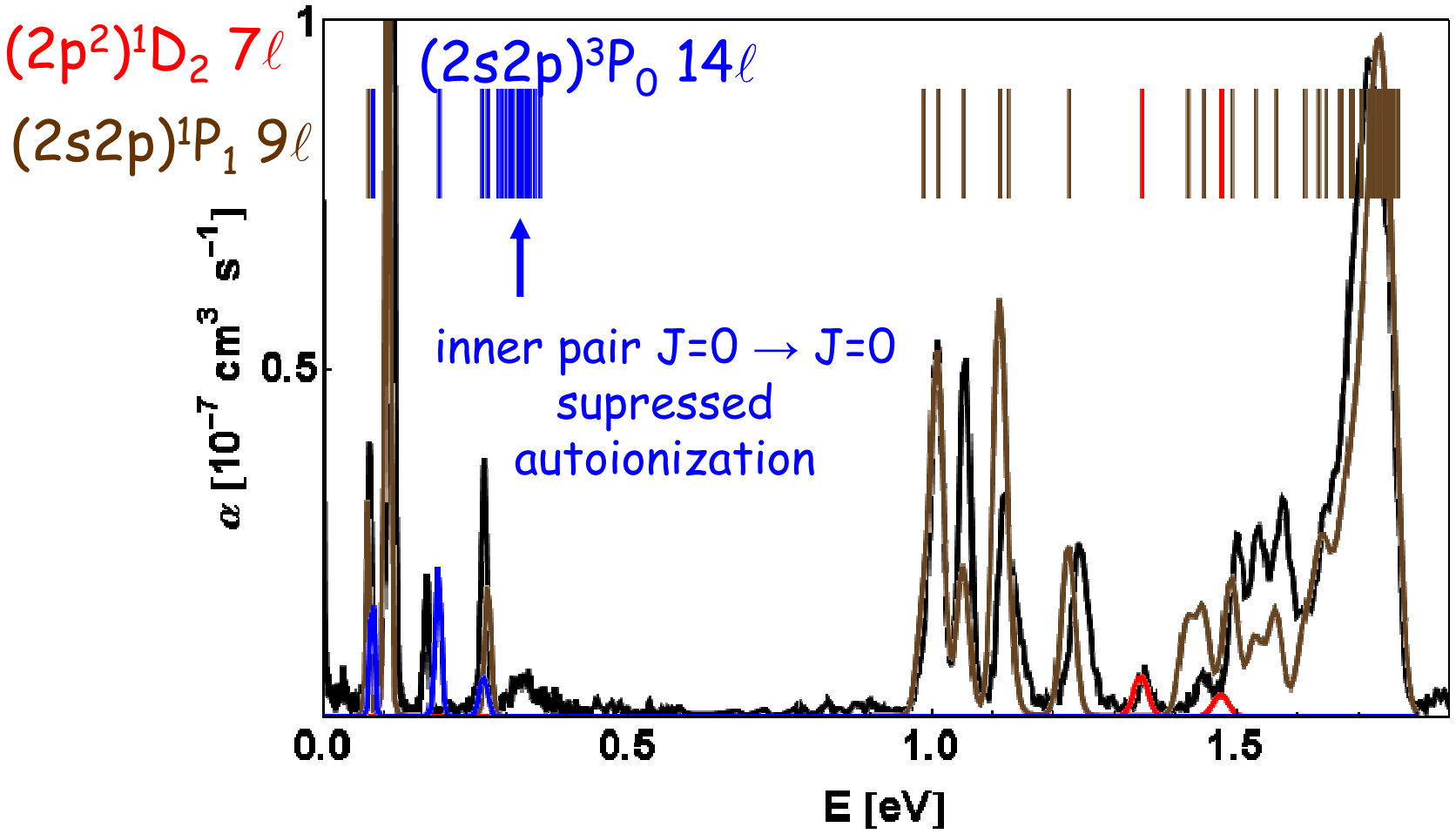
"Tri-electronic" recombination



Exp: A. Wolf et al. (TSR)

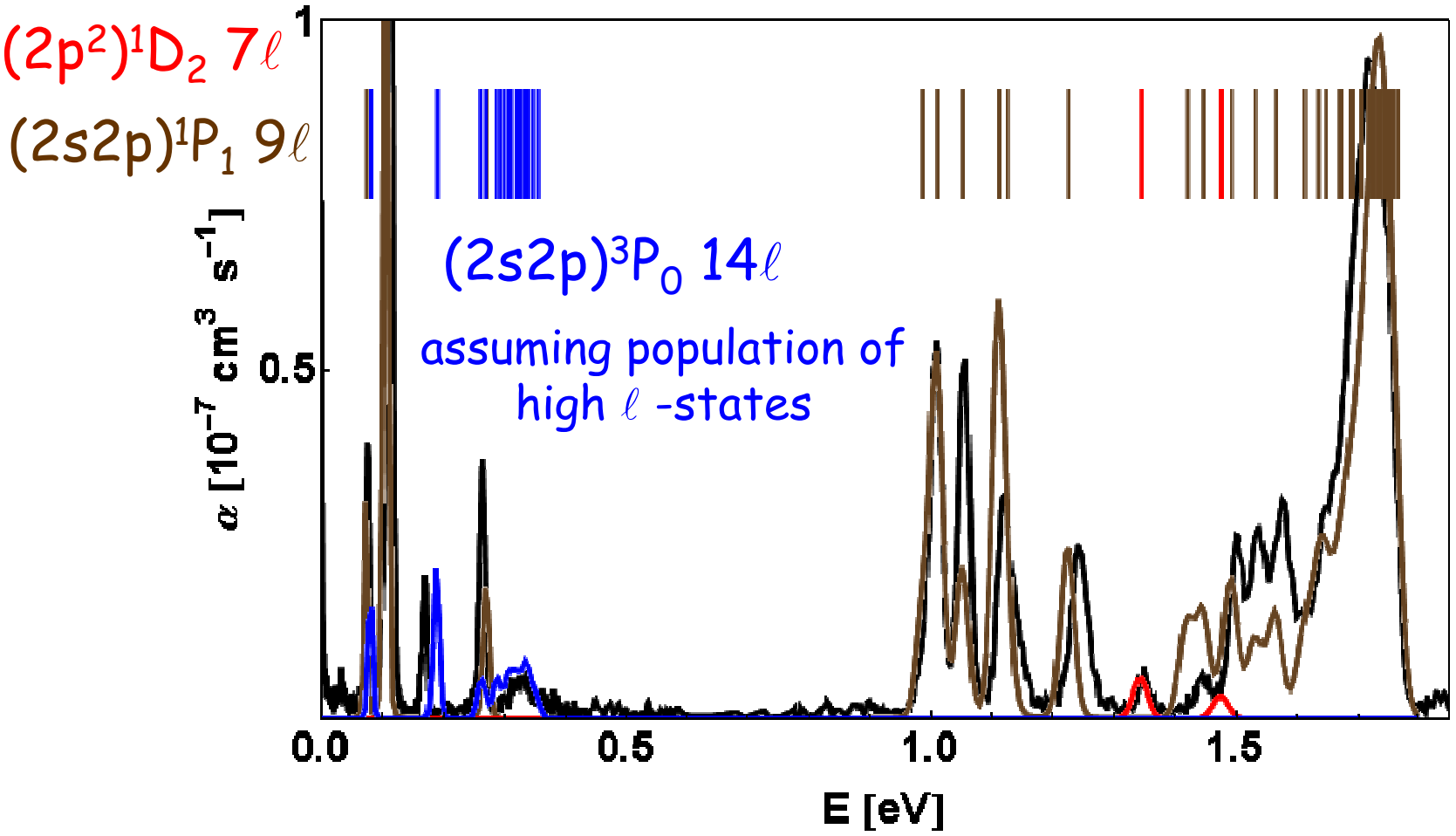
$e^- + Ge^{28+}(1s^2 2s^2) \rightarrow Ge^{27+} 1s^2 (2s2p)^3P_0\ 14\ell$

$(1s^2 2s^2)\ ^1S_0\ \varepsilon\ \ell \pm 1$



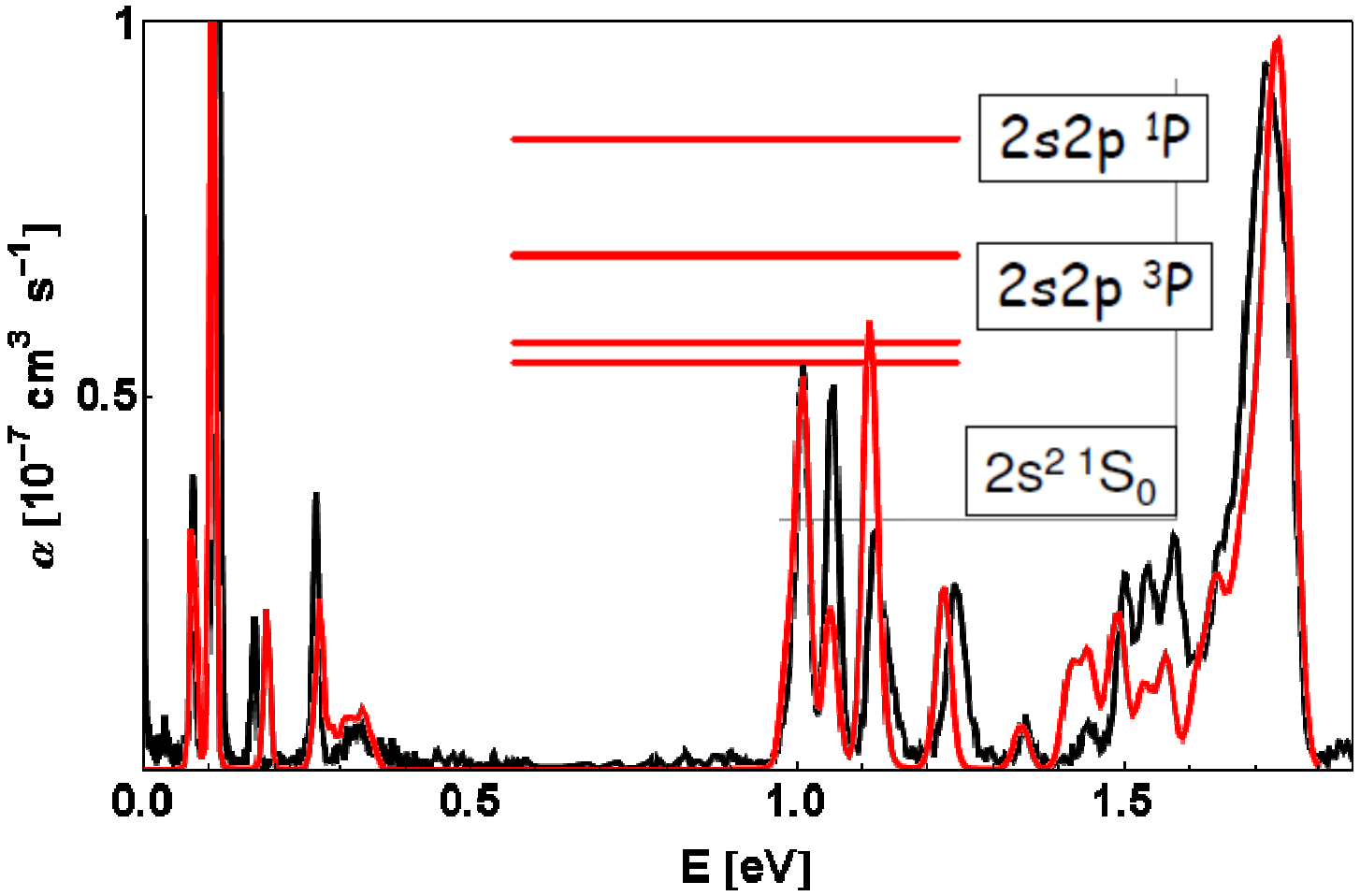
Exp: A. Wolf et al. (TSR)

$e^- + Ge^{28+}(1s^2 2s^2) \rightarrow Ge^{27+} 1s^2 (2s2p)^3P_0\ 14\ell$

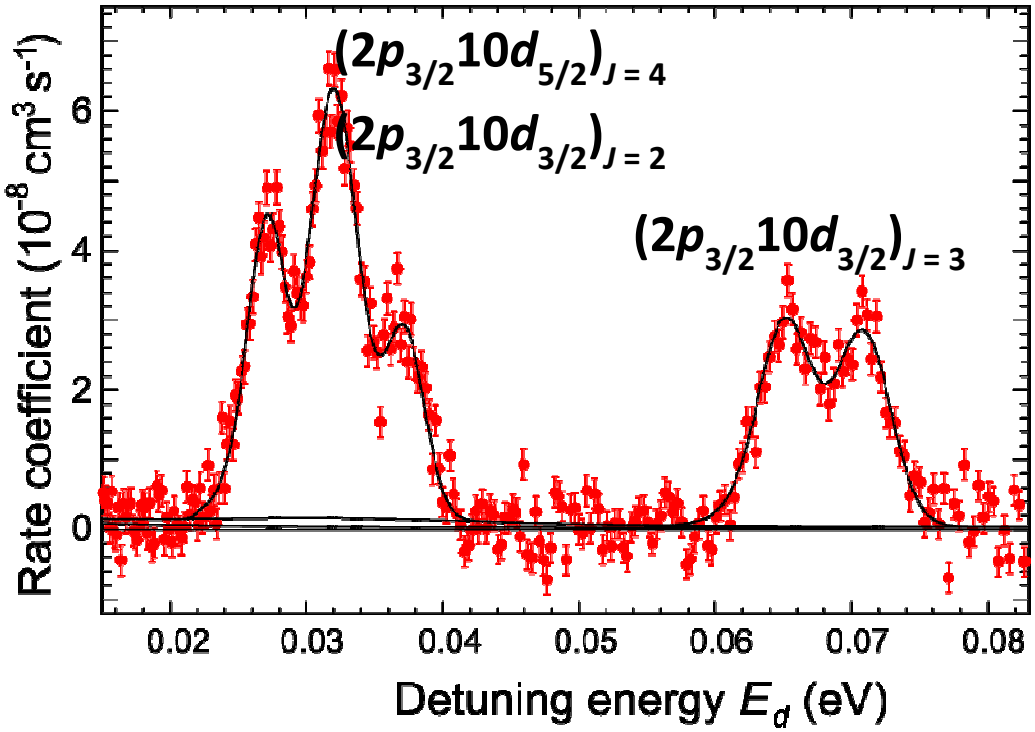


Exp: A. Wolf et al. (TSR)

First step towards more complicated systems (3 open shells) ....

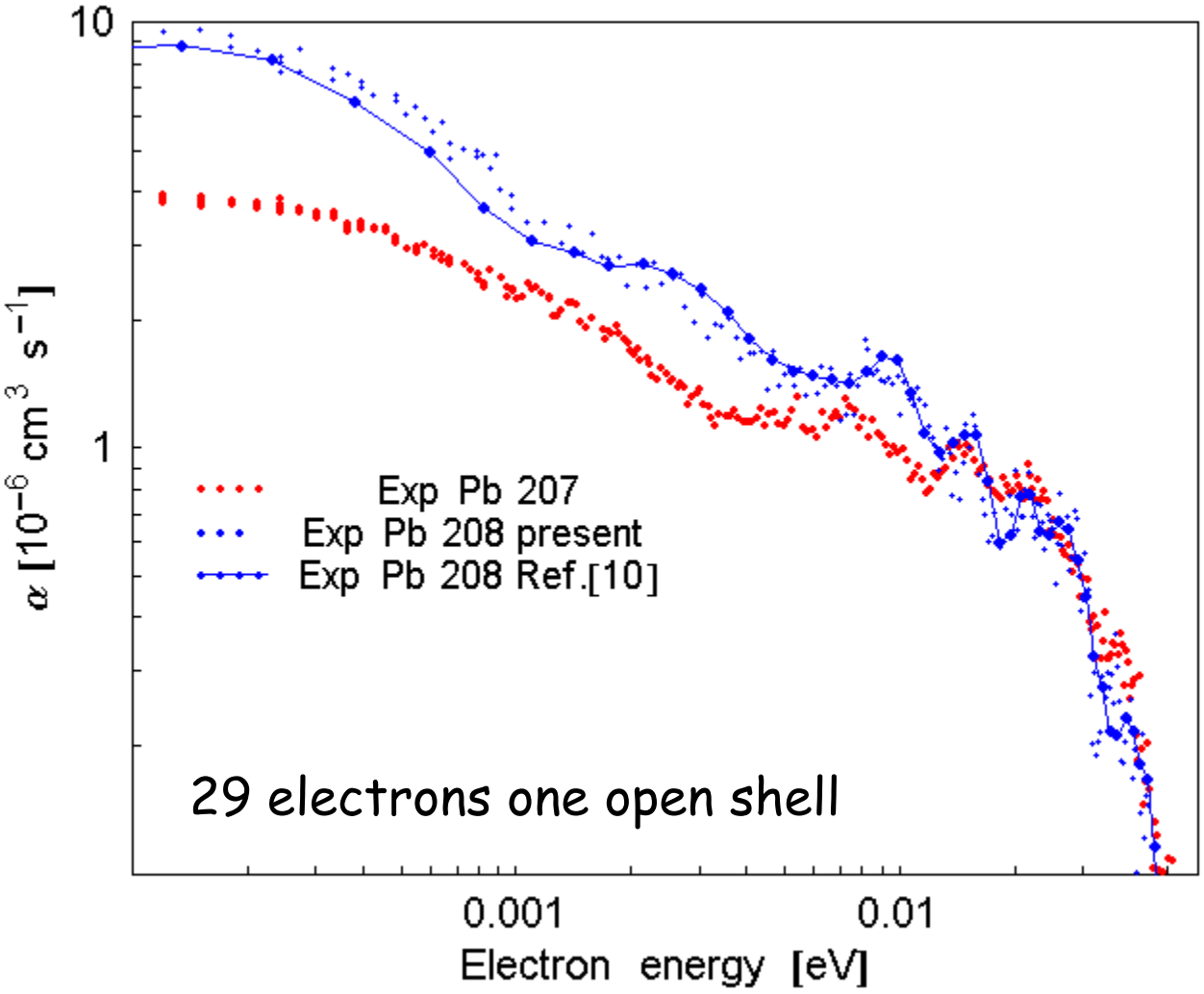


Exp: A. Wolf et al. (TSR)

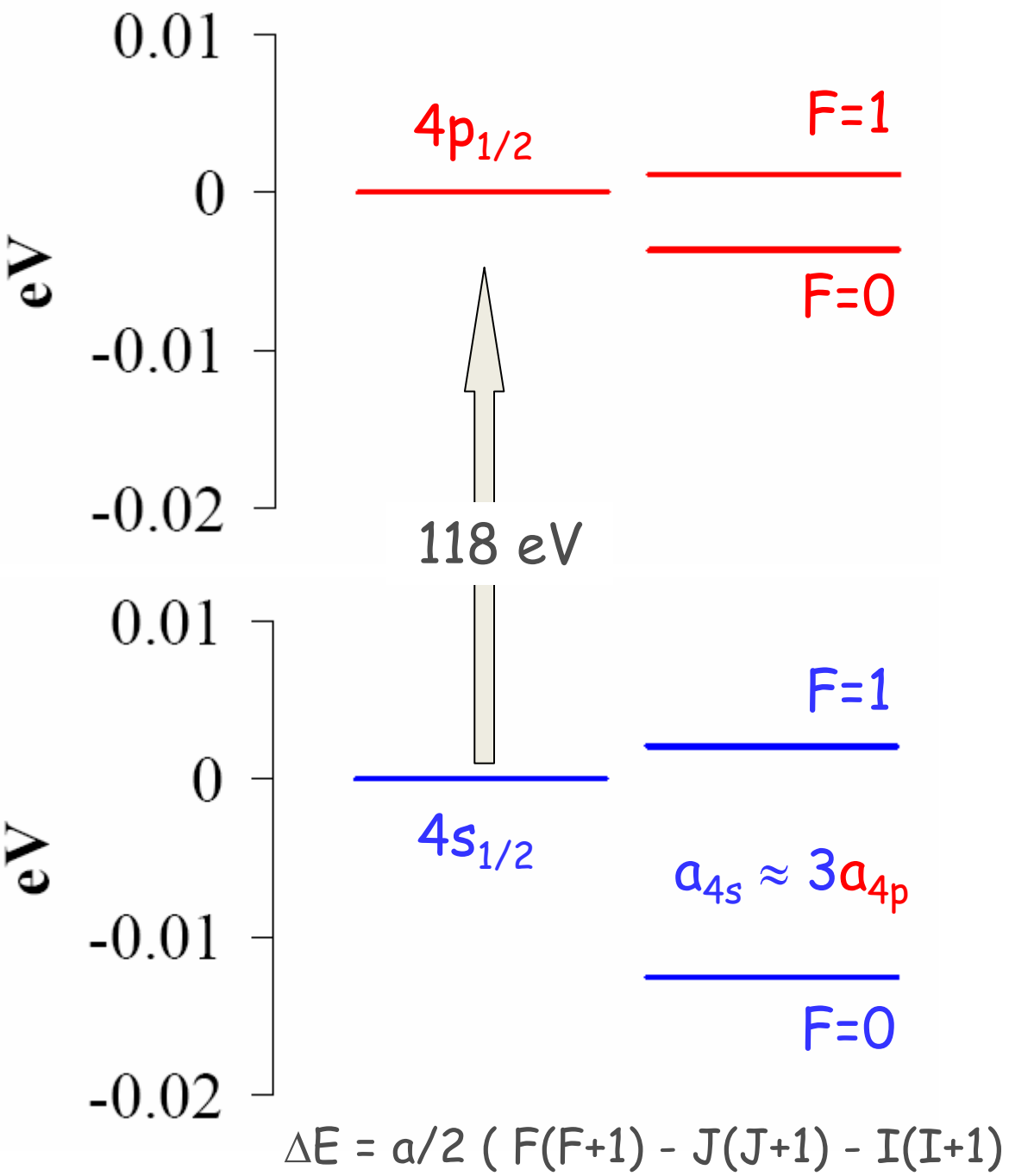


Nuclear Effects!

$^{208}Pb^{53+}$ versus $^{207}Pb^{53+}$



Schuch et al. Phys. Rev. Lett. **95**, 183003



$\Delta E = a/2 \, (F(F+1) - J(J+1) - I(I+1))$

$\Delta E = a/2 \, (F(F+1) - J(J+1) - I(I+1))$

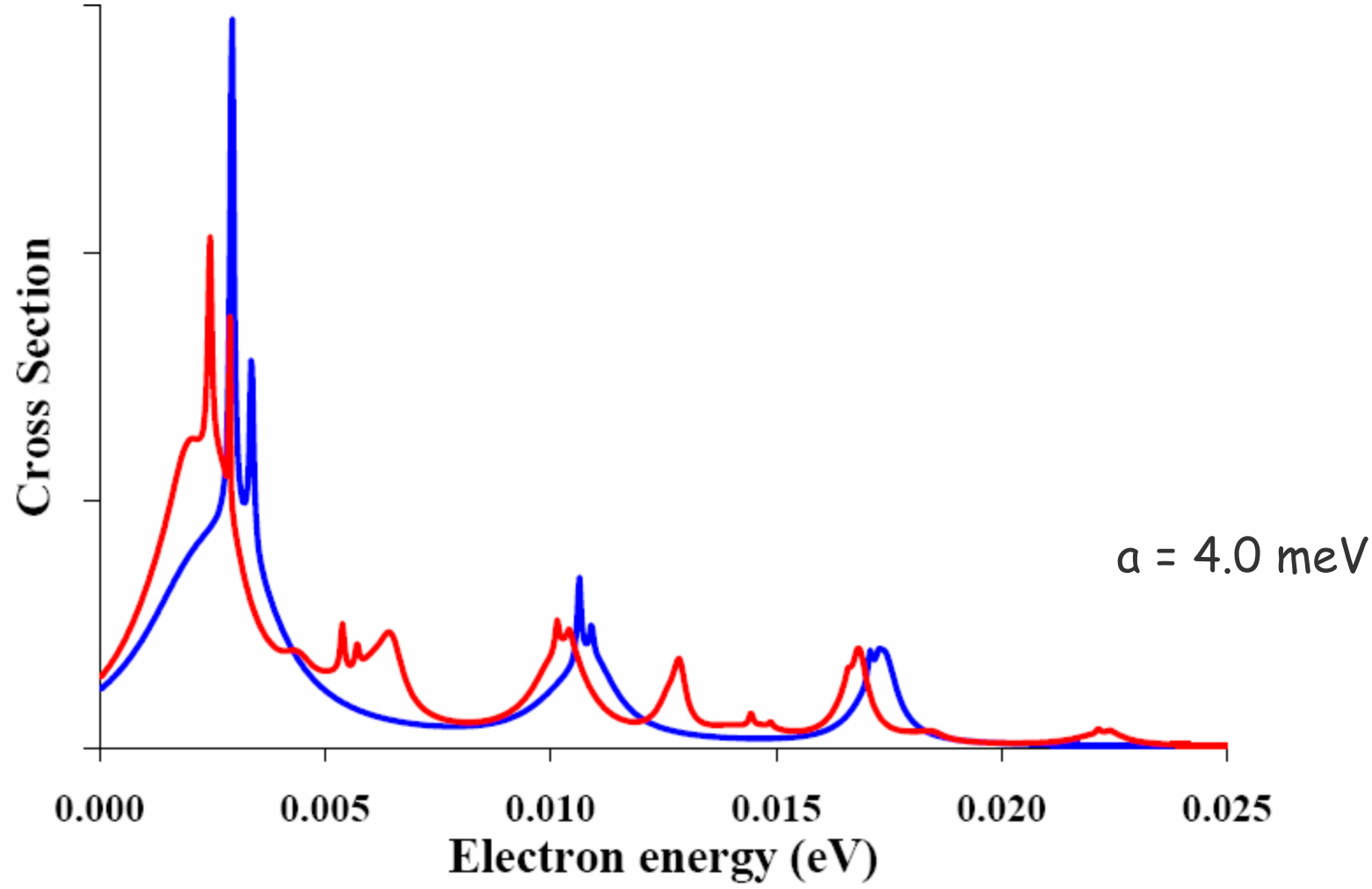
$a = 4.0$ meV

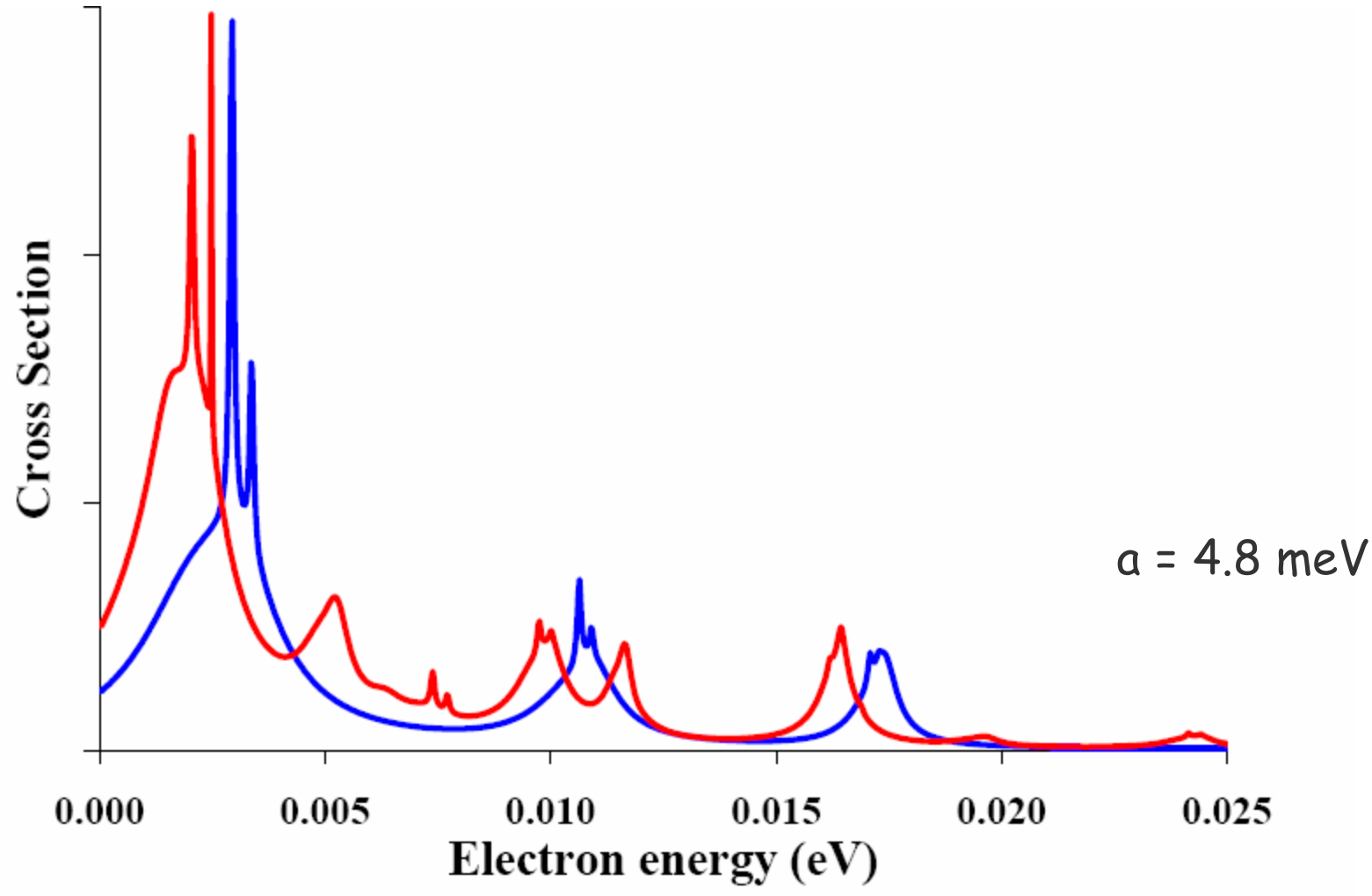
$\Delta E = a/2 \, (F(F+1) - J(J+1) - I(I+1))$

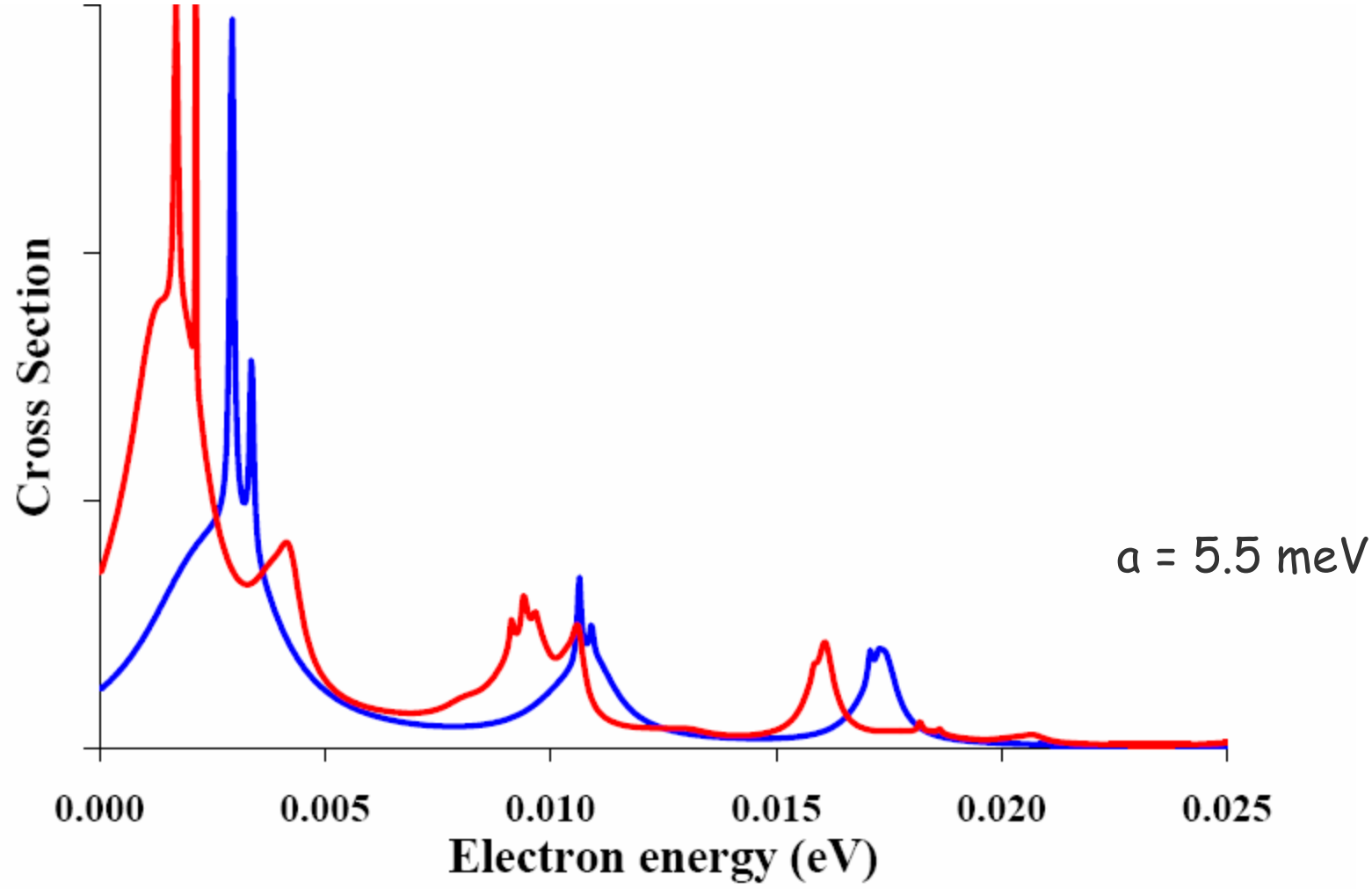
$a = 4.8$ meV

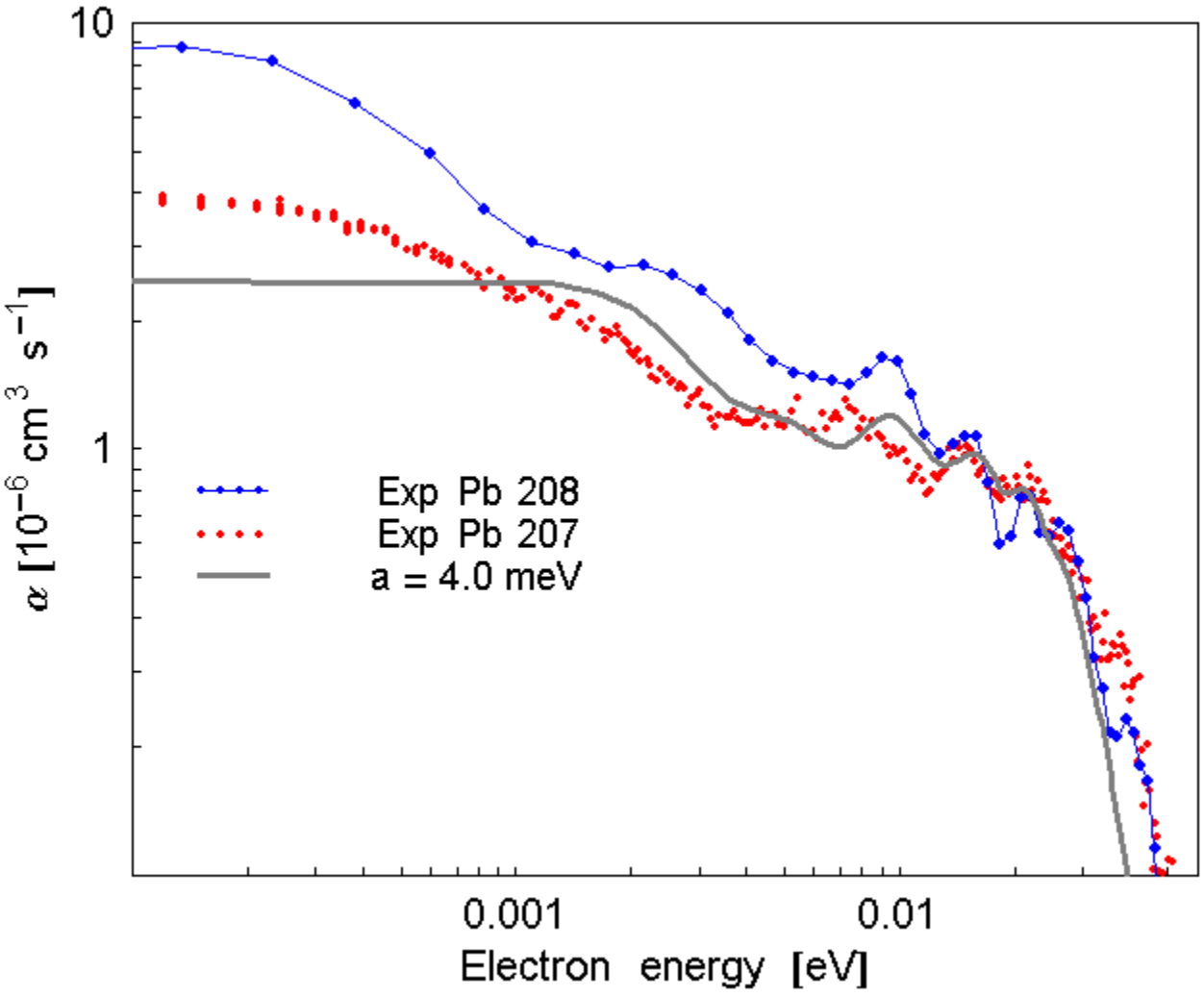
$\Delta E = a/2 \, (F(F+1) - J(J+1) - I(I+1))$

$a = 5.5$ meV

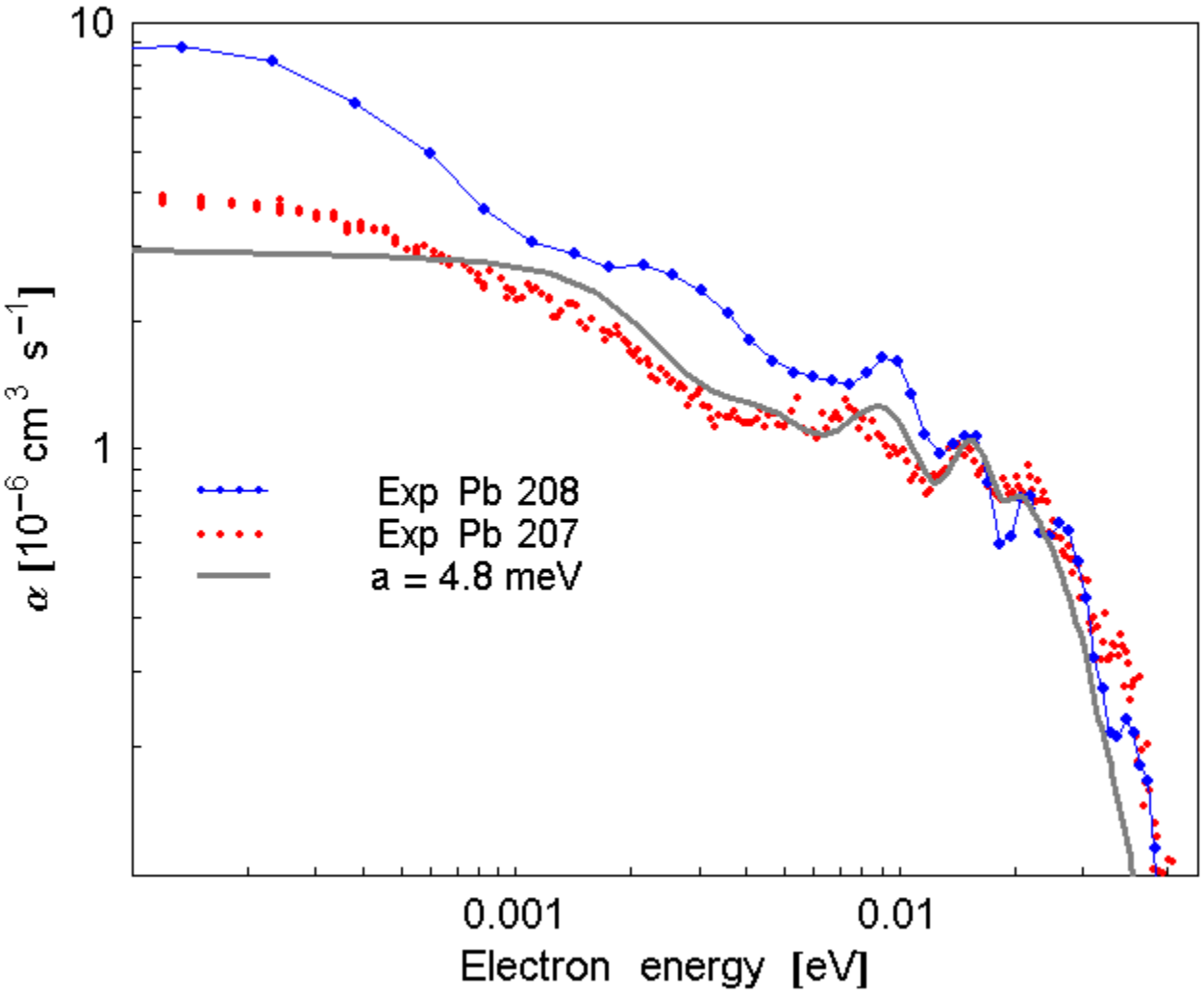

Cross Section
0.000
0.005
0.010
0.015
0.020
0.025
Electron energy (eV)
a = 4.0 meV
No hfs
With hfs


Cross Section
0.000
0.005
0.010
0.015
0.020
0.025
Electron energy (eV)
a = 4.8 meV
No hfs
With hfs

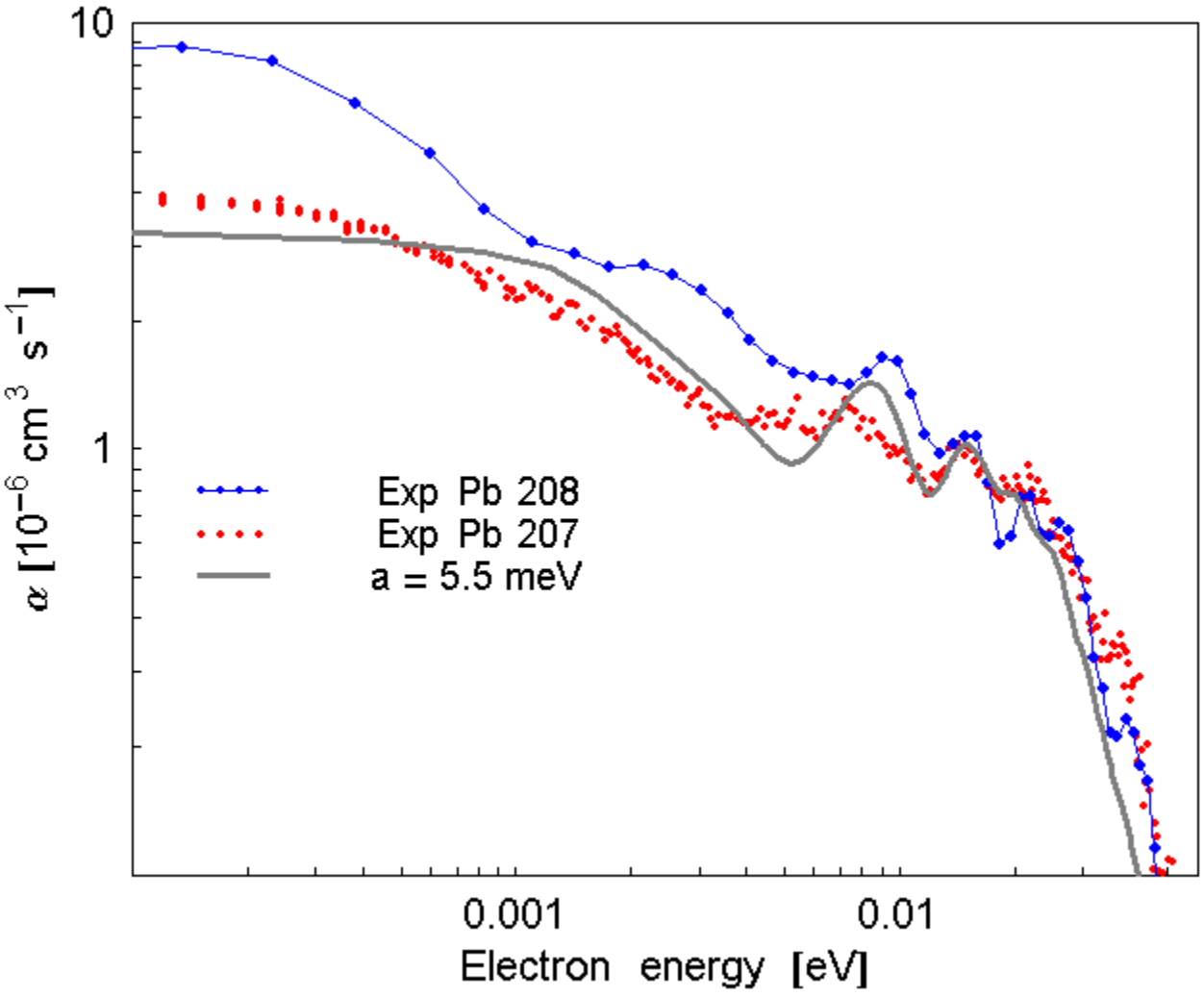

Cross Section
0.000
0.005
0.010
0.015
0.020
0.025
Electron energy (eV)
a = 5.5 meV
No hfs
With hfs



Schuch et al. Phys. Rev. Lett. **95**, 183003

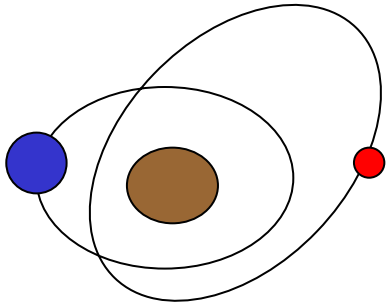


Schuch et al. Phys. Rev. Lett. **95**, 183003

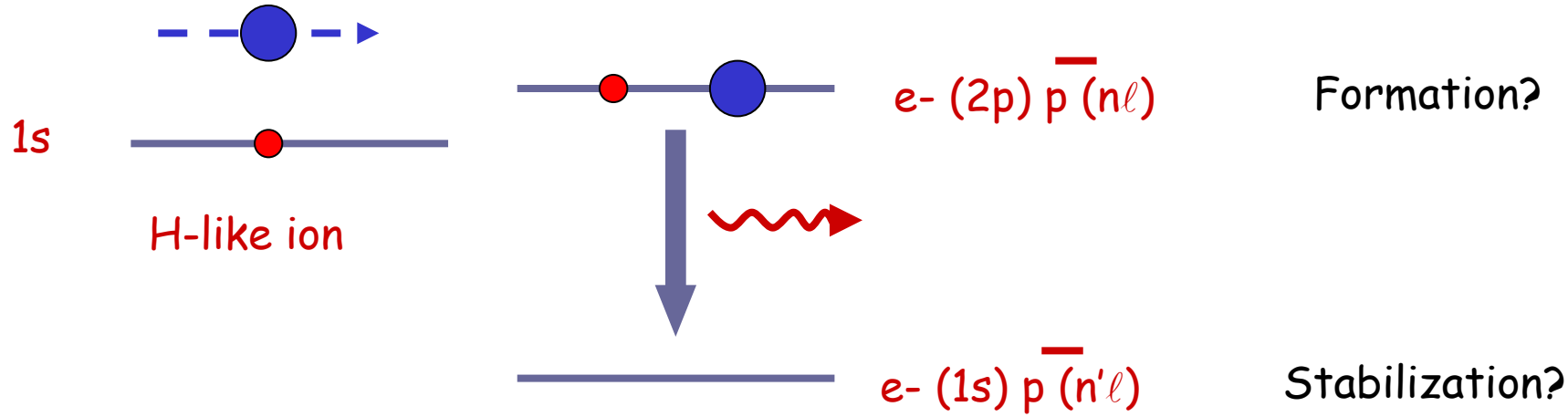


Schuch et al. Phys. Rev. Lett. **95**, 183003

Is it possible to make antiprotonic ions through "di-particle recombination"??



$\bar{p} + A^{q+} \rightarrow (A^{(q-1)+})^{**} \rightarrow A^{(q-1)+} h\nu$



- Formation: Time reversal of Antiprotonic Autoionization
- Stabilization: Photon emission and/or Electron ejection

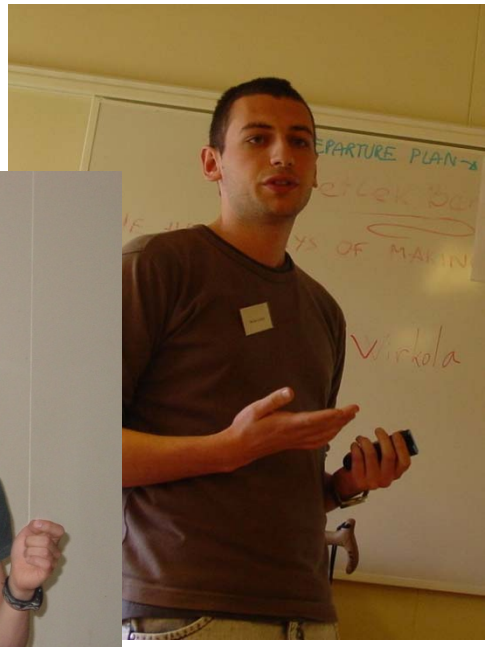
$$\text{Strength} \sim (2J+1) A_a^J A_S / \Sigma A \sim \text{Min}(A)$$

(electronic case: $S \sim A_{rad}$)

Eur. Phys. J. D **51**, 205 (2009)







Luca Argenti, Fabrizio Ferro, Jakob Bengtsson, Erik Waltersson, Michael Genkin,

In connection with experiments by A. Müller, S. Schippers, R. Schuch, A. Wolf and their co-workers

THANK YOU FOR YOUR ATTENTION