

## Plan of lectures

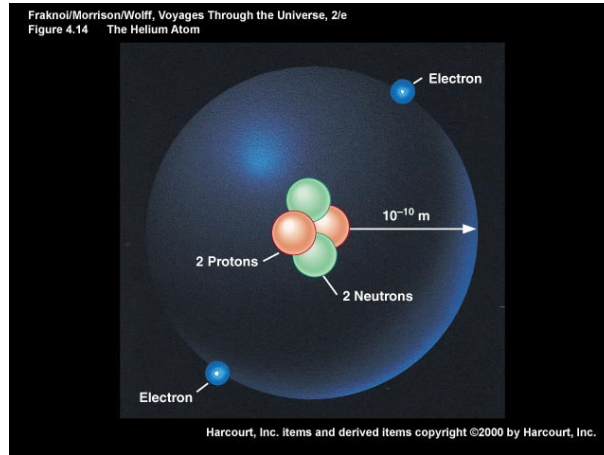
- 1 15.04.2015 Preliminary Discussion / Introduction
- 2 22.04.2015 Experiments (discovery of the positron, formation of antihydrogen, ...)
- 3 29.04.2015 Experiments (Lamb shift, hyperfine structure, quasimolecules and MO spectra)
- 4 06.05.2015 Theory (from Schrödinger to Dirac equation, solutions with negative energy)
- 5 13.05.2015 Theory (bound-state solutions of Dirac equation, quantum numbers)
- 6 20.05.2015 Theory (bound-state Dirac wavefunctions, QED corrections)
- 7 27.05.2015 Experiment (photoionization, radiative recombination, ATI, HHG...)
- 8 03.06.2015 Theory (description of the light-matter interaction)
- 9 10.06.2015 Experiment (Kamiokande, cancer therapy, ...)
- 10 17.06.2015 Theory (interaction of charged particles with matter)
- 11 24.06.2015 Experiment (Auger decay, dielectronic recombination, double ionization)
- 12 01.06.2015 Theory (interelectronic interactions, extension of Dirac (and Schrödinger) theory for the description of many-electron systems, approximate methods)
- 13 08.07.2015 Experiment (Atomic physics PNC experiments (Cs,...), heavy ion PV research)

## The helium atom and many-electron-systems

Auger decay, dielectronic recombination,  
double ionization

## The helium atom

Three-body Coulomb-problem: No accurate solution



## States in the helium atom

$$H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} - \frac{Ze^2}{r_1} - \frac{Ze^2}{r_2} + \frac{e^2}{|\vec{r}_1 - \vec{r}_2|}$$

Therefore we have two times the Hamilton operator for the hydrogen atom (but  $Z=2$ ) and in addition the repulsion-term  $V$

$$H = H_1 + H_2 + V \quad \text{with} \quad V(\vec{r}_1, \vec{r}_2) = \frac{e^2}{|\vec{r}_1 - \vec{r}_2|}$$

In 0th approximation we neglect the term  $V$ , die Coulomb repulsion between the electrons – and use the product-states of the hydrogen atom

$$u(\vec{r}_1, \vec{r}_2) = \Psi_{n_1 l_1 m_1}(\vec{r}_1) \cdot \Psi_{n_2 l_2 m_2}(\vec{r}_2) \quad \begin{array}{l} U \text{ are not eigenfunctions of the} \\ \text{Hamiltonian, if the repulsion } V \text{ is} \\ \text{taken into account} \end{array}$$

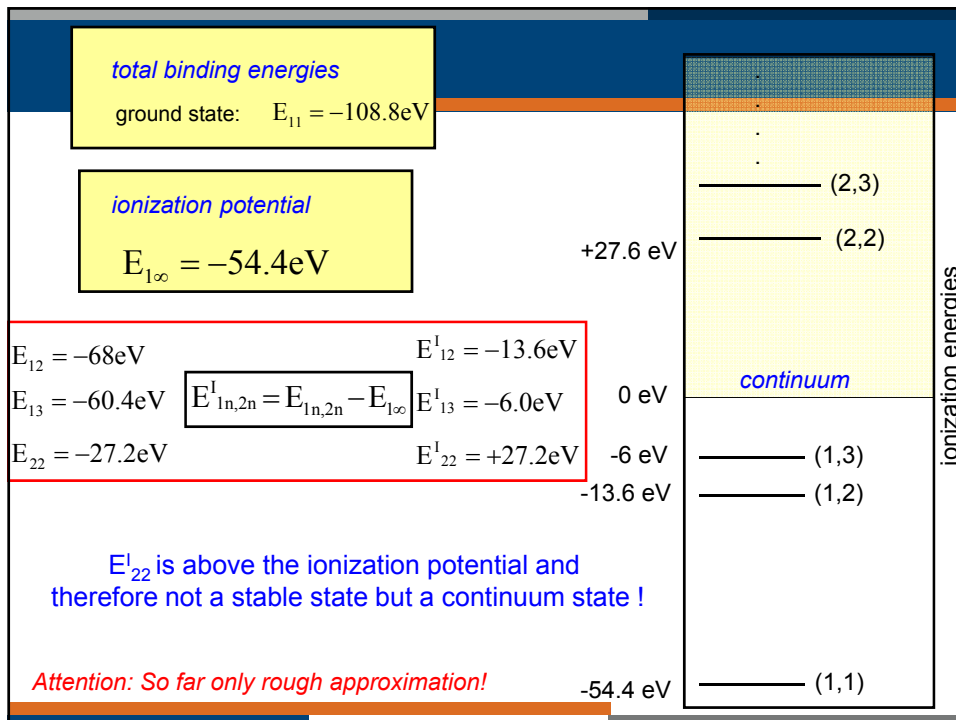
According to this, the problem would be accurately solvable because both electrons can be separated as

$$(H_1 + H_2)u = Eu$$

and we get

$$E_{n_1, n_2} = E_{n_1} + E_{n_2} = -Ry \cdot Z^2 \left( \frac{1}{n_1^2} + \frac{1}{n_2^2} \right) = -54.4 \text{ eV} \cdot \left( \frac{1}{n_1^2} + \frac{1}{n_2^2} \right)$$

ground state:	$E_{11} = -108.8 \text{ eV}$	}	<i>total binding-energies (without Coulomb repulsion)</i>
1st excited state:	$E_{12} = -68 \text{ eV}$		



### Example: $^3S_1$ and $^1S_0$

$$\Psi_{S,A}(1,2) = \frac{1}{\sqrt{2}} [\Psi_{100}(r_1)\Psi_{200}(r_2) \pm \Psi_{100}(r_2)\Psi_{200}(r_1)] \cdot \chi_{A,S}$$

$$H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} - \frac{Ze^2}{r_1} - \frac{Ze^2}{r_2} + \frac{e^2}{|\vec{r}_1 - \vec{r}_2|}$$

Calculate electron-electron-interaction

$$\Delta E_{S,A} = + \iint \Psi_{SA}^{g*}(1,2) \frac{e^2}{|\vec{r}_1 - \vec{r}_2|} \Psi_{SA}^g(1,2) d^3r_1 d^3r_2$$

+ sign, because of the repulsion.  
Convention: binding energies are negative

for  $S=0$  ( $^1S_0$ )  $\Delta E_S = \Delta E_{COUL} + \Delta E_{Exchange}$

for  $S=1$  ( $^3S_1$ )  $\Delta E_A = \Delta E_{COUL} - \Delta E_{Exchange}$

The energy shift due to the symmetry-energy (exchange interaction)

$$\Delta E(^3S_1 - ^1S_0) \approx 0.8\text{eV}$$

(stronger repulsion by symmetric space function)

Compare: fine structure splitting  $\approx 10^{-4}\text{eV}$

## States in He-atoms: a current problem of physics

### Some numerical results for the helium ground state

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In this contribution we would like to report about two numerical results related to the ground state of the helium atom. The first one is precise determination of the ground state nonrelativistic energy (Table 1).

Table 1: Nonrelativistic energies for the ground state of a helium atom  ${}^4\text{He}$ .  $N$  is the number of basis functions.

$N$	$E_{\text{gr}}$ (in a.u.)
4200	-2.9037243770341195983111540
4600	-2.9037243770341195983111572
5200	-2.9037243770341195983111587
extrap	-2.9037243770341195983111594(4)
Sims and Hagstrom[1]	-2.9037243770341195982999
Drake <i>et al.</i> [2]	-2.903724377034119598905

The next result (see Table 2) is a very accurate calculation of the Bethe logarithm. It is known that this quantity has been considered for many years as most difficult for numerical evaluation. It is formally defined as follows [3]:

$$\beta = \ln k_0 / R_y = \sum_n | \langle 0 | p | n \rangle |^2 (E_n - E_0) \ln | E_n - E_0 | / R_y / \sum_n | \langle 0 | p | n \rangle |^2 (E_n - E_0).$$

Table 2: The Bethe logarithm for the ground state of a helium atom  ${}^4\text{He}$ .

$N$	$\beta$
1200	4.3701602230
1400	4.3701602223
1600	4.3701602222
Drake, Goldman [4]	4.370160218(3)
J. Baker <i>et al.</i> [5]	4.370159(2)
C. Schwartz [6], (1961)	4.370(4)

#### References

- [1] J.S. Sims and S.A. Hagstrom, *Int. J. Quantum Chem.*, to be published.
- [2] G.W.F. Drake, M.M. Cossar, and R.A. Nisior, *Phys. Rev. A* **65**, 054501 (2002).
- [3] H. Bethe and E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms*, Springer-Verlag, Berlin-Göttingen-Heidelberg 1957.
- [4] G.W.F. Drake and S.P. Goldman, *Can. J. Phys.* **77**, 835 (1999).
- [5] J. Baker, R.C. Forrey, M. Jezzińska, and J.D. Morgan III, unpublished.
- [6] C. Schwartz, *Phys. Rev.* **123** 1700 (1961).

For the ground state the prevailing value of the binding energies is

$$E_{11} = -79.0034 \text{ eV}$$

ionization potential

$$24.5874 \text{ eV}$$

contribution of the electron-electron interaction

$$\Delta E = +29.8 \text{ eV}$$

## LS-coupling (light atoms)

The spins couple independently of the orbital angular momentum

$$\left. \begin{aligned} \vec{S} &= \vec{s}_1 + \vec{s}_2; \vec{S} = \sum_i \vec{s}_i \\ \vec{L} &= \vec{l}_1 + \vec{l}_2; \vec{L} = \sum_i \vec{l}_i \end{aligned} \right\} \vec{J} = \vec{L} + \vec{S}$$

$$l_1 = l_2 = 0$$

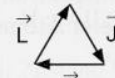
$$m_{s_1} = +\frac{1}{2}, m_{s_2} = -\frac{1}{2}$$

$$l_1 = l_2 = 0$$

$$m_{s_1} = m_{s_2} = +\frac{1}{2}$$



$$m_{s_1} = m_{s_2} = -\frac{1}{2}$$



$$1^1S_0$$

$$2^1S_0$$

$$L=0, S=0, J=0$$

$$2^3S_1$$

$$L=0, S=1, J=1$$

$$2^3P_2$$

$$L=1, S=1, J=2$$

$$2^3P_0$$

$$L=1, S=1, J=0$$

$$2^3P_1$$

$$L=1, S=1, J=1$$

## The first excited electrons of helium

Nomenclature for an atomic state (n, l, m, s)

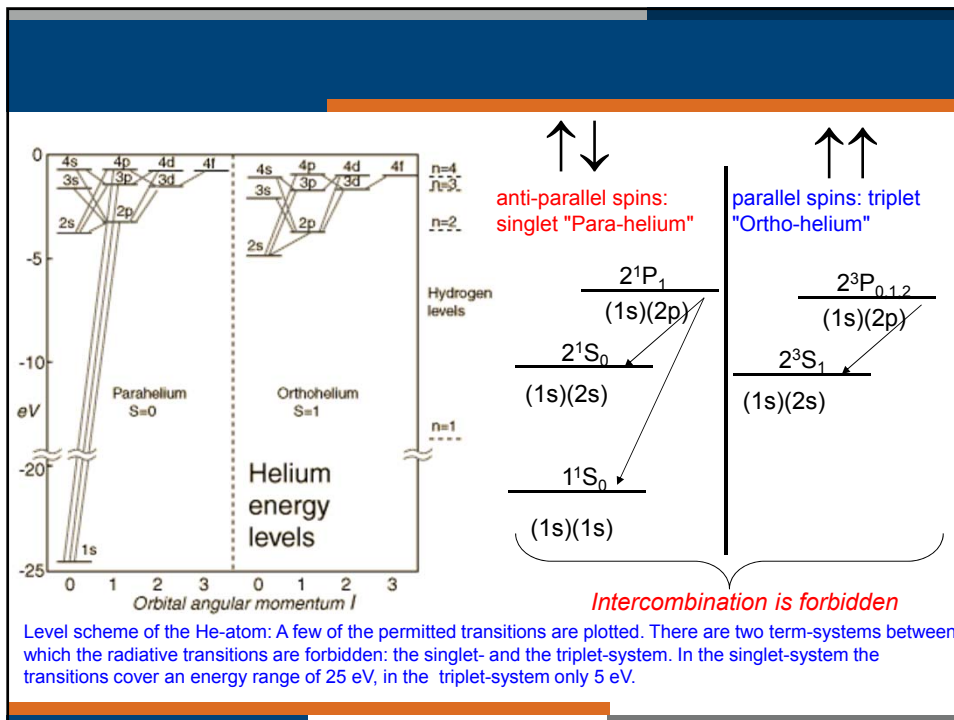
$n^{2s+1}X_J$

N gives the principle quantum number  
 X is the total angular momentum S(L=0), P(L=1),...  
 The index (top left) describes the multiplicity (total spin  $S = \sum_i s_i$ )  
 The total angular momentum is given by  $J=L+S$

Example:

$2^3P_1$

2 gives the principle quantum number (1s)(2p)  
 P is the total angular momentum L=1  
 The index (top left) describes the multiplicity ( $S=s_1+s_2=1$ )  
 The total angular momentum is given by  $L=1, S=1$ .  
 They couple to  $J=1$



## jj-coupling (heavy atoms)

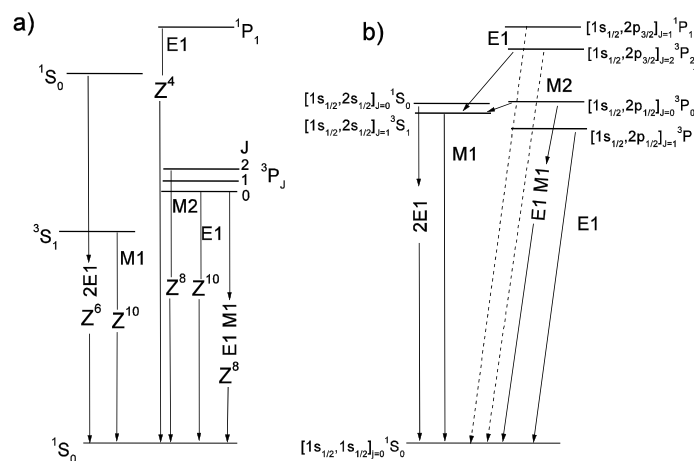
$$\vec{J}_1 = \vec{\ell}_1 + \vec{s}_1 \quad \vec{J} = \vec{j}_1 + \vec{j}_2 \quad \vec{J} = \sum_i \vec{j}_i$$

In heavy atoms the jj-coupling dominates. Here the spin-orbit-interaction (fine structure) is much stronger than the exchange interaction. The electrons behave like in an effective one-electron-system.

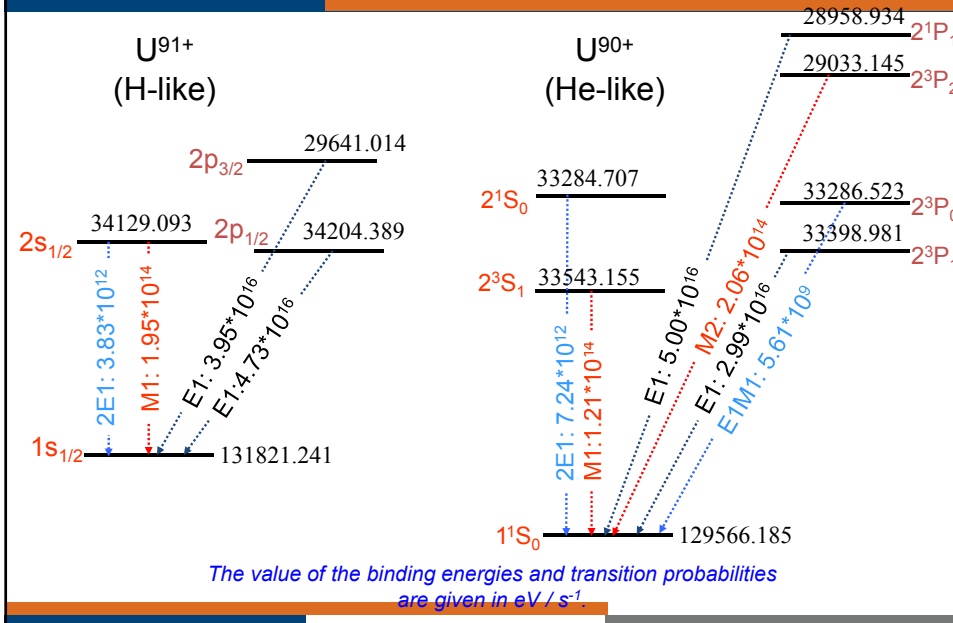
Example: Uran L-shell

Spin-orbit-coupling:  $\approx 4.5 \text{ keV}$   
Exchange interaction:  $\approx 100 \text{ eV}$

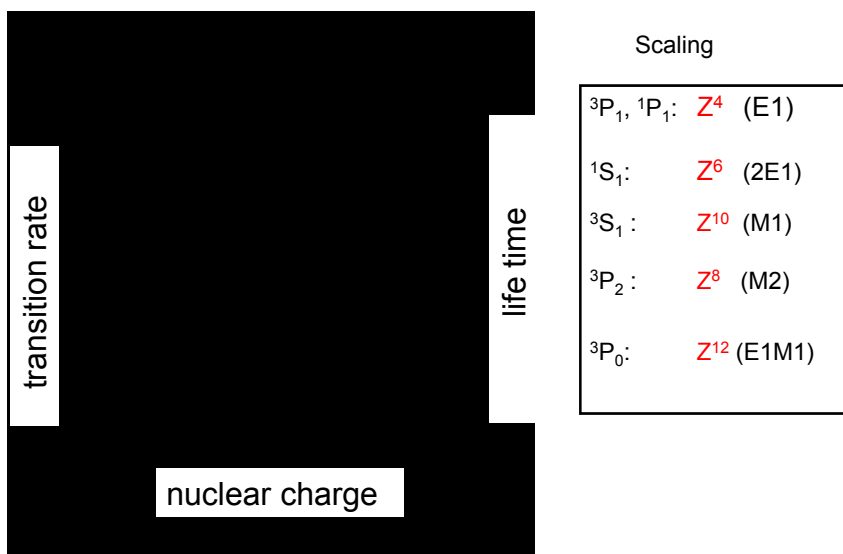
## Compare: Helium and Helium-like Uranium (ls-coupling und jj-coupling)



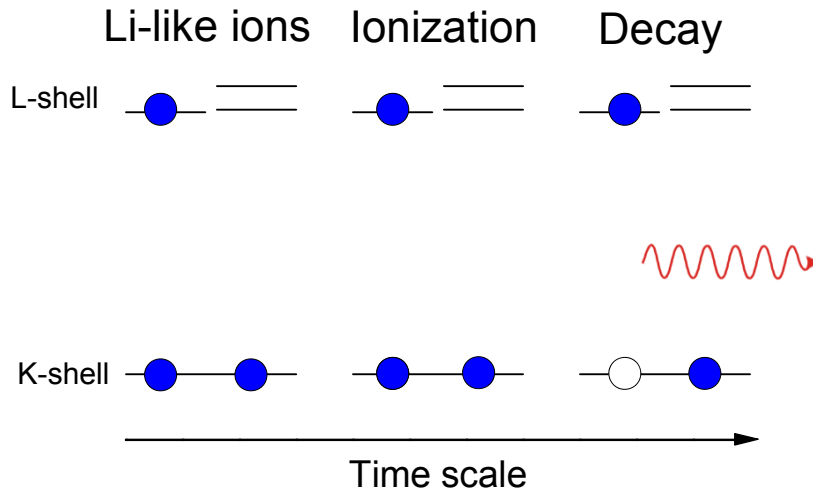
In comparison to Helium, He-like Uranium interacts like an effective one-electron-system



## Transition rates in He-like systems (L → K)

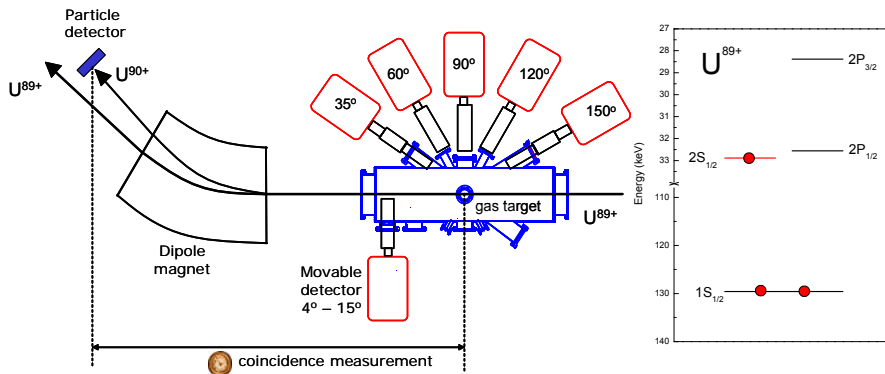


# Structure investigation with $U^{90+}$



## Experiment

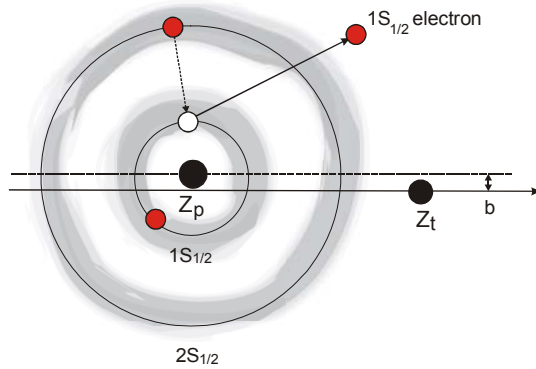
- Li-like Uranium ( $U^{89+}$ ) with a velocity of about  $\beta \cong 0.6$ .
- The produced x-ray radiation (in collisions with  $N_2$ ) is measured in coincidence with ions, which have lost an electron during the collision.





# Selective K-shell Ionization

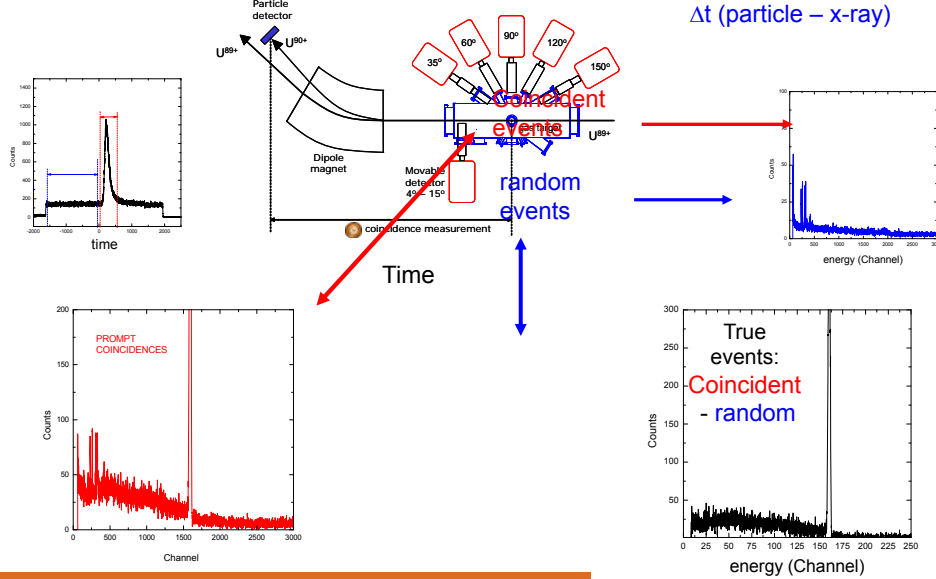
- Ionization of a K-shell electron. The L-shell-electron stays undisturbed.



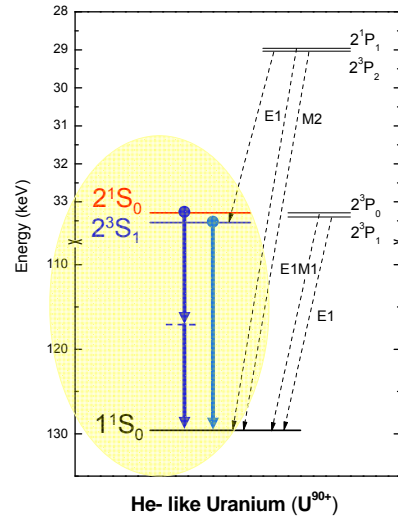
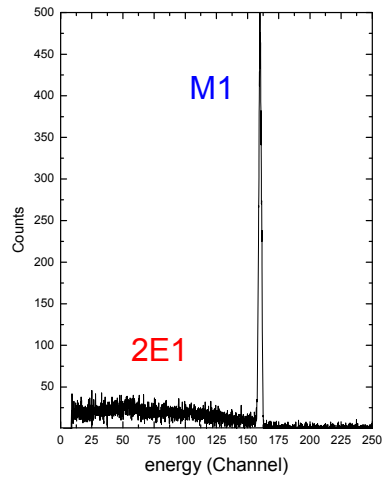
# Coincidence technique

Time:  $\Delta t$  (particle - x-ray)

Time-spectrum  
 $\Delta t$  (particle - x-ray)

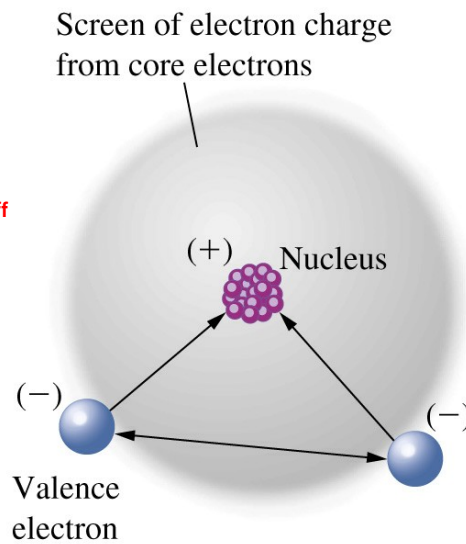


# Coincident x-ray-spectra



# Many-electron systems

→ Use effective nuclear charge  $Z_{eff}$



## The effective nuclear charge

$$Z_{\text{eff}} = Z - S$$

Z: nuclear charge

$Z_{\text{eff}}$ : effective or shielded nuclear charge

S: shielding constant



Binding energies

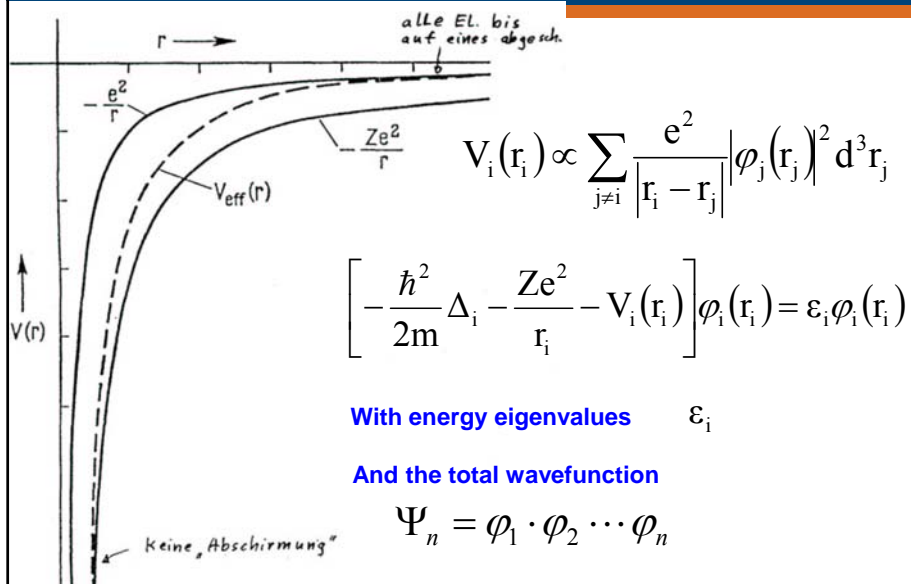
$$E_B = Ry \cdot \frac{Z_{\text{eff}}^2}{n^2} \quad \xrightarrow{\text{Compare}} \quad E_B = Ry \cdot \frac{Z^2}{n^2}$$

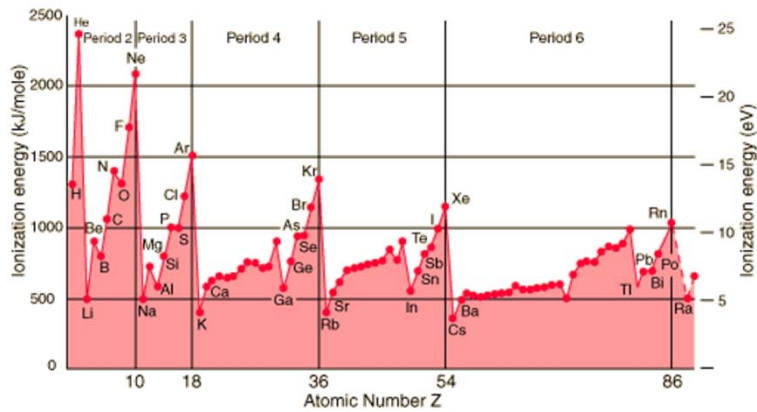
Orbit radius

$$r_{\text{eff}} = a_0 \cdot \frac{n^2}{Z_{\text{eff}}} \quad \xrightarrow{\quad} \quad r = a_0 \cdot \frac{n^2}{Z}$$

$$(a_0 = 0.53 \cdot 10^{-8} \text{ cm})$$

## The many-electron potential

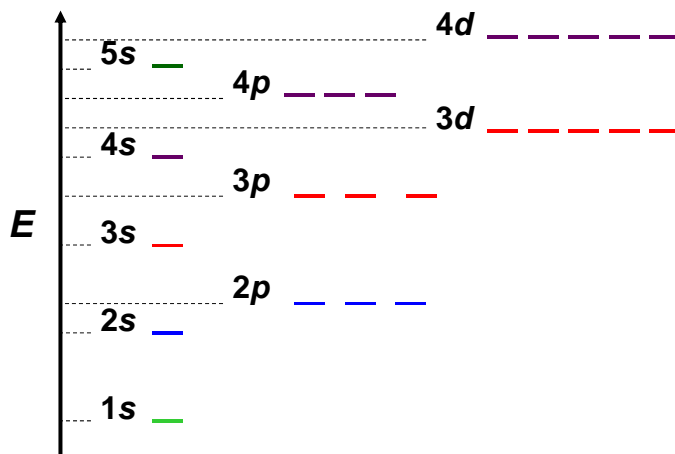




Ionization potential: *At least this energy has to be deposited to remove an electron.*

$$E_I = Ry \cdot \frac{Z_{\text{eff}}^2}{n^2}$$

## Energy levels in a many-electron system



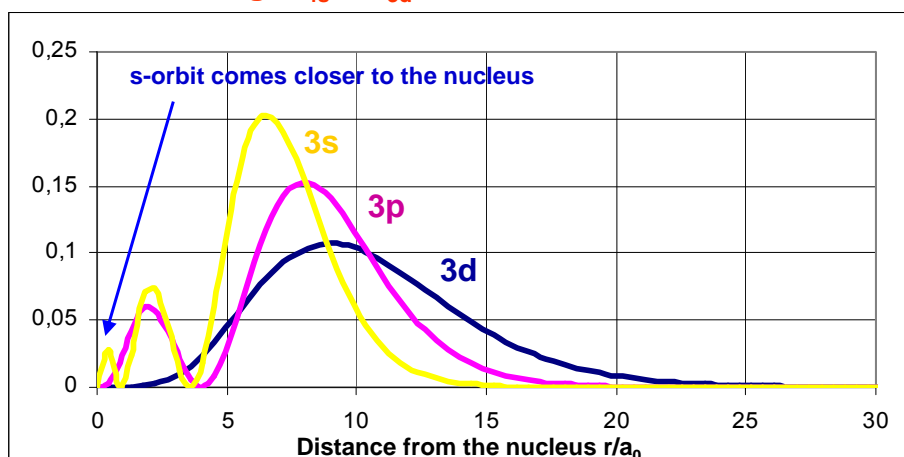
## The many-electron wavefunctions

The order of the energy levels changes

$$Z_{\text{eff}}(\text{s}) > Z_{\text{eff}}(\text{p}) > Z_{\text{eff}}(\text{d})$$

e.g.  $E_{4\text{s}} < E_{3\text{d}}$

$$E_{\text{B}} = R_{\text{y}} \cdot \frac{Z_{\text{eff}}^2}{n^2}$$



## Slater-rules for calculate $Z_{\text{eff}}$

Electron orbitals are classified as follows

$[1s][2s2p][3s3p][3d][4s4p][4d][4f][5s5p][5d][5f]$  etc.

Rules for calculate the screening constant  $s$

- 1.)  $[ns np]$  Group: Electrons in a higher group **do not shield**.
- 2.)  $[ns np]$  Group : Electrons in the same group contribute with **-0.35** in shielding.
- 3.)  $[ns np]$  Group : Electrons in the next lower group  $[n-1]$  shield with **-0.85**.
- 4.)  $[ns np]$  Group : Electrons in the  $[n-2]$  group (and lower) shield with **-1**.
- 5.)  $[nd nf]$  Group : Rule 1.) and 2.) but electrons in  $[n-1]$  shield with **-1**.
- 6.)  $[1s]$  Shielding by the **second 1s-electron: -0.3**.

18

Example  
Potassium Z=19

[1s<sup>2</sup>] [2s<sup>2</sup> 2p<sup>6</sup>] [3s<sup>2</sup> 3p<sup>6</sup>] [3d<sup>1</sup>]

for [3d<sup>1</sup>] follows: s=18 => Z<sub>eff</sub>=1

[1s<sup>2</sup>] [2s<sup>2</sup> 2p<sup>6</sup>] [3s<sup>2</sup> 3p<sup>6</sup>] [3d<sup>0</sup>] [4s]

10      8x 0.85

for [4s] follows: S=10+6.8 = 16.8 => Z<sub>eff</sub>=2.2

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Example  
Sodium Z=11

[1s<sup>2</sup>] [2s<sup>2</sup> 2p<sup>6</sup>] [3s<sup>1</sup>]

2      8x 0.85

for [3s] follows: S=2+6.8 = 8.8 => Z<sub>eff</sub>=2.2

*Exact calculations: Z=2.51*

## The Auger-effect (many-electron systems)

An excited atomic system can, besides emitting photons, also de-excite by (radiationless) emission of electrons → Auger electrons

pure electron-electron interaction

$$\Gamma_A \propto \left| \left\langle \Psi^{i_1} \cdot \Psi^{i_2} \left| \frac{1}{|r_1 - r_2|} \right| \Psi^{f_1} \cdot \Psi^{f_2} \right\rangle \right|^2$$

In general, doubly-excited states are formed,  
e.g. as a consequence of a produced K-shell vacancy,  
and an excited many-electron system can decay by the emission of Auger electrons.

fluorescence

KLL-Auger

Pierre Auger (1899\*-1998\*):  
Studied atomic physics and cosmic radiation. In 1926 he discovered the effect named after him.  
(Herder Lexikon)

**Auger rates are in first order approximation independent of the nuclear charge**

$$\Gamma_A \propto \left| \left\langle \Psi_1^i \cdot \Psi_2^i \left| \frac{1}{|r_1 - r_2|} \right| \Psi_1^f \cdot \Psi_2^f \right\rangle \right|^2$$

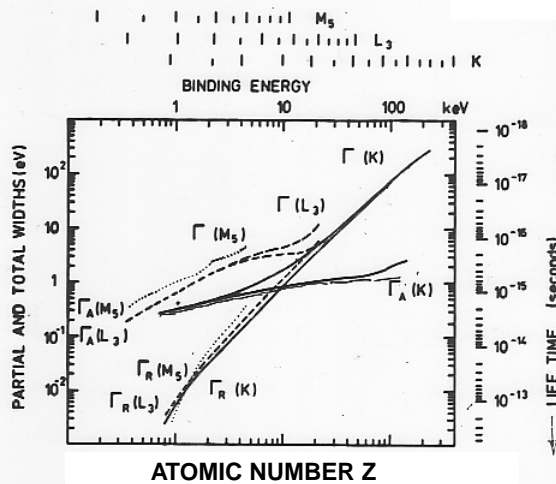
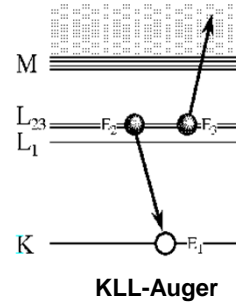
(non-relativistic, while all distances scale with Z)

- $\Psi_1^i$  : initial bound state of electron 1  $\propto Z^{3/2}$
- $\Psi_2^i$  : initial bound state of electron 2  $\propto Z^{3/2}$
- $\Psi_1^f$  : final bound state of electron 1  $\propto Z^{3/2}$
- $\Psi_1^f$  : final free state of electron 1  $\propto Z^{1/2}$

$$\frac{1}{r} \propto Z; \quad d^3 r_1 \propto \frac{1}{Z^3};$$

$$d^3 r_2 \propto \frac{1}{Z^3};$$

$$\Gamma_A \propto \left| Z^{3/2} \cdot Z^{3/2} \cdot Z \cdot Z^{3/2} \cdot Z^{1/2} \cdot \frac{1}{Z^3} \cdot \frac{1}{Z^3} \right|^2 = Z^0$$



**Auger rates**

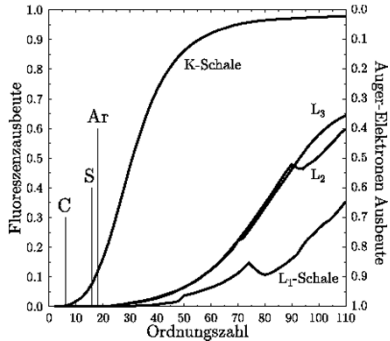
$$\Gamma_A \propto Z^0$$

**Radiative rates**

$$\Gamma_X \propto Z^4$$

*Auger rates are almost constant, when plotted as a function of Z, over a large range of elements.*

# Fluorescence yield



## Fluorescence yield

$$\omega = \frac{\Gamma_x}{\Gamma_x + \Gamma_A} = \frac{\Gamma_x}{\sum_i \Gamma_i}$$

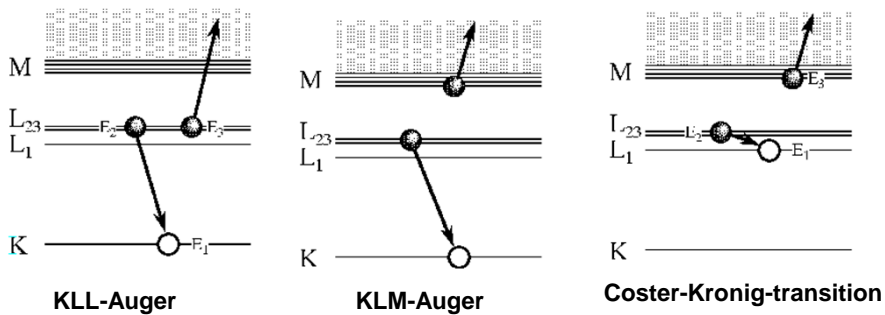
$$\omega \propto \frac{Z^4}{Z^4 + Z^0} \rightarrow 1 \text{ for } Z > 50$$

**Fluorescence yield:** ratio of the fluorescence yield to the total yield  $\Gamma_i$ , is also called **Fluorescence coefficient** ( $\omega$ ).

Note: so far we only treated approximations: The complete electron-electron interaction is given by the function  $f$ , also called the current-current-interaction. For certain states this function could also be the dominant term.

$$\frac{1}{|r_1 - r_2|} + f(j_1, j_2)$$

# Nomenclature of the Auger-effect



Radiationless transitions from state X (L-shell) to state Y (K-shell) and electron emission from the state Z (L-shell) into the continuum are termed XYZ, e.g. KLL, KLM, KMN, etc.

hole  
 ↓  
 ↓  
 ↓  
 Auger electron  
 ↓  
 decaying electron

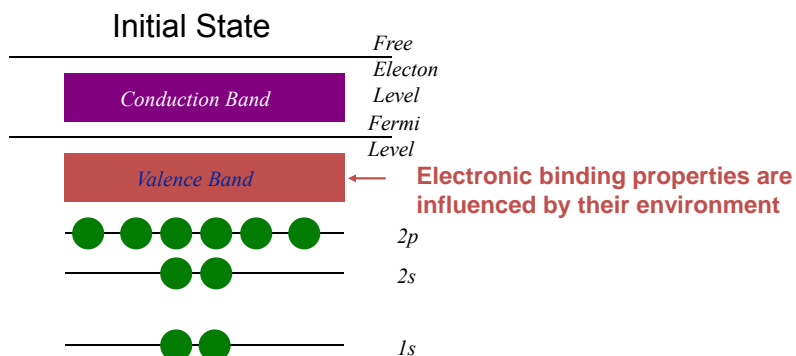
## Coster-Kronig-transitions

If  $x_i$  and  $x_f$  are the lower states of level X and Y is an excited state, then  $x_i \rightarrow x_f Y$  is a Coster-Kronig-transition



# Binding energies

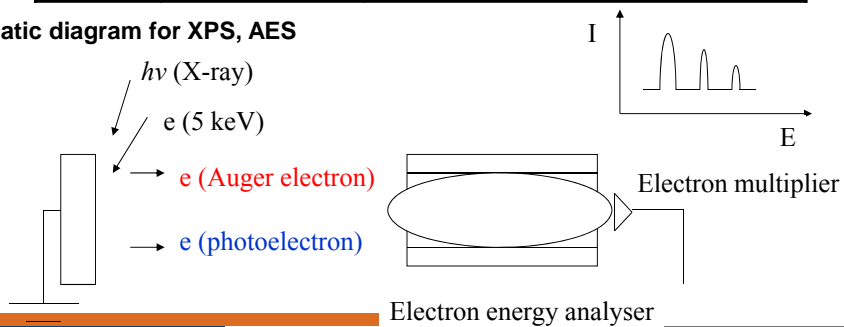
-how to identify elements and binding properties  
e.g. of atoms in their environment =



# Analysis of materials, chemical properties

	Probe beam	detection
XPS	photons (X-ray)	X-ray photo electron spectroscopy (core electrons)
UPS	photons (UV)	UV Photo electron spectroscopy (valence electrons)
AES	electrons	Auger electron spectroscopy
SIMS	ions	secondary ion mass spectroscopy

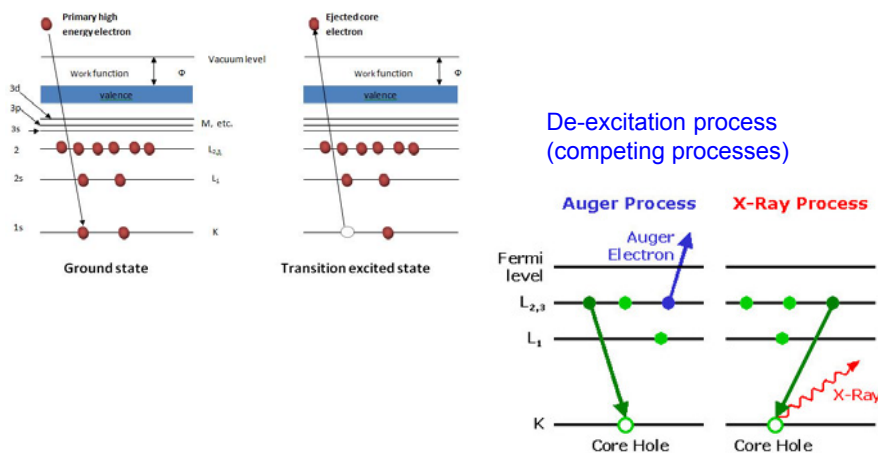
schematic diagram for XPS, AES



- XPS(x-ray photoelectron spectroscopy) was developed in the mid-1960s by Kai Siegbahn & his research groups (at the Univ. of Uppsala, Sweden)
- The technique was first known by the acronym ESCA(electron spectroscopy for chemical analysis)
- The advent of commercial manufacturing of surface analysis equipment in the early 1970s => equipment in laboratories
- In 1981, Siegbahn was awarded the Nobel Prize for Physics for his work with XPS

## AES: Auger electron spectroscopy (1925 )

Excitation by primary electrons (5keV)  
or x-rays



# Binding energies (BE)

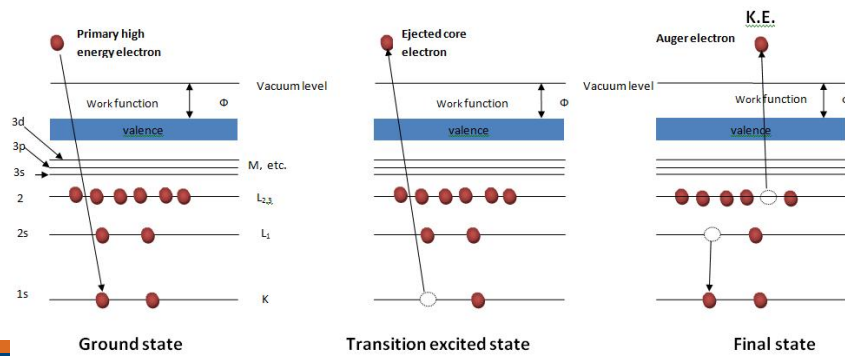
$$BE = h\nu - KE - \Phi_{spec} - E_{ch}$$

$BE$  = Electron-binding energy

$KE$  = Kinetic electron energy

$\Phi_{spec}$  = Spectrometer Work Function

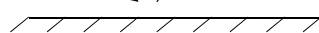
$E_{ch}$  = Surface energy (Ablösearbeit)



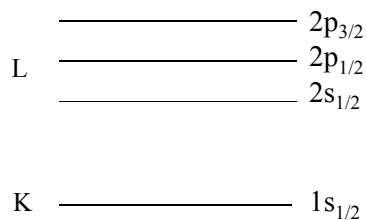
## XPS (X-ray photoelectron spectroscopy) oder ESCA (electron spectroscopy for chemical analysis)

$h\nu$  (x-ray) → e (photoelectron)

by Siegbahn



Mg $K_{\alpha}$ : 1253.6 eV	half width: 0.8 eV
Al $K_{\alpha}$ : 1486.6 eV	: 0.9 eV
Cu $K_{\alpha}$ : 8047.8 eV	: ~ 3 eV



### Photoelectron kinetic energy

Photoelectron kinetic energy

$$E_{K.E.} = h\nu - E_B$$

photon energy (constant) ↑  
 “Binding energy” of the electron in the orbital in the atom

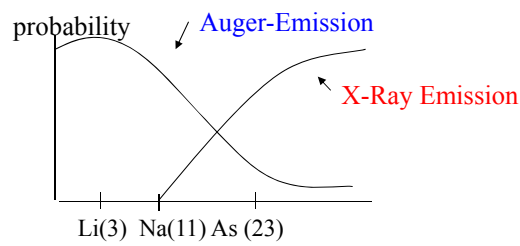
Auger-Electron-spectroscopy: typically used for elements between Li and U

$$E_{KL_1L_{III}} = E_K - E_{L_1} - E_{L_{III}}$$

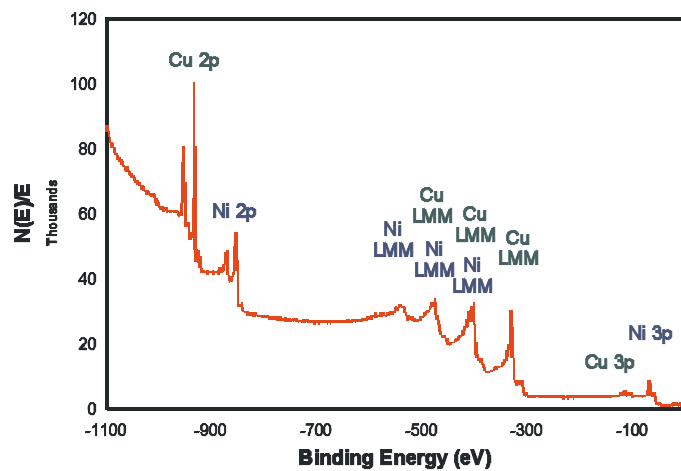
X-ray spectroscopy: typically used for elements between Li and U

$$\begin{aligned} E_{K\alpha_1} &= E_K - E_{L_{III}} \\ E_{K\alpha_2} &= E_K - E_{L_{II}} \end{aligned} \quad \left[ \begin{array}{l} K_{\alpha} : L \rightarrow K \\ K_{\beta} : M \rightarrow K \end{array} \right.$$

Effective probe thickness ~ 1 μm, sensitivity ~ 0.1%



## Element identification



## Element identification

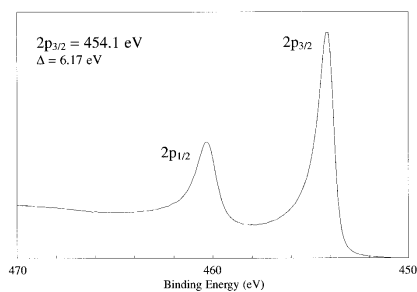
Element	Binding Energy (eV)		
	$2p_{3/2}$	$3p$	$\Delta$
Fe	707	53	654
Co	778	60	718
Ni	853	67	786
Cu	933	75	858
Zn	1022	89	933

*Electron-nucleus interaction is used for the element analysis*

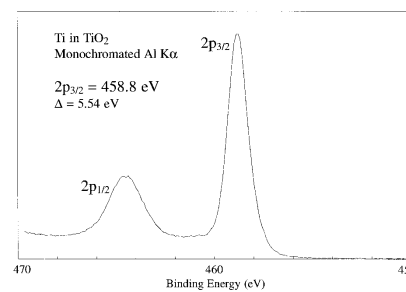
## Chemical properties

### Spin-Orbit Coupling

*Ti Metal*

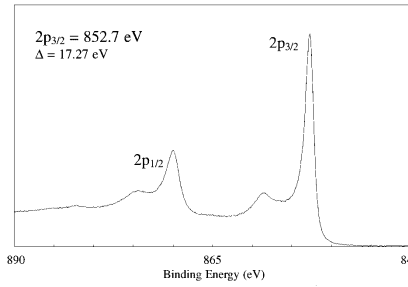


*Ti Oxide*

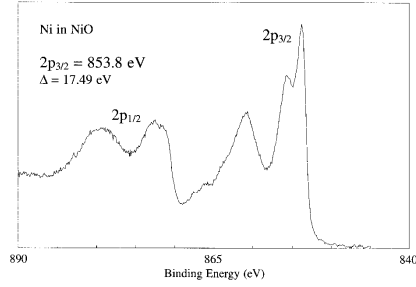


# Shakeoff/Shakeup

*Ni Metal*



*Ni Oxide*



# Final State Effects Shake-up/ Shake-off

*L(2p) -> Cu(3d)*

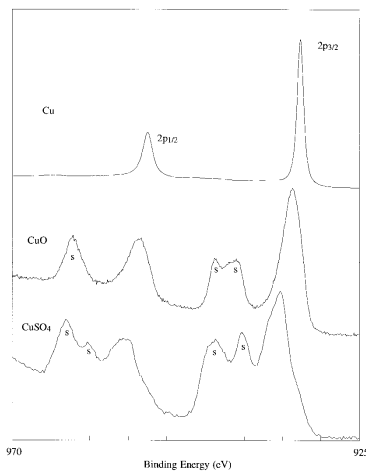
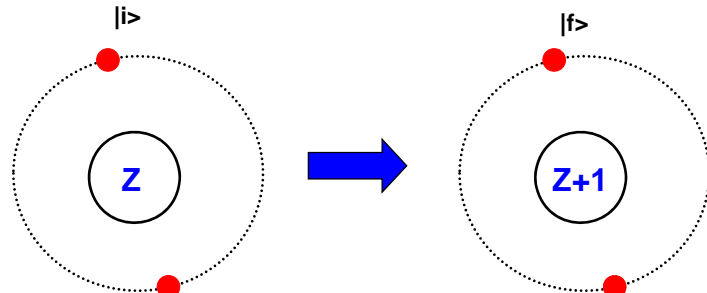


Figure 8. Examples of shake-up lines (s) of the copper 2p observed in copper compounds.

## Shake-off process

The *shake-off process* occurs when the *effective Coulomb potential* changes its strength and leads to an autoionization of the electron cloud. Examples are: K-shell ionization and  $\beta$ -decay.



In general, the valence electrons are most affected, since they have the lowest ionization potential (smallest binding energy).

Non-adiabatic regime:

Two-step process 'sudden approximation'. The first process (e.g. K-shell ionization) does not influence the second one (emission).

## Shake-off process

The probability that an electron remains in its orbit is:

$$P = \int \Psi^*(Z) \cdot \Psi(Z+1) d^3r$$

This probability is given by the overlap between the wavefunctions of the initial state  $\Psi(Z)$

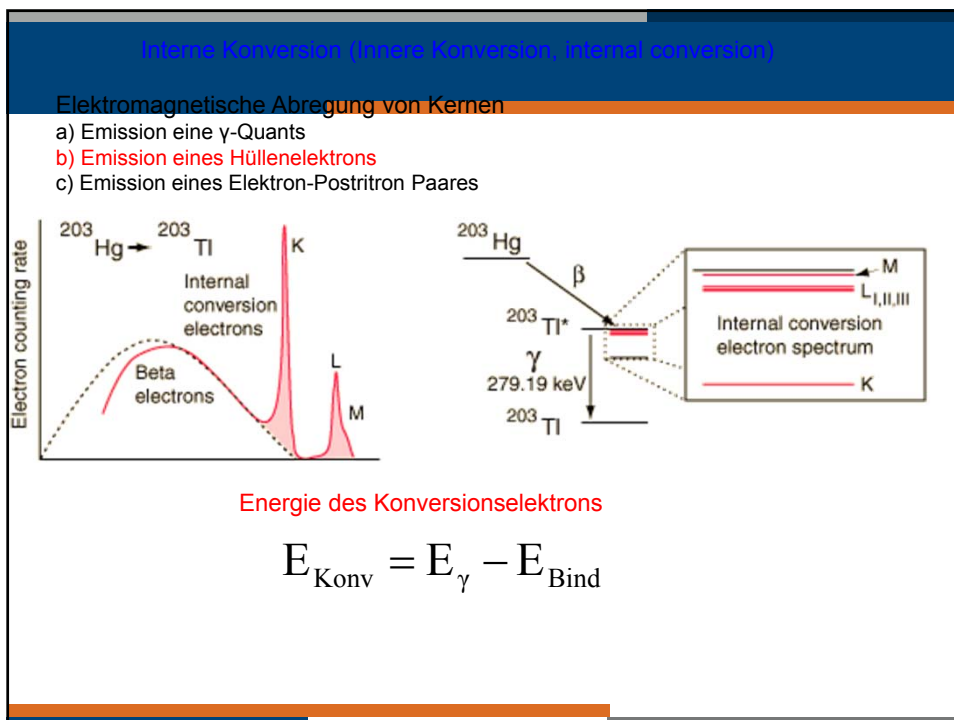
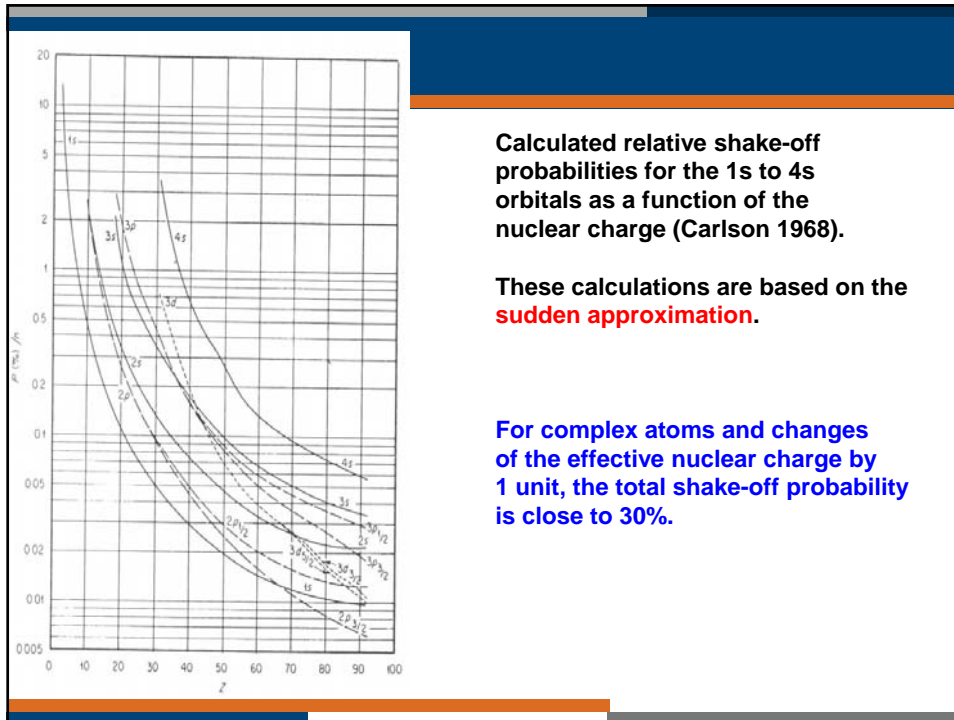
and the final state.  $\Psi(Z+1)$

The probability that an electron is being ionized is:

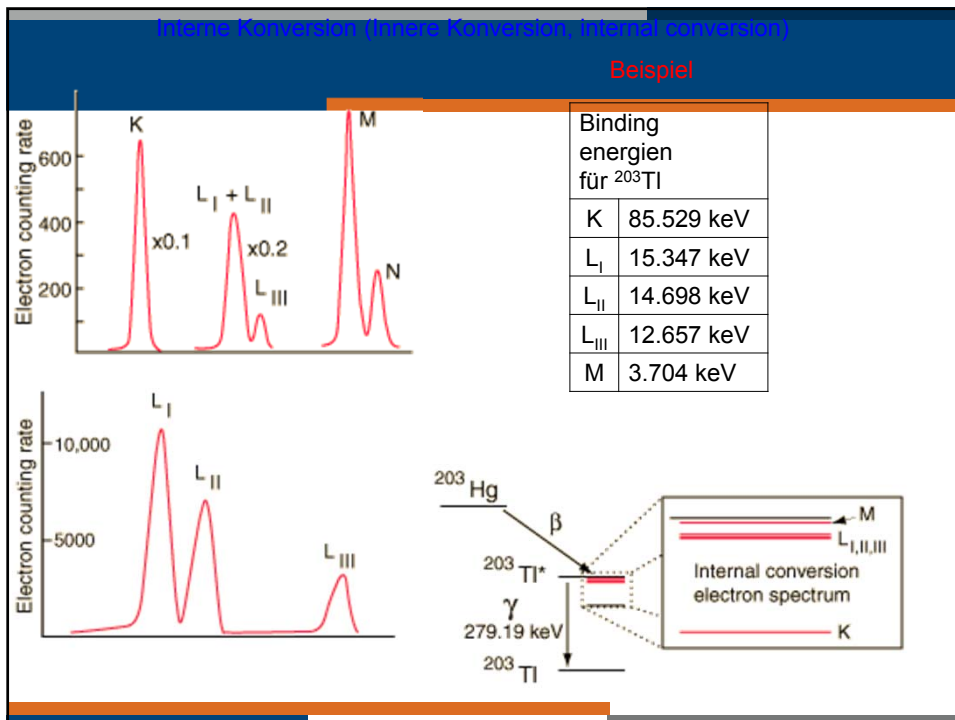
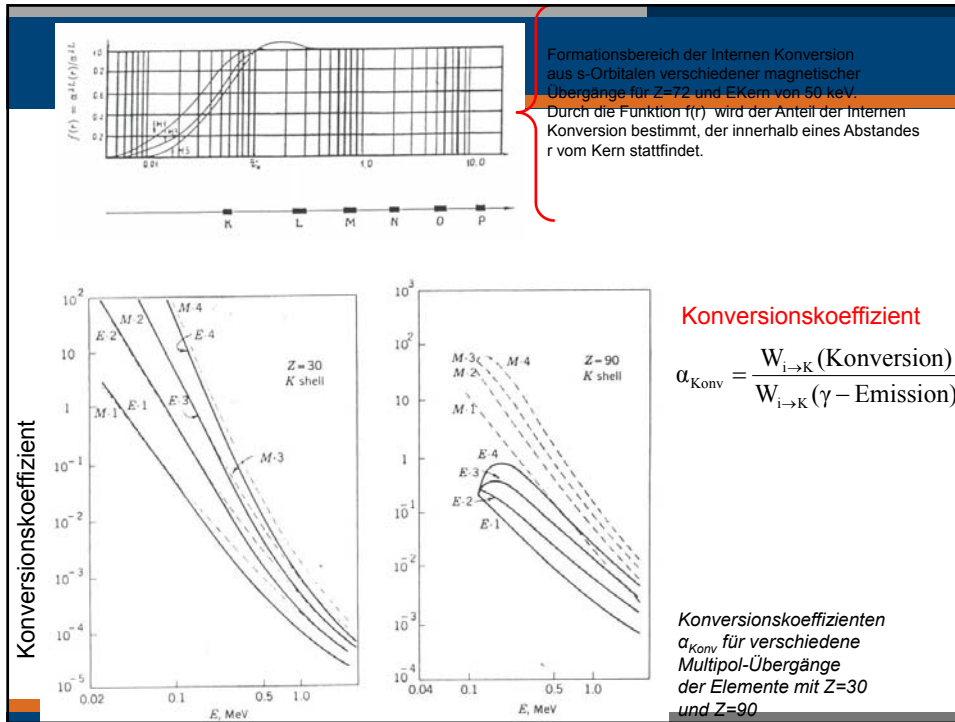
$$P_{\text{ION}} = 1 - \int \Psi^*(Z) \cdot \Psi(Z+1) d^3r \quad (P_{\text{ION}} = 1 - P)$$

*Note: High-energy approximation!*

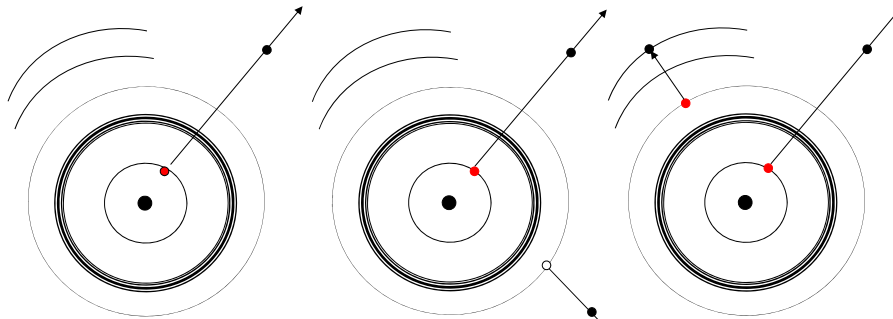
*Question: What is the energy distribution of the electrons ?*





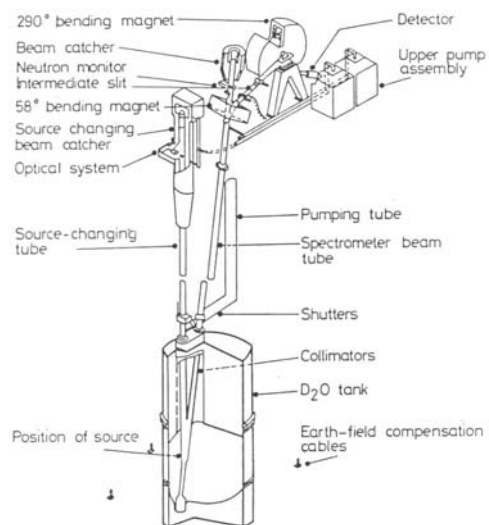
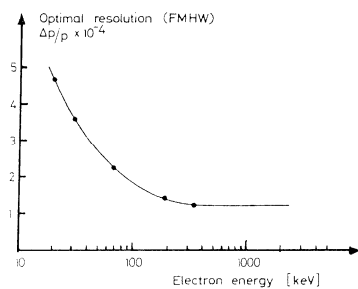
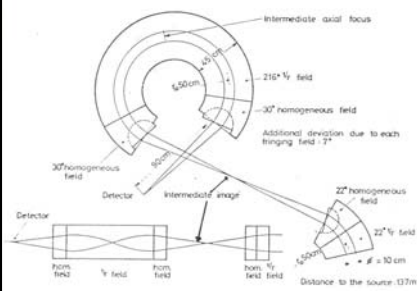


## Interne Konversion (Innere Konversion, internal conversion)

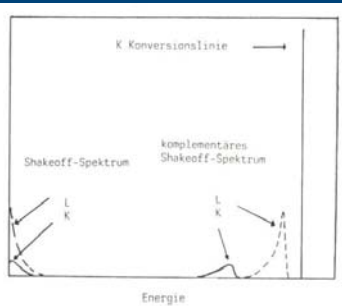


- Die Innere Konversion hinterlässt das Atom in einem einfach ionisierten Zustand
- Shakeoff im Prozess der Inneren Konversion*: das Atom wird zweifach ionisiert
- Shakeup*: Das Atom wird in einem einfach ionisierten und angeregten Zustand hinterlassen

## Magnetisches Elektronenspektrometer für hohe Energien (15 keV bis 10 MeV)



## Konversionselektronen



Konversionselektronenlinie

Shakeoff bzw. Energieverlust  
(enfaltetes Spektrum)

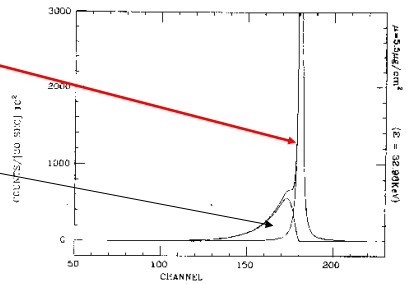
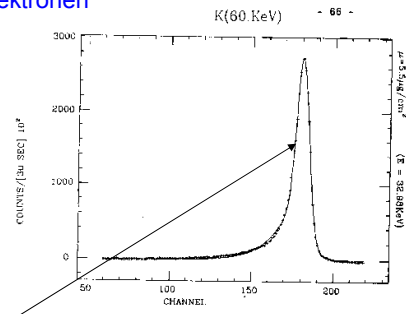
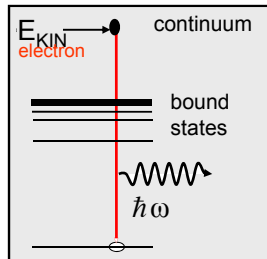


Abb. 6.5 : K(60) von  $^{215}\text{Po}$

- Dielectronic Recombination

## Electron Pickup Processes of HCl in Collisions with Electrons (Dynamic Processes)

### Radiative Recombination/Electron Capture

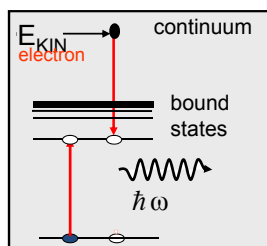


- *Electron capture into a bound ionic state by emission of a photon*

$$\hbar \omega = E_B + E_{KIN}$$

- *Time-reversed photoionization*
- *Only possible capture/recombination process for bare ions colliding with electrons*

### Dielectronic Recombination/Electron Capture



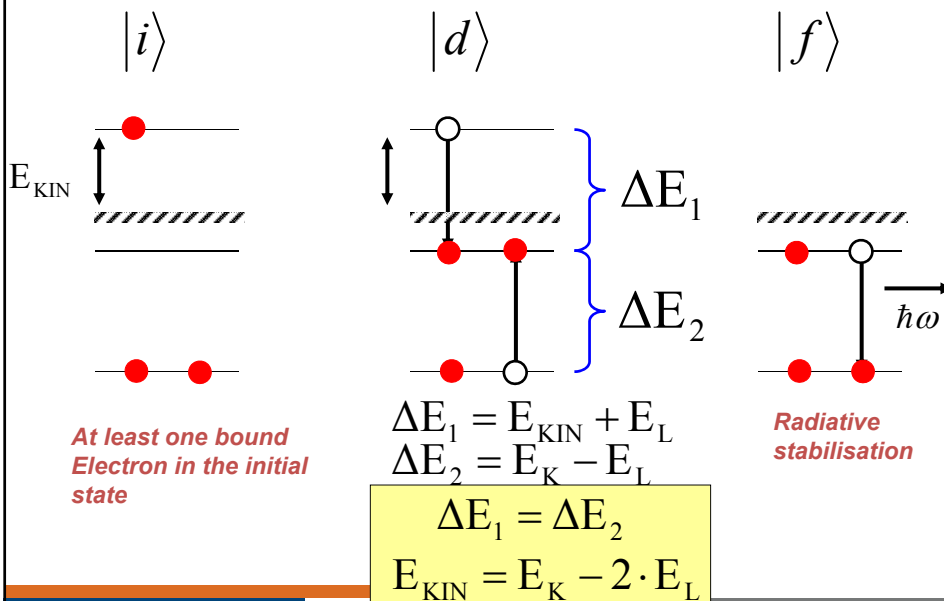
- *Resonant (non-radiative) capture of an electron into a bound state*

- *Time-reversed Auger process*

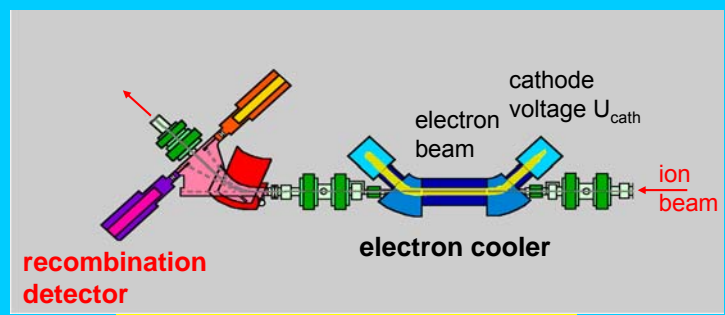
- *Important charge exchange process for multi-electron ions*

## Dielectronic Recombination

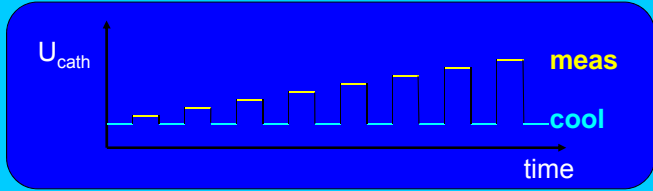
Resonance process => time reversed Auger effect



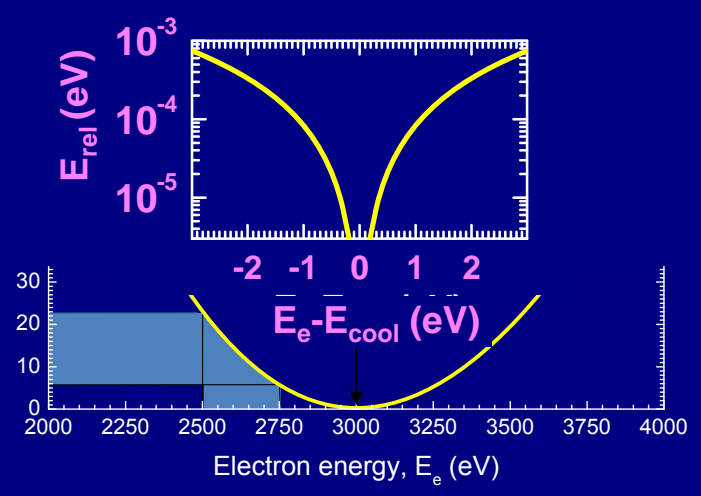
## Dielectronic recombination: the technique



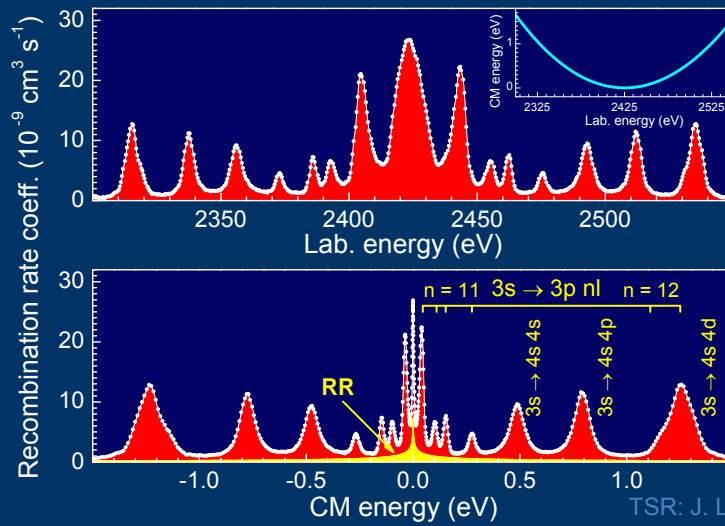
merged-beams rate coefficient:  $\alpha = \langle \sigma v \rangle$



## Merged-Beams Kinematics (access to low relative energies)

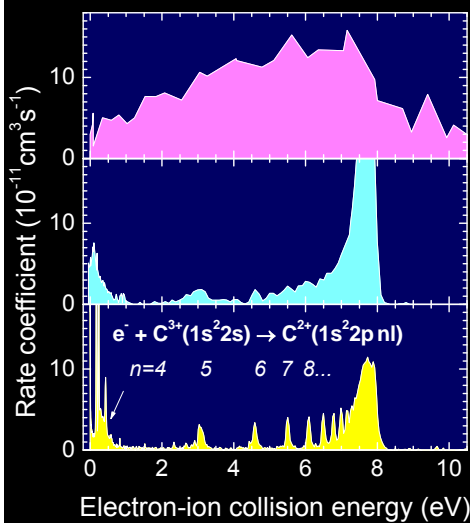


## Recombination of Na-like $\text{Se}^{23+}$



TSR: J. Linkemann et al. (1996)

## Experimental Energy Spread vs. Time (DR of Li-like $\text{C}^{3+}$ )

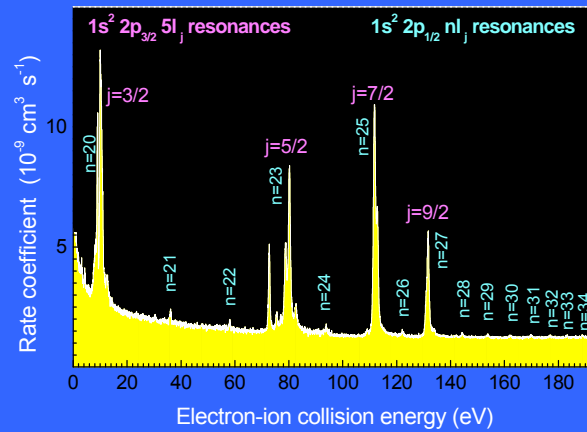


1983: Dittner et al., PRL **51**, 31  
electron beam compression  
no cooling of ion beam  
 $kT_{\perp} = 5000 \text{ meV}$ ,  $kT_{\parallel} = 1 \text{ meV}$

1990: Andersen et al., PRA **41**, 1293  
constant electron-beam diameter  
no cooling of ion beam  
 $kT_{\perp} = 135 \text{ meV}$ ,  $kT_{\parallel} = 1 \text{ meV}$

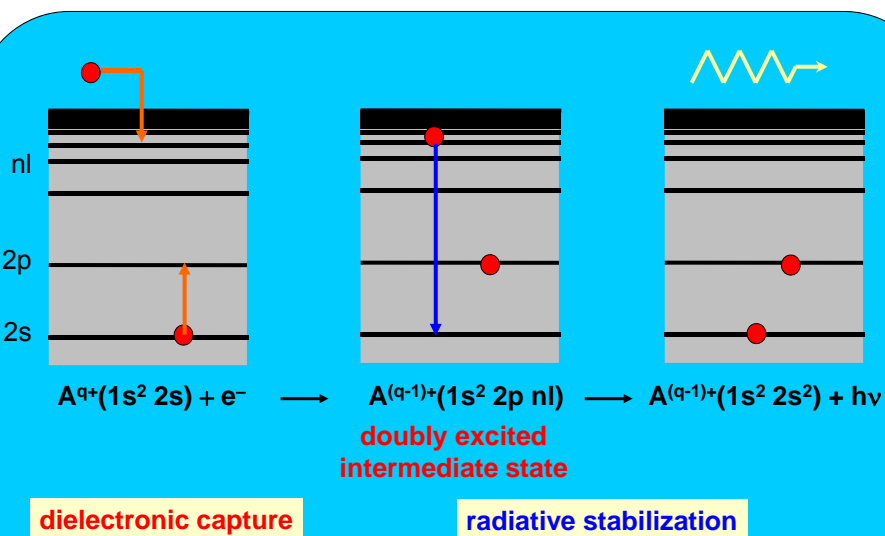
2001: Schippers et al., ApJ **555**, 1027  
electron-beam expansion  
electron cooling of ion beam  
 $kT_{\perp} = 10 \text{ meV}$ ,  $kT_{\parallel} = 0.15 \text{ meV}$

## Recombination of Li-like $U^{89+}$ (ESR experiment)



C. Brandau et al.,  
NIMB 205, 66 (2003)

## Dielectronic Recombination



# Extrapolation of Rydberg Series

$\text{Au}^{75+}(2p_{1/2} nl)$  resonances

