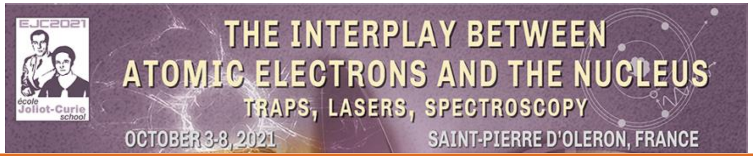
Physics and chemistry of the heaviest elements

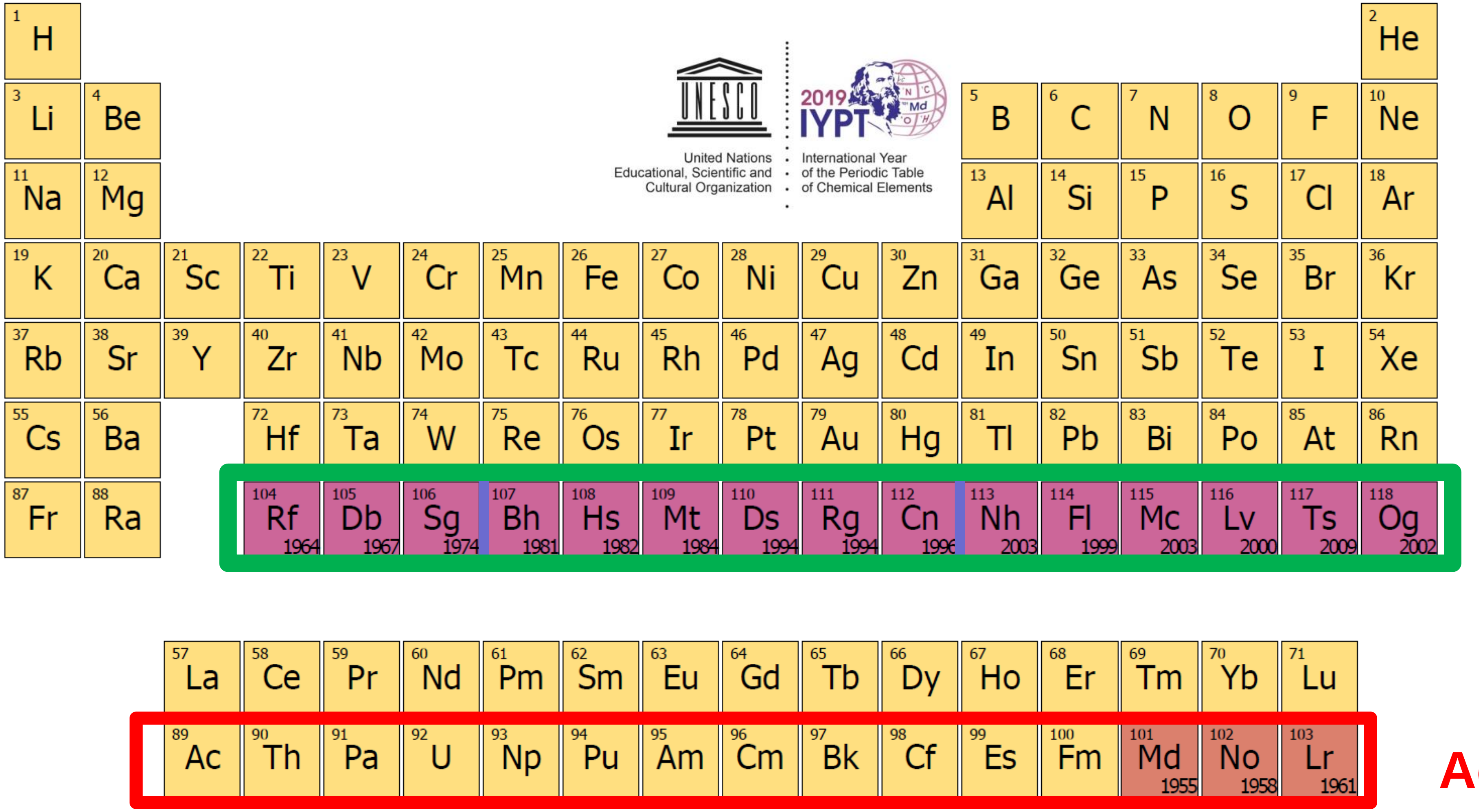
S. Raeder

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany



HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Heavy Elements - The far end of the periodic table

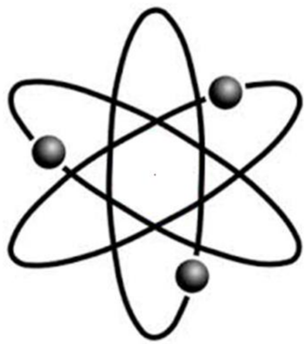


Electron shell

atomic structure

chemical properties

→ defines the element



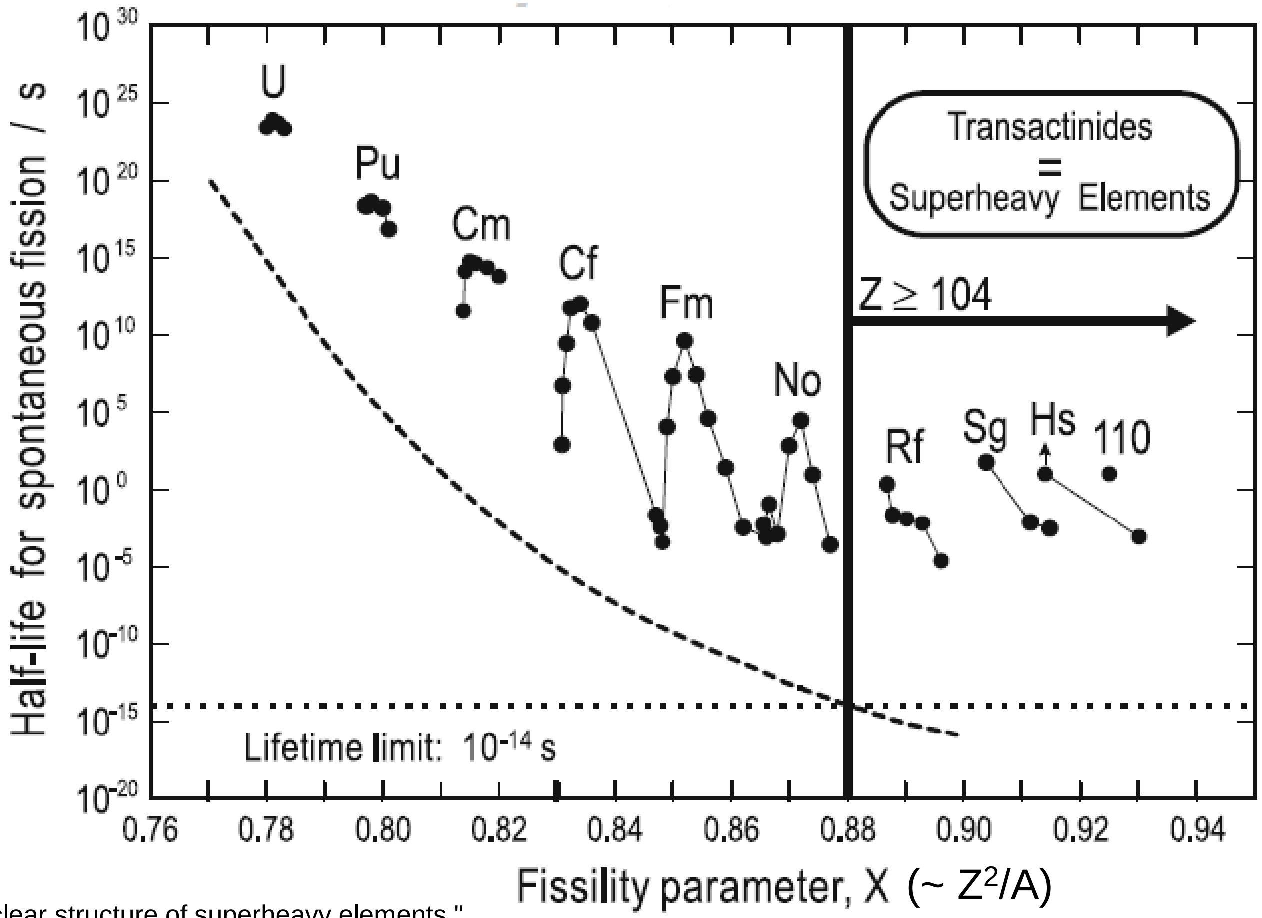
Super Heavy Elements

Actinides

Stabilized from shell effects

Droplet Model (DM):

Z ≥ 104 spontaneous fission is faster then formation of the atom shell

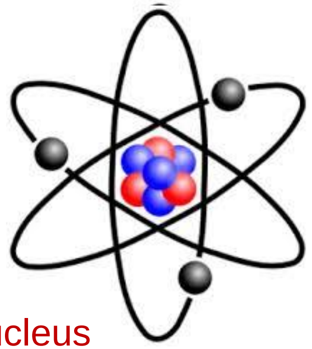


Electron shell

atomic structure

chemical properties

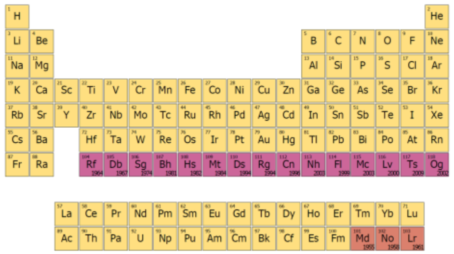
→ defines the element



Nucleus

nuclear structure

stability of elements

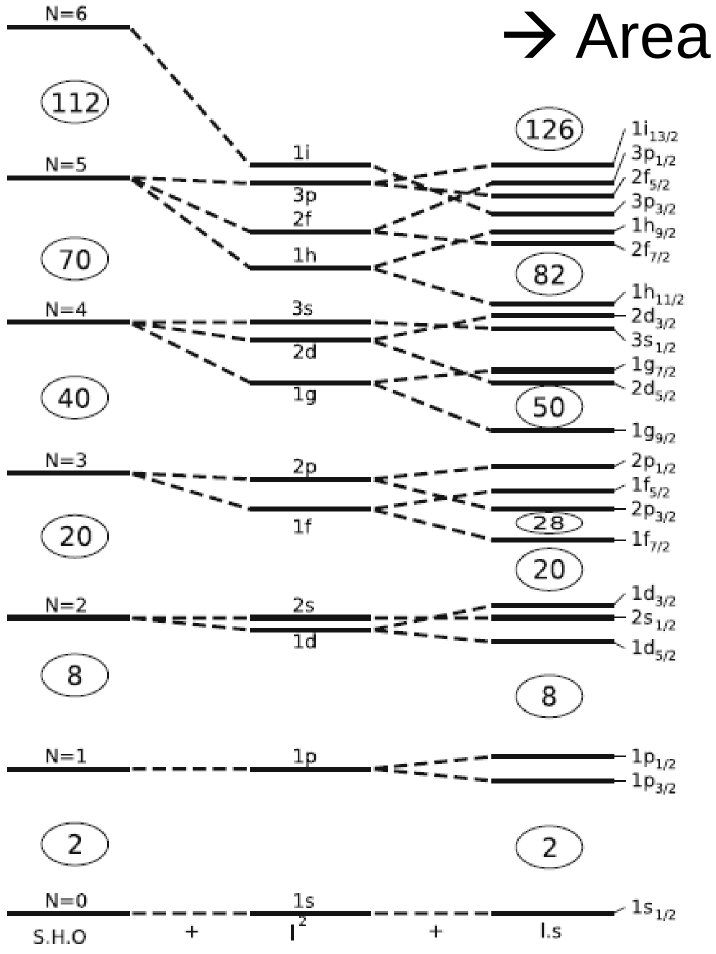


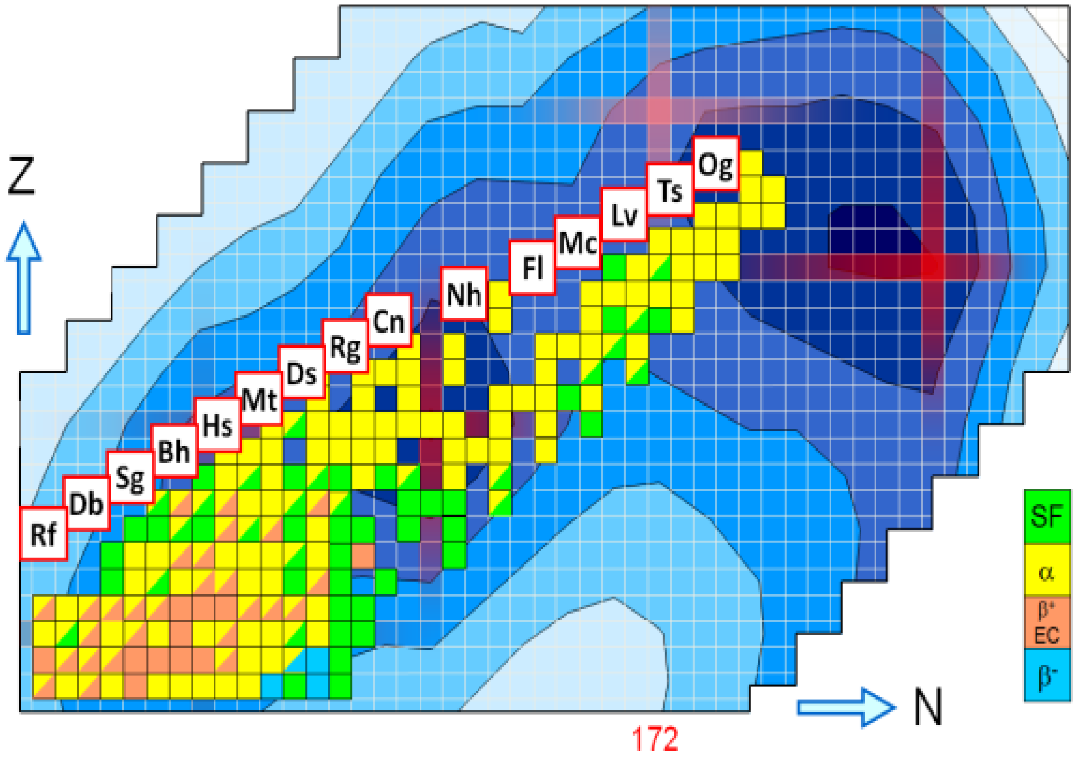
Herzberg, R.-D. "Nuclear structure of superheavy elements." *The chemistry of superheavy elements*. Springer, Berlin, Heidelberg, 2014. 83-133.

Stabilized from shell effects

Additional stabilzation from nuclear shell effects

→ Area of enhanced stabilty around *N*~180



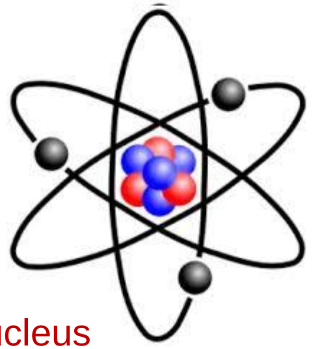


Electron shell

atomic structure

chemical properties

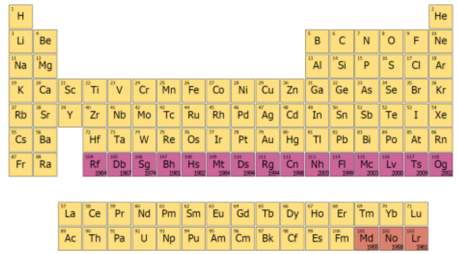
→ defines the element



Nucleus

nuclear structure

stability of elements

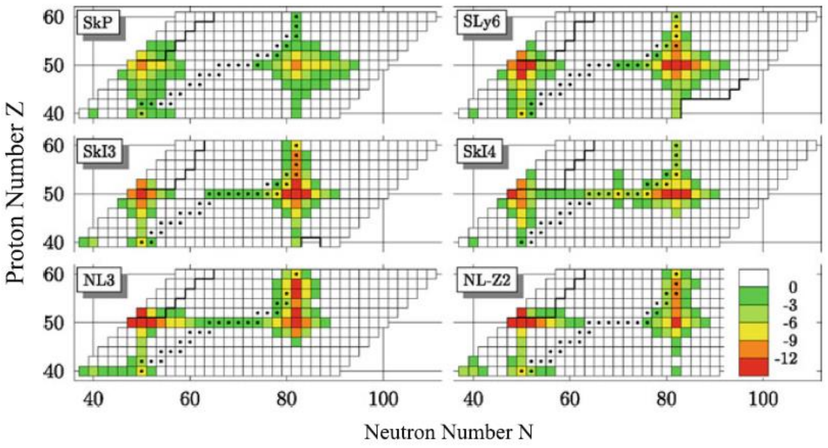


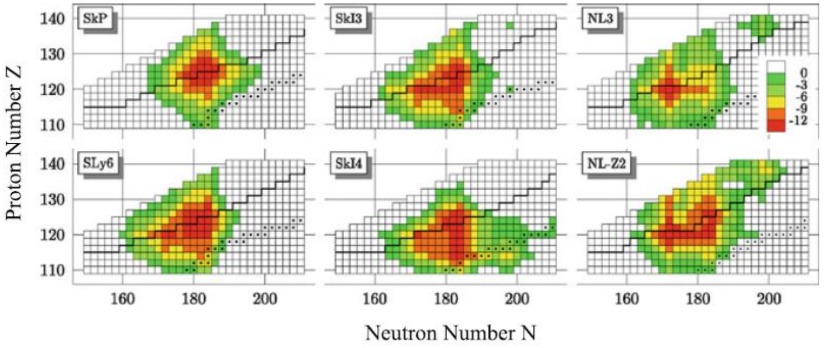
Herzberg, Rolf-Dietmar. "Nuclear structure of superheavy elements." *The chemistry of superheavy elements*. Springer, Berlin, Heidelberg, 2014. 83-133.

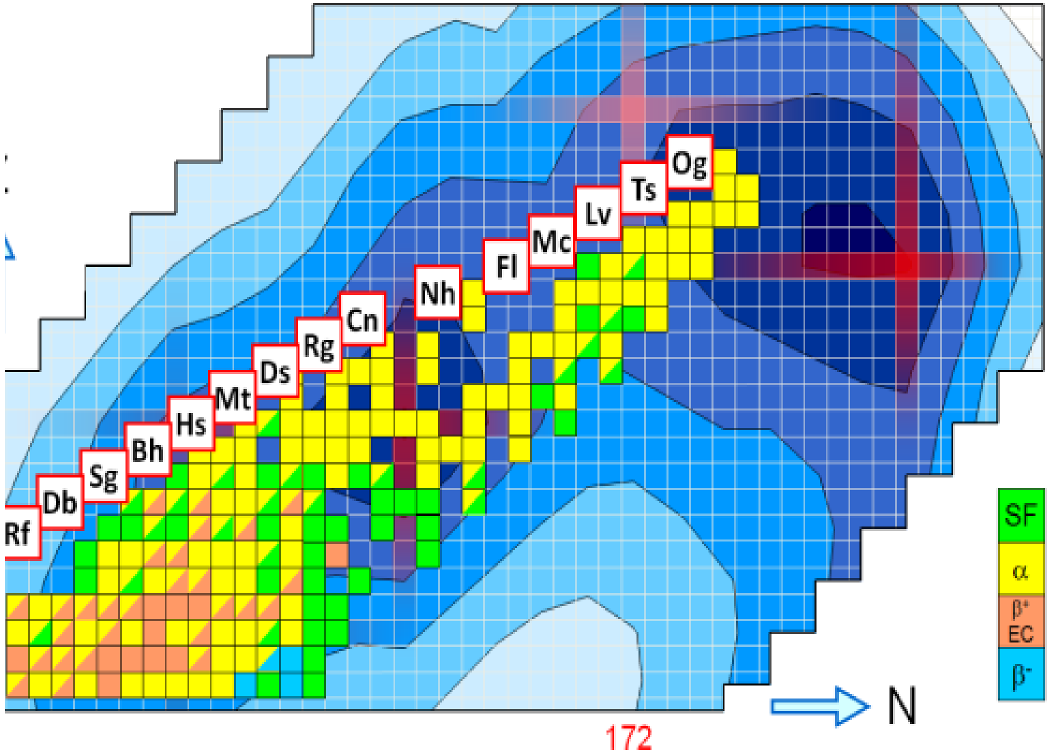
Stabilized from shell effects

Additional stabilzation from nuclear shell effects

→ Area of enhanced stabilty around *N*~180





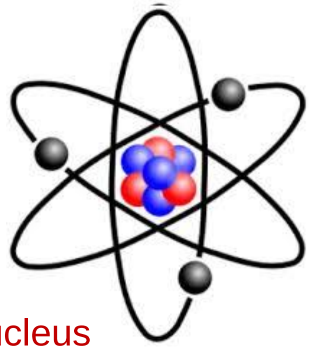


Electron shell

atomic structure

chemical properties

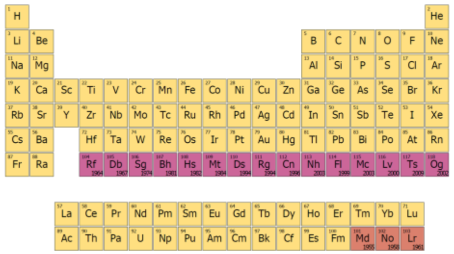
→ defines the element



Nucleus

nuclear structure

stability of elements



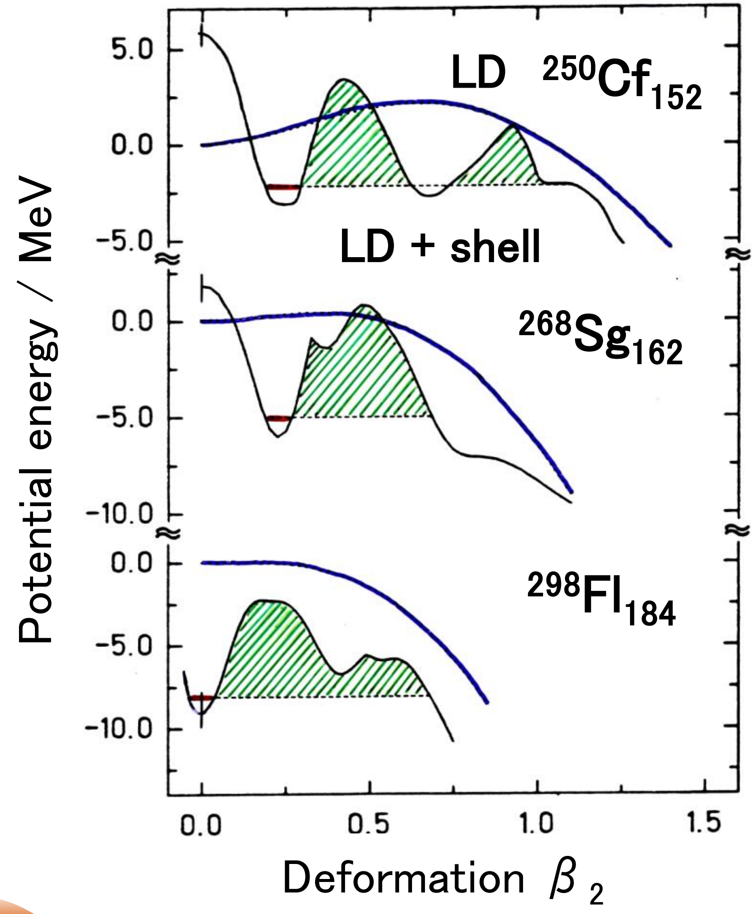
Bender, M., Nazarewicz, W., Reinhard, P.-G.: Shell stabilization of super- and hyper-heavy nuclei without magic gaps. Phys. Lett. B 515, 42–48 (2001)

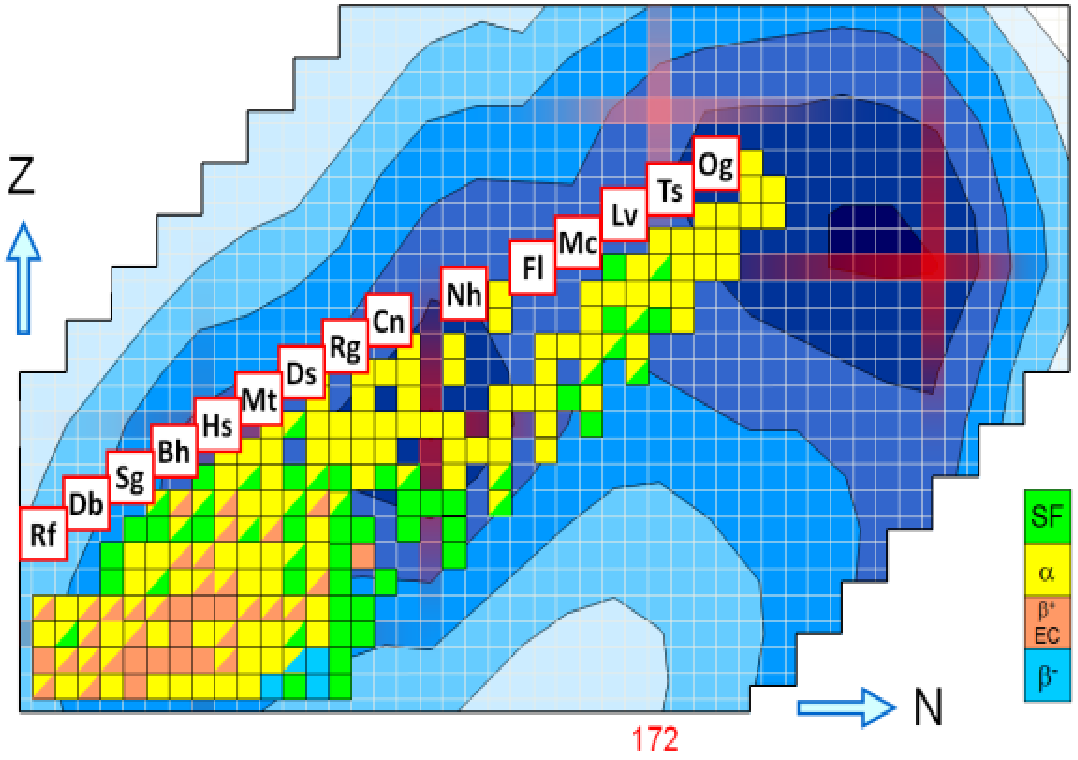
Herzberg, Rolf-Dietmar. "Nuclear structure of superheavy elements." *The chemistry of superheavy elements*. Springer, Berlin, Heidelberg, 2014. 83-133.

Stabilized from shell effects

Additional stabilzation from nuclear shell effects

→ deformation of ground state



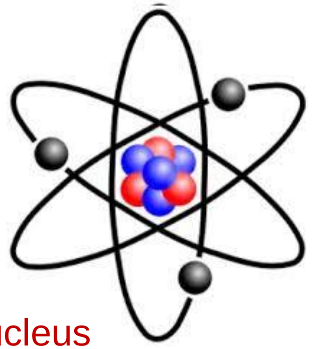


Electron shell

atomic structure

chemical properties

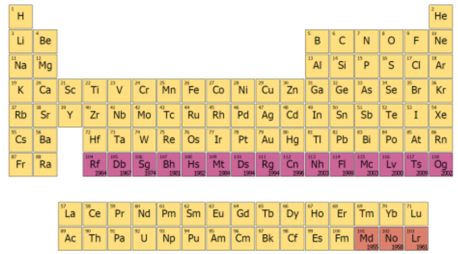
→ defines the element



Nucleus

nuclear structure

stability of elements



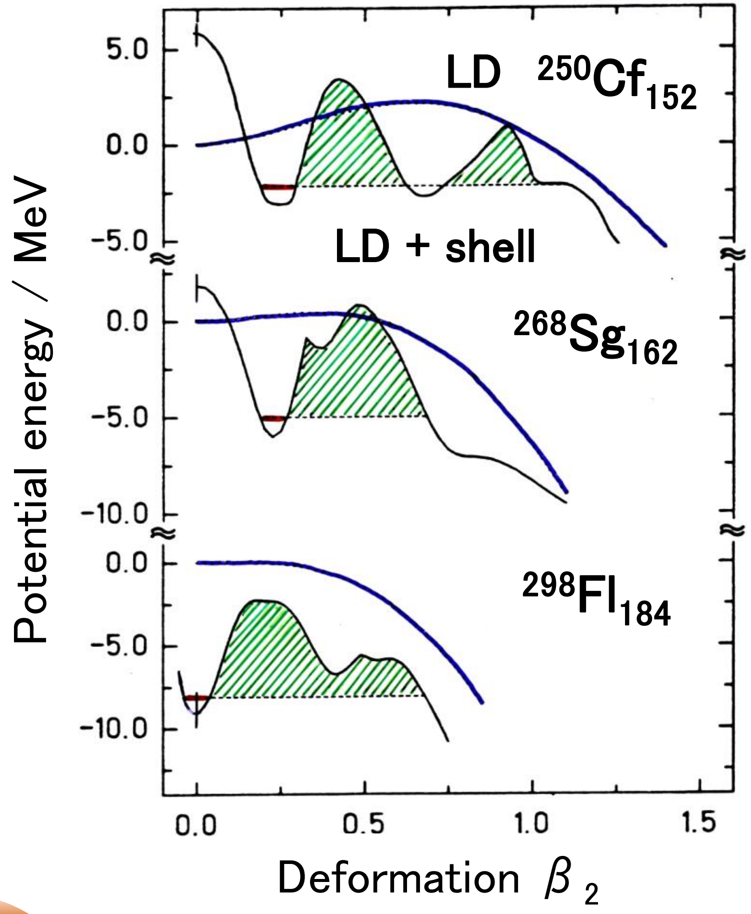
Herzberg, Rolf-Dietmar. "Nuclear structure of superheavy elements." *The chemistry of superheavy elements*. Springer, Berlin, Heidelberg, 2014. 83-133.

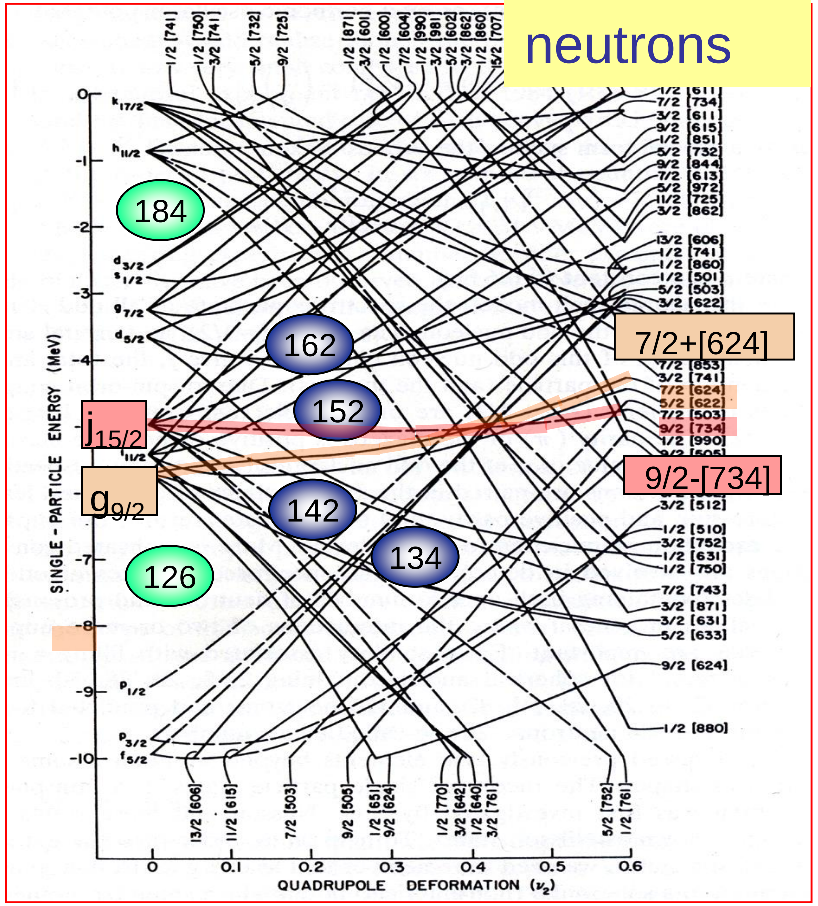
HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Stabilized from shell effects

Additional stabilzation from nuclear shell effects

→ deformation of ground state



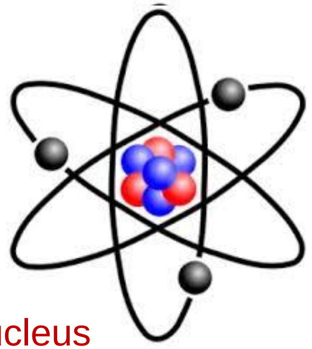


Electron shell

atomic structure

chemical properties

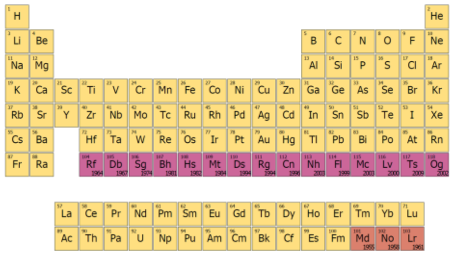
→ defines the element



Nucleus

nuclear structure

stability of elements

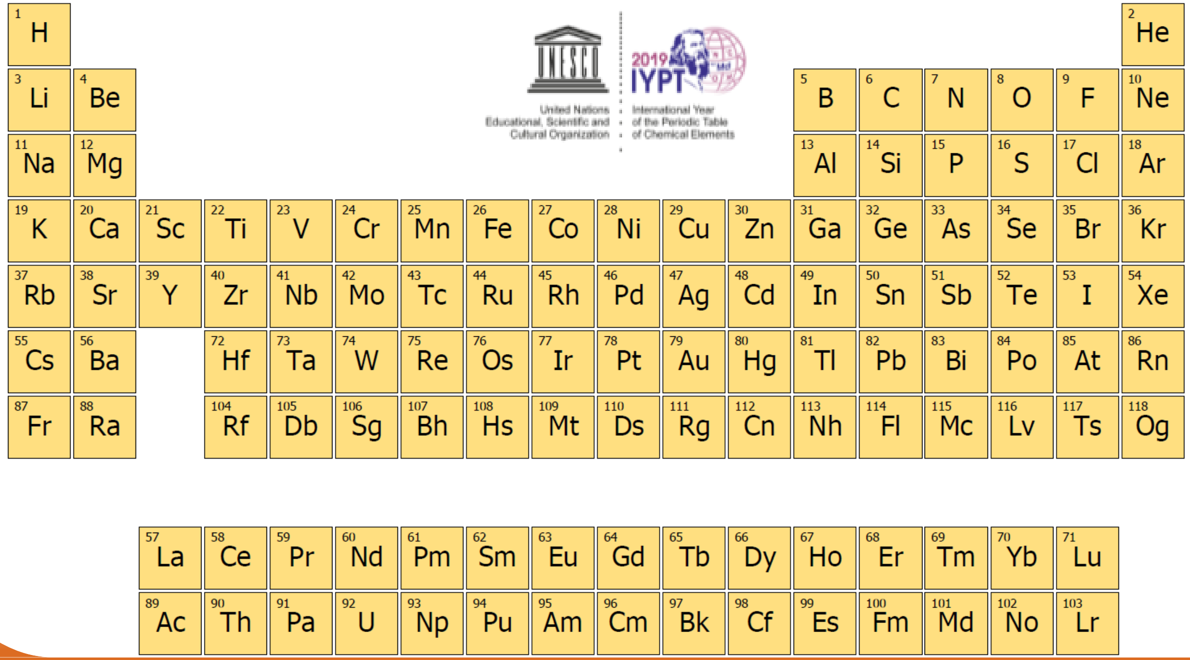


Herzberg, Rolf-Dietmar. "Nuclear structure of superheavy elements."
The chemistry of superheavy elements. Springer, Berlin, Heidelberg, 2014. 83-133.

Heaviest Elements

Elements at the limits of nuclear stability

- Why do SHE exist at all ? → **Shell effects**
- How are they best produced in the lab ?
- What is nuclear structure: binding energies, excitations, shape and sizes
- How do their atomic and chemical properties compare to known (lighter) elements ?

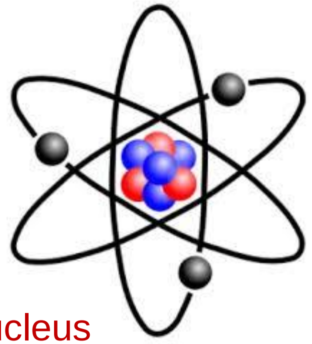


Electron shell

atomic structure

chemical properties

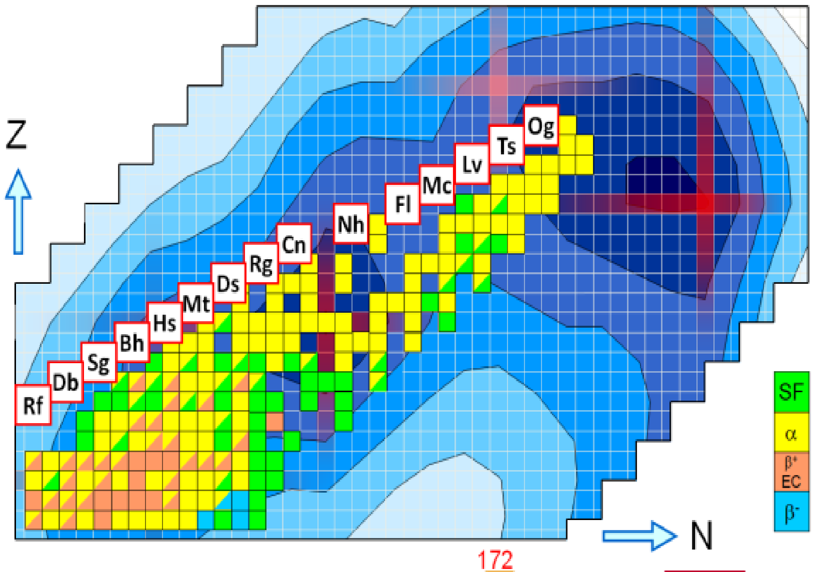
→ defines the element



Nucleus

nuclear structure

stability of elements



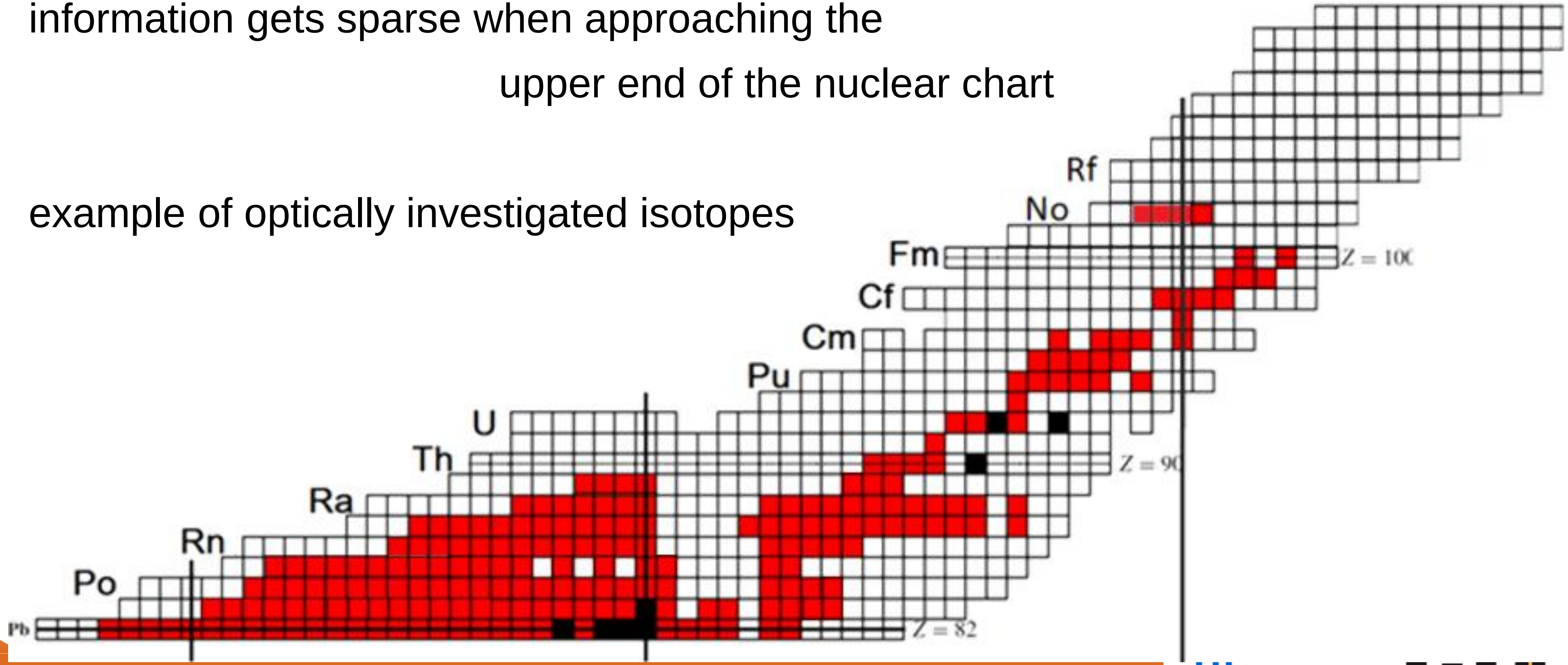
HIM HELMHOLTZ Helmholtz-Institut Mainz · GSI RESEARCH FOR GRAND CHALLENGES · JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Accessing heavy elements

How to access the heaviest elements?

information gets sparse when approaching the
upper end of the nuclear chart

example of optically investigated isotopes



P. Campbell et al., Prog. Part Nucl. Phys 86 (2016) 127

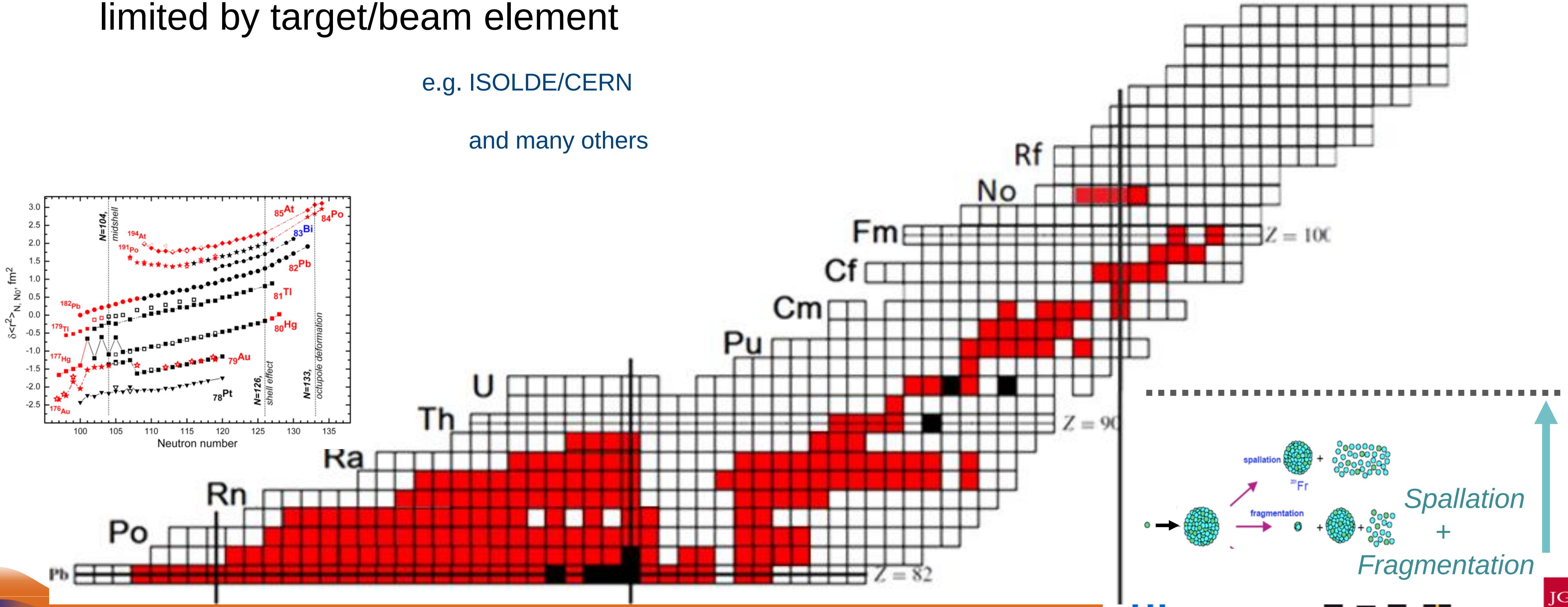
Accessing heavy elements

Spallation and Fragmentation

- large isotope range of light elements
- limited by target/beam element

e.g. ISOLDE/CERN

and many others



P. Campbell et al., Prog. Part Nucl. Phys 86 (2016) 127

Accessing heavy elements

Spallation and Fragmentation

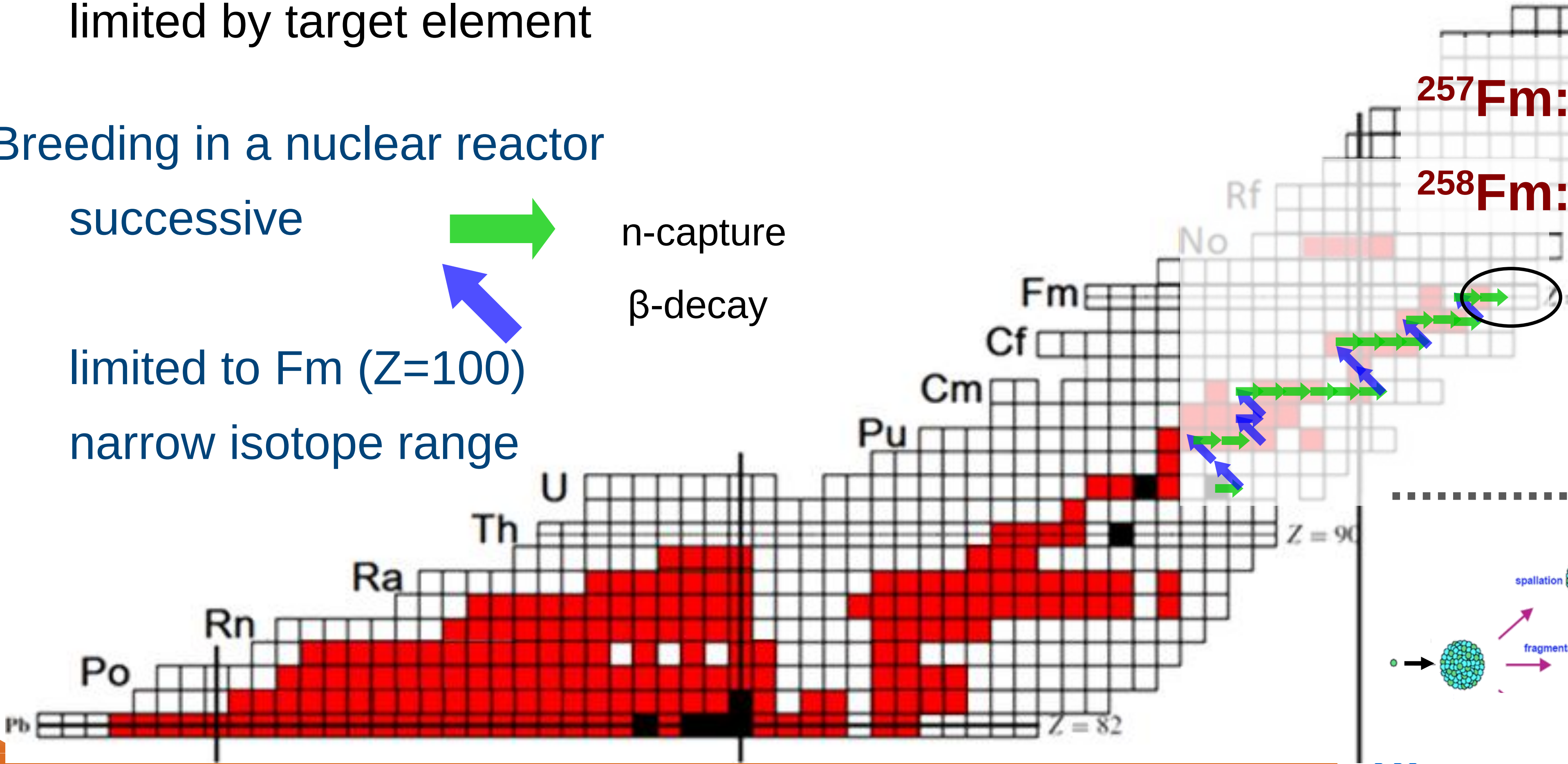
- large isotope range of light elements
- limited by target element

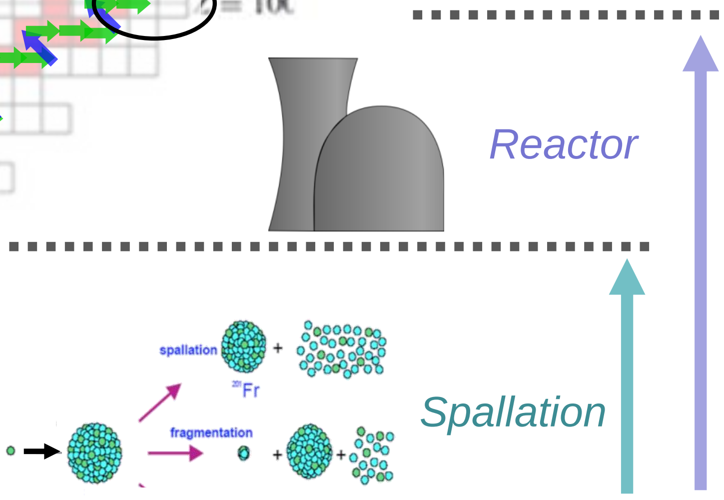
Breeding in a nuclear reactor

- successive — n-capture (green arrow), β-decay (blue arrow)
- limited to Fm (Z=100)
- narrow isotope range

^{257}Fm: $T_{1/2}$=100 d (α)

^{258}Fm: $T_{1/2}$=0.38 ms (SF)

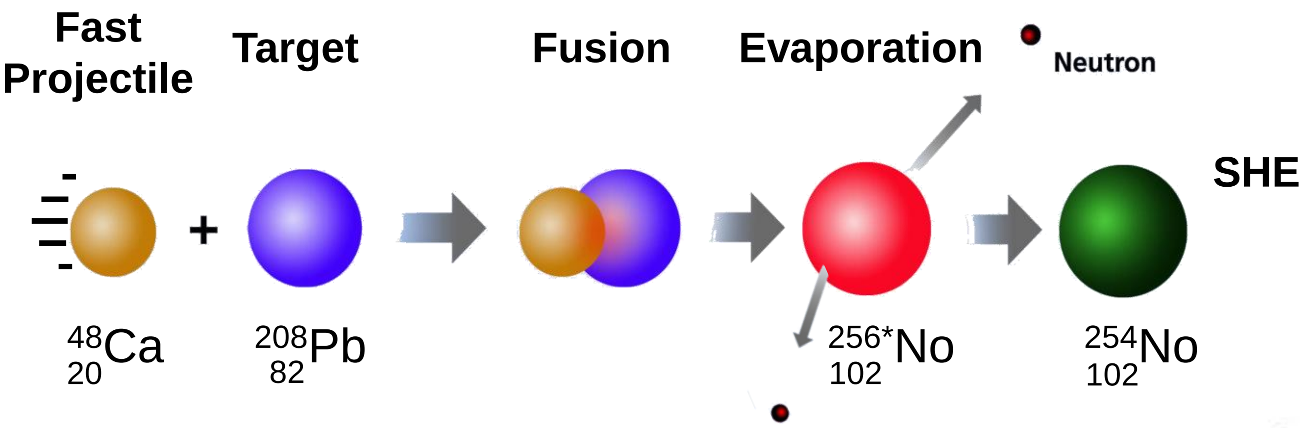


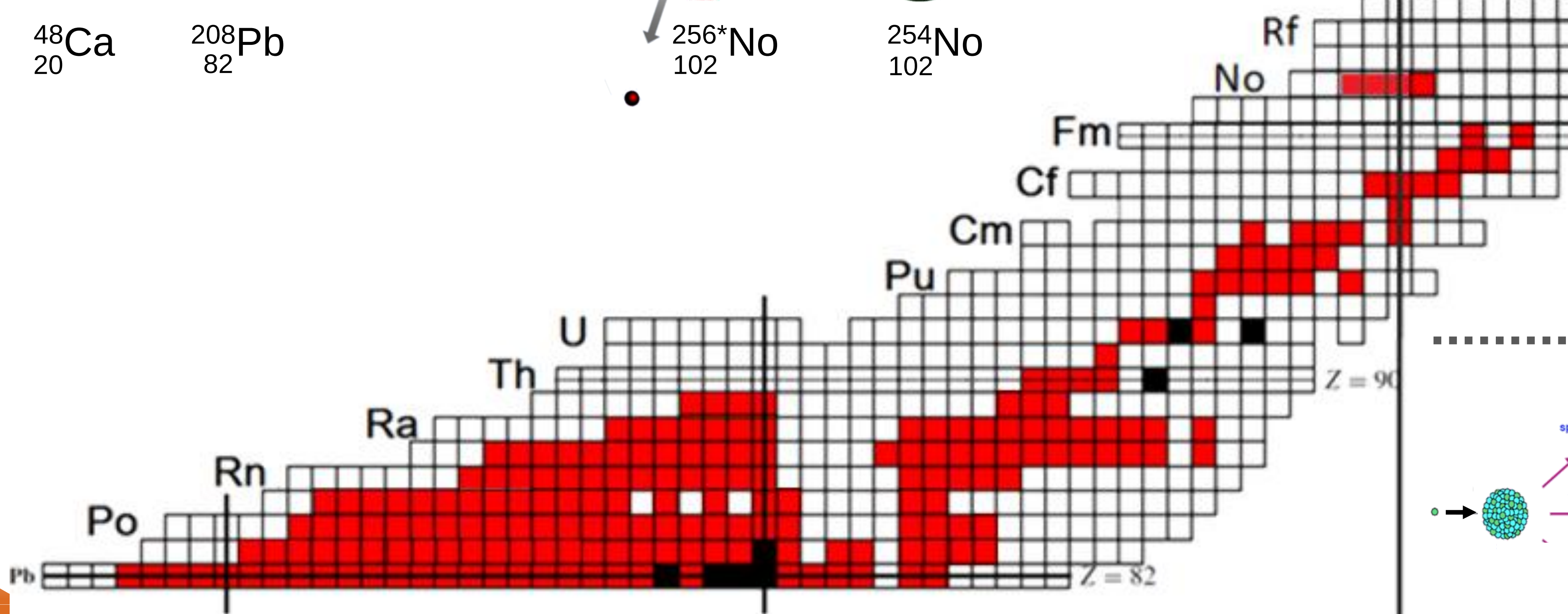


P. Campbell et al., Prog. Part Nucl. Phys 86 (2016) 127

Accessing heavy elements

Fusion evaporation reactions





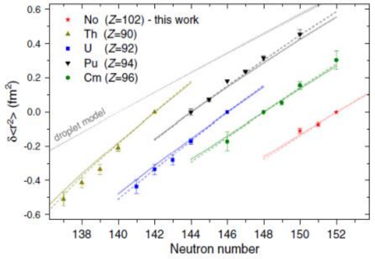
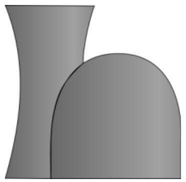
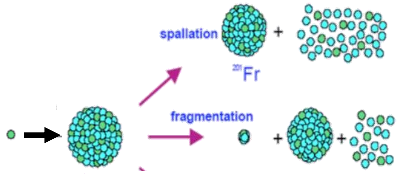


Bild: GSI Helmholtzzentrum für Schwerionenforschung

Accelerator produced



Reactor

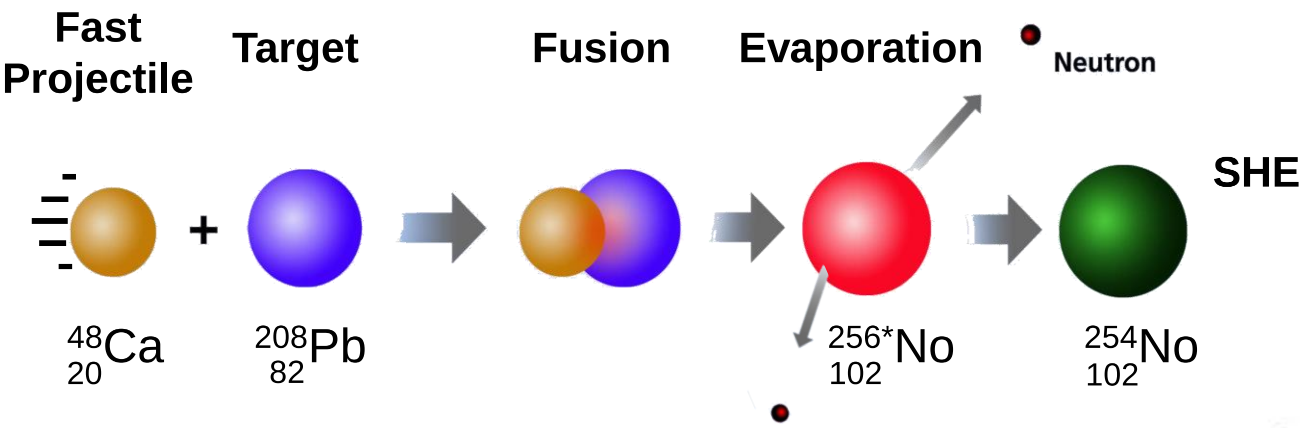


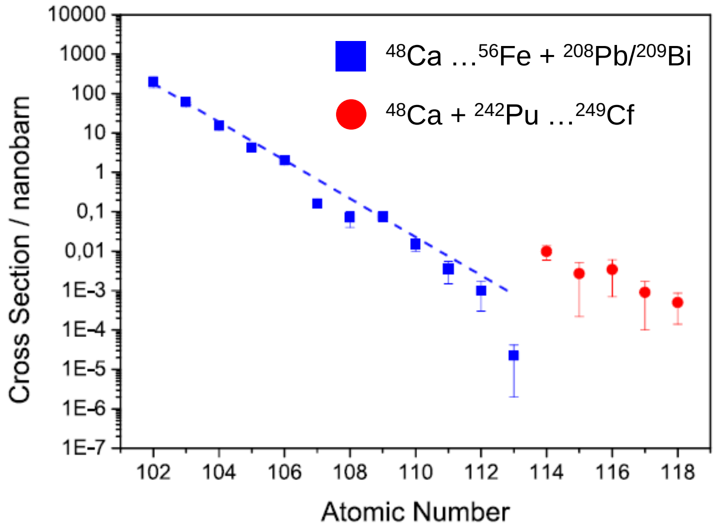
Spallation

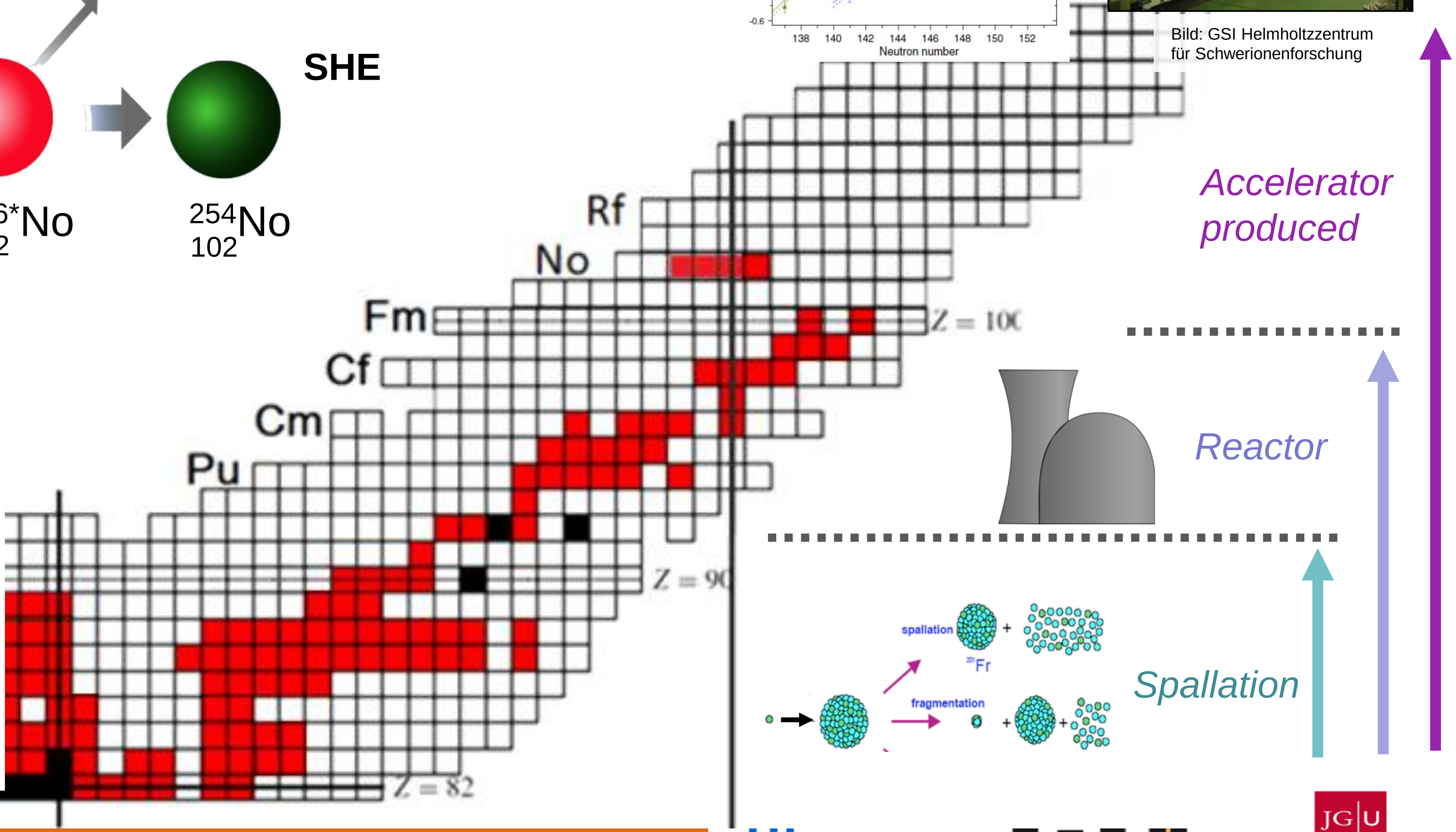
P. Campbell et al., Prog. Part Nucl. Phys 86 (2016) 127

Accessing heavy elements

Fusion evaporation reactions







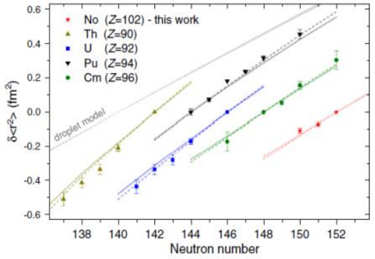
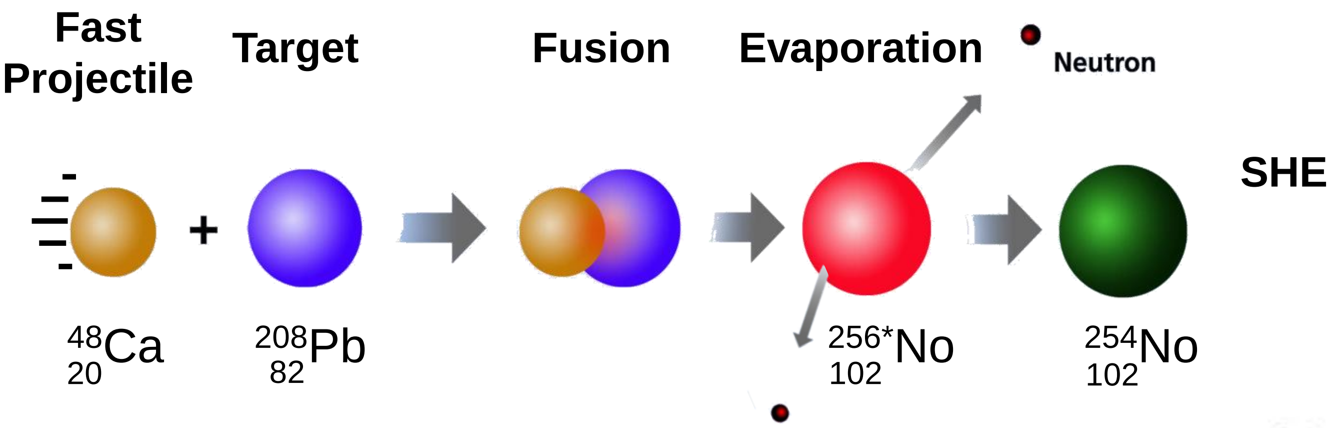


Bild: GSI Helmholtzzentrum für Schwerionenforschung

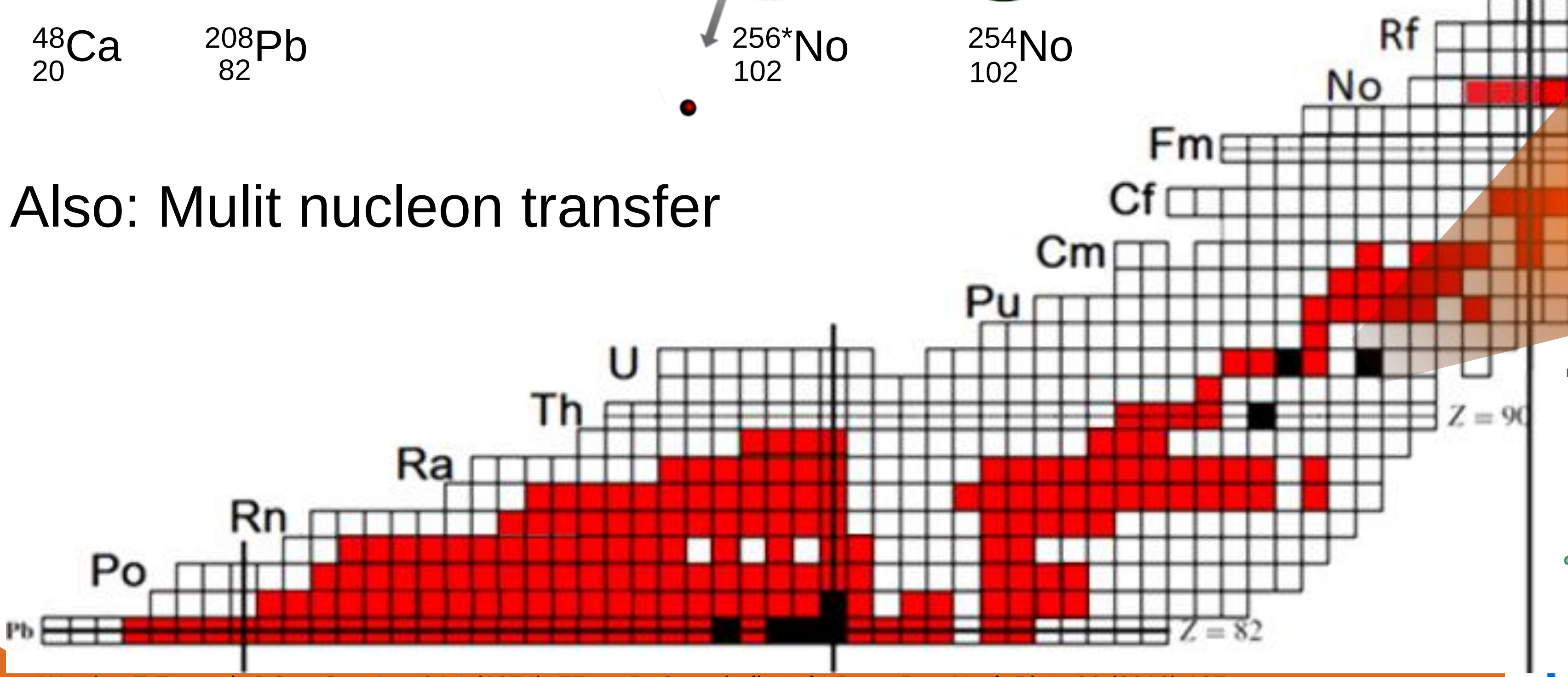
P. Campbell et al., Prog. Part Nucl. Phys 86 (2016) 127

Accessing heavy elements

Fusion evaporation reactions



Also: Mulit nucleon transfer



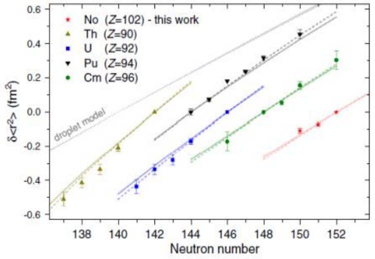
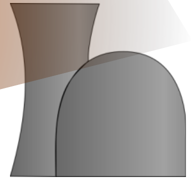
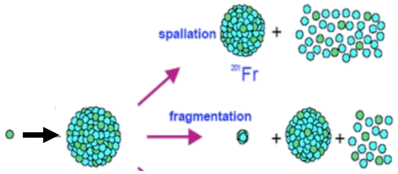


Bild: GSI Helmholtzzentrum für Schwerionenforschung

Accelerator produced



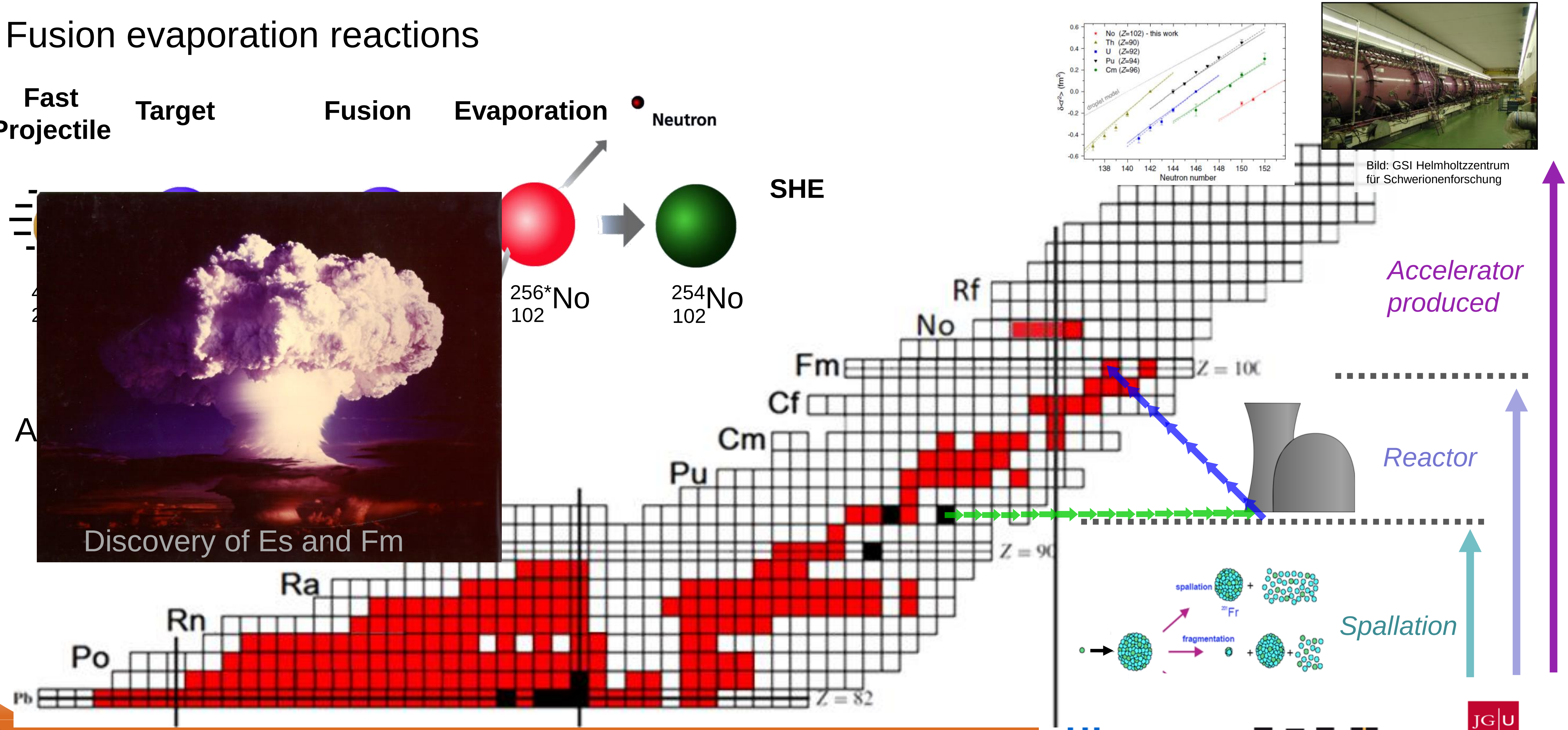
Reactor



Spallation

Accessing heavy elements

Fusion evaporation reactions

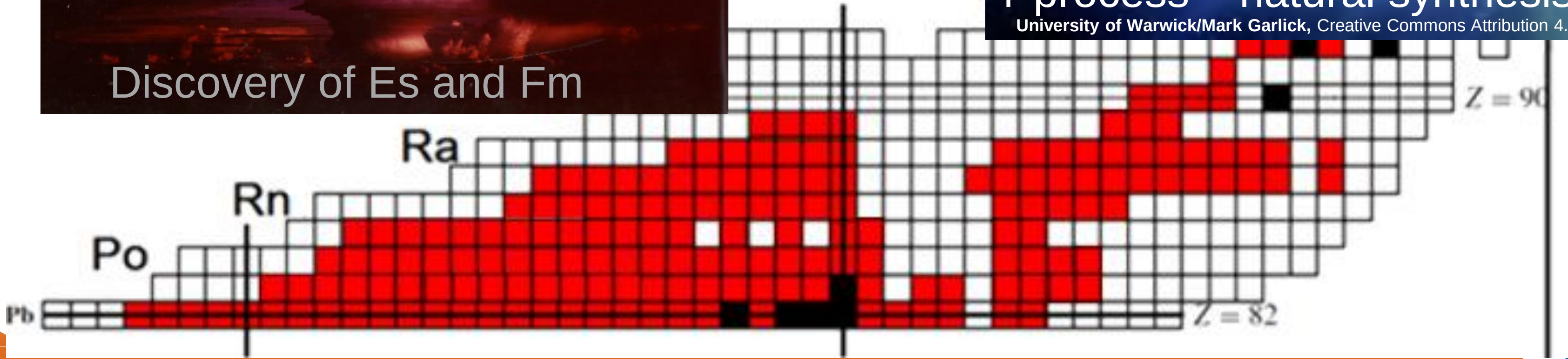


The New Elements Einsteinium and Fermium, Atomic Numbers 99 and 100, Ghiorso, A. et al, June 9, 1955.

Accessing heavy elements

Fusion evaporation reactions

Fast Projectile **Target** **Fusion** **Evaporation** **Neutron**



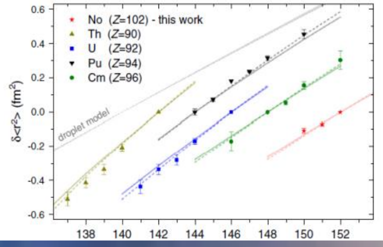
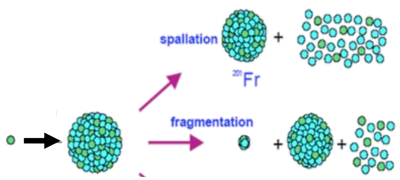


Bild: GSI Helmholtzzentrum ...werionenforschung

...ccelerator ...roduced

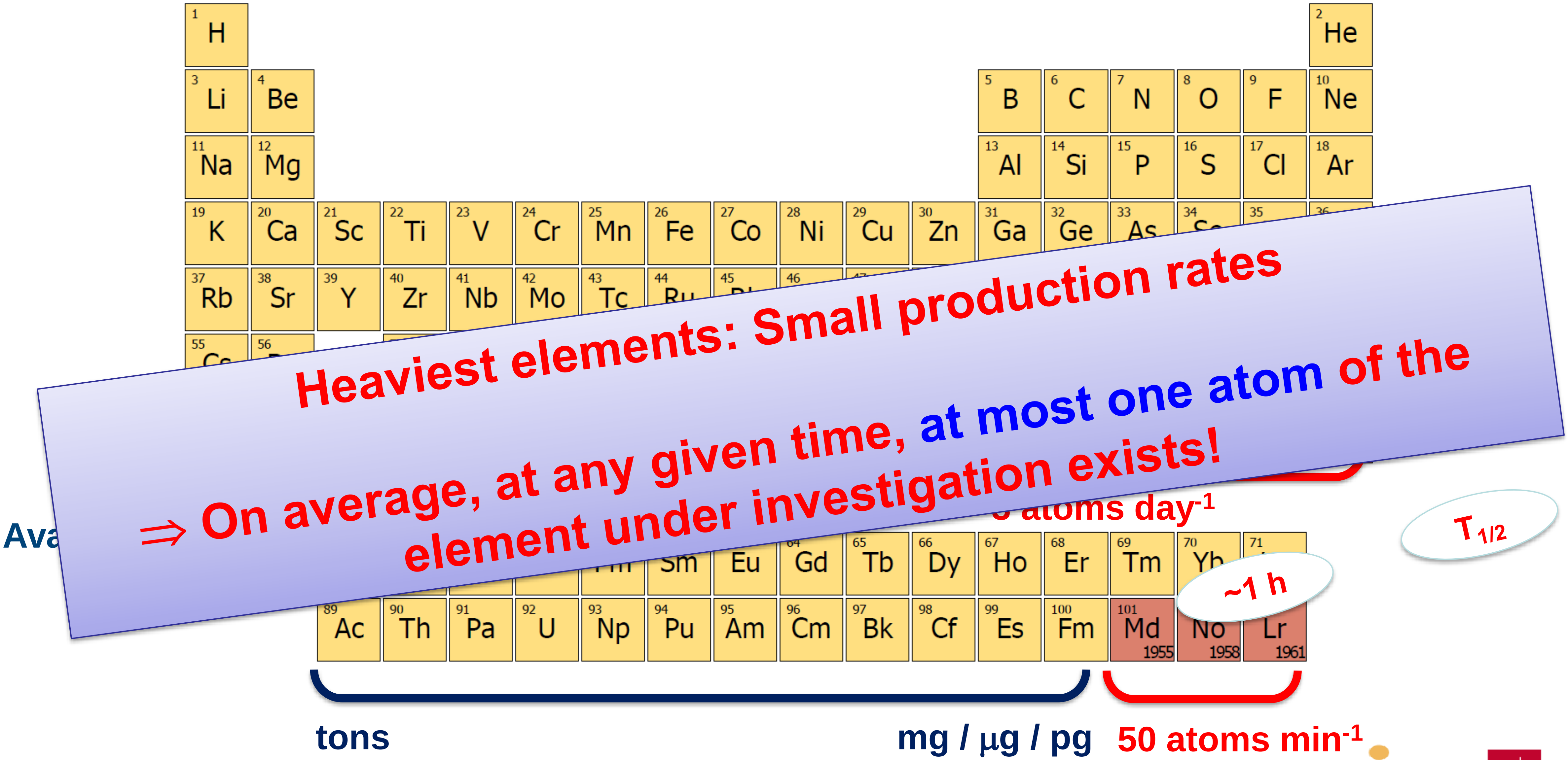
...eactor



Spallation

The New Elements Einsteinium and Fermium, Atomic Numbers 99 and100, Ghiorso, A. et al, June 9, 1955.

Heavy Elements - The far end of the periodic table



Heaviest elements: Small production rates

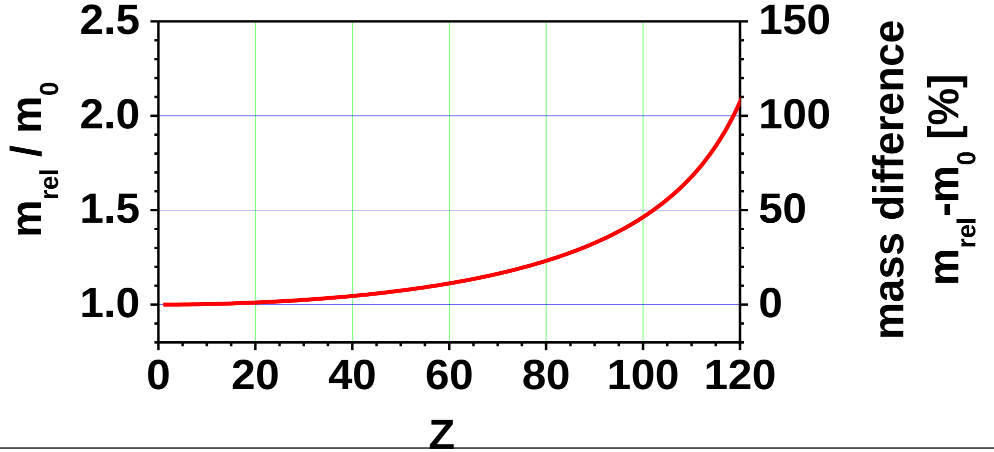
⇒ On average, at any given time, at most one atom of the element under investigation exists!

Influence of Relativity on Atomic and Chemical Properties

Relativistic speed of electrons near the atomic nucleus → mass increase

Scaling: ~Z^2

⇒ **most pronounced in SHE**



Relativistic effects

1) Direct effect:

$s_{1/2}$; $p_{1/2}$: ⇒ **stabilized / contracted**

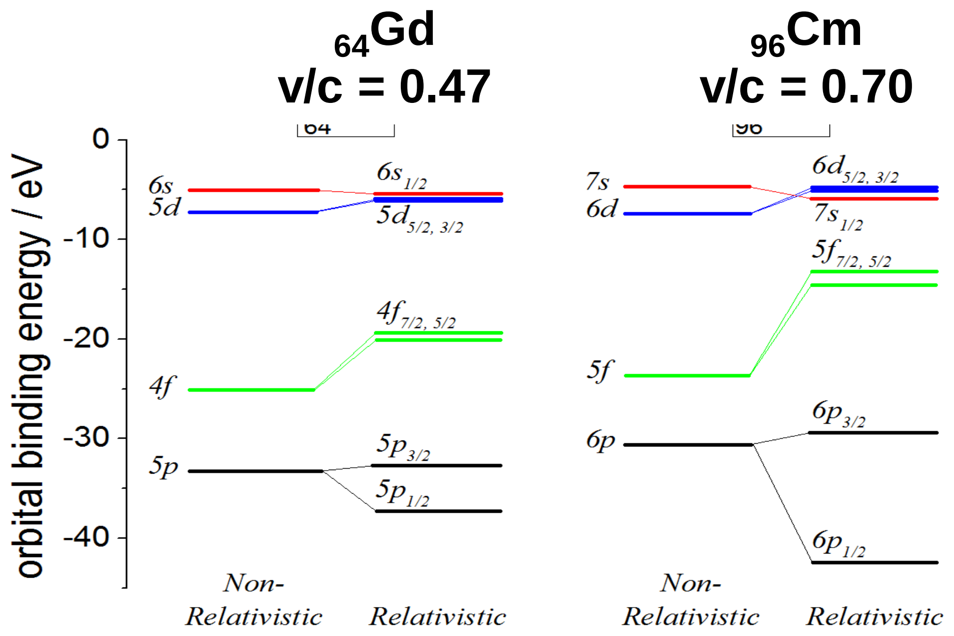
2) Indirect effect:

$p_{3/2}$; d; f: **better shielded from core ⇒destabilized / expanded**

3) Spin-orbit splitting:

$p \rightarrow p_{1/2}/p_{3/2}$; $d \rightarrow d_{3/2}$; $d_{5/2}$; ..

jj-coupling lifts energy. degeneracy

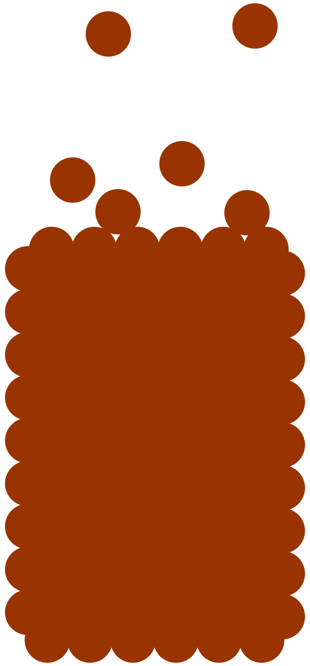


J.P. Desclaux, At. Data Nucl. Data Tab. 12 (1973) 311

Chemistry with limited number of atoms

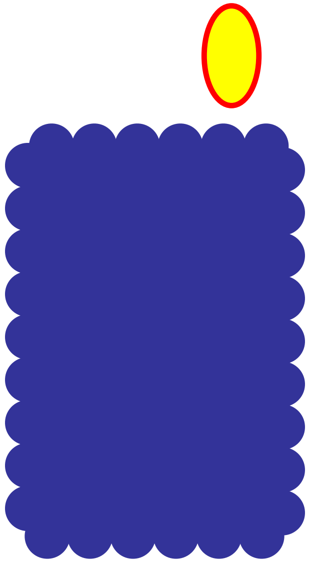
Classical chemistry ⇔ Atom-at-a-time

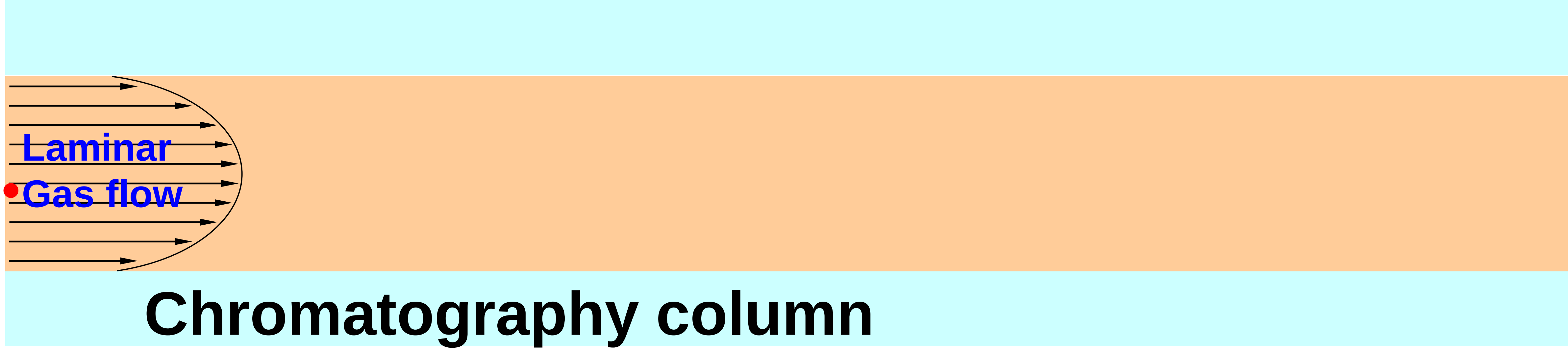
Classical chemistry	Atom-at-a-time
Macroamount	**Microamount**
$10^{\sim 20}$ atoms	**1 atom**



Gas

Solid





Strength of interaction is expressed by adsorption enthalpie ΔH_{ads} of A on B

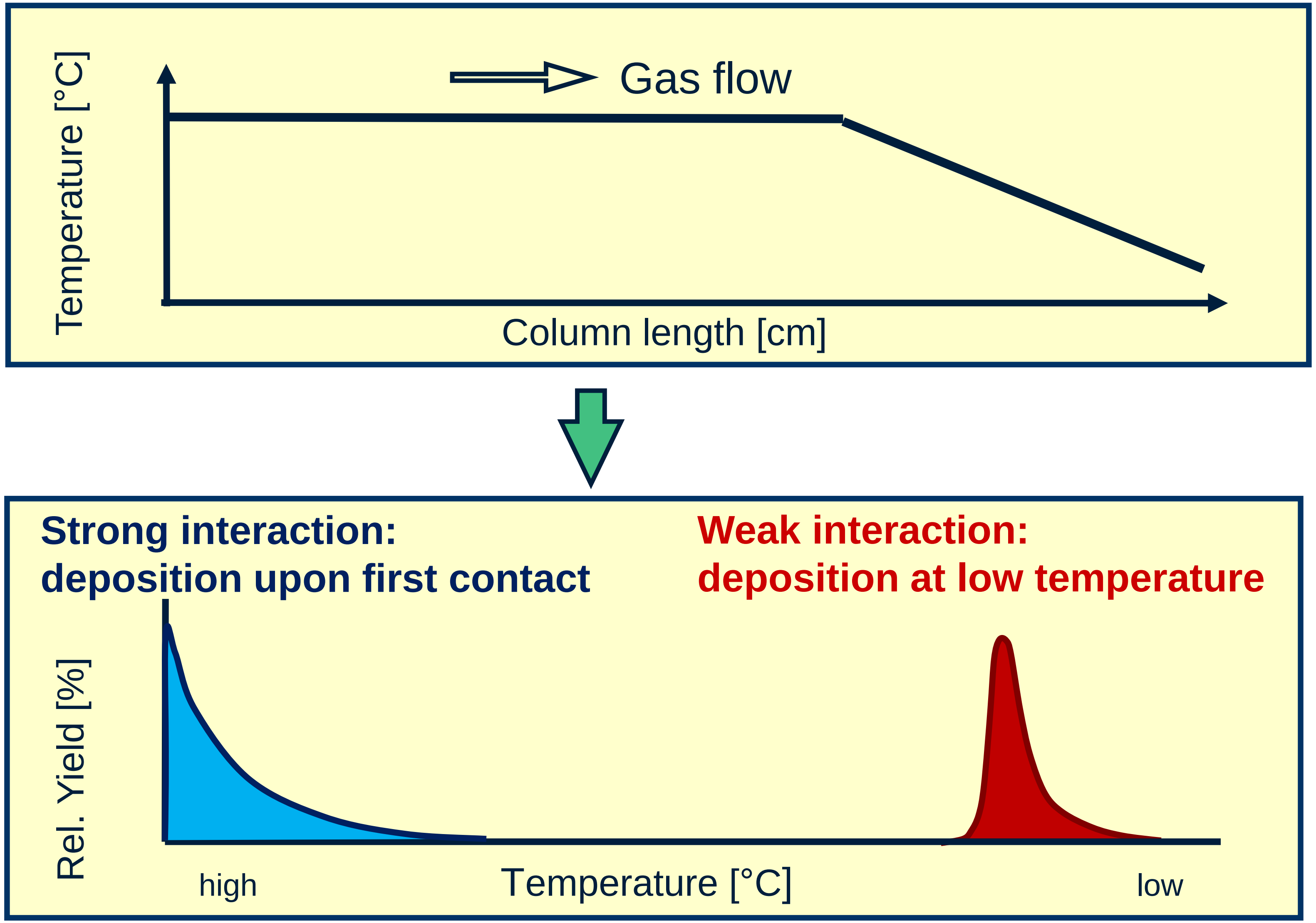
Mean time spent in adsorbed state:

Frenkel-Equation

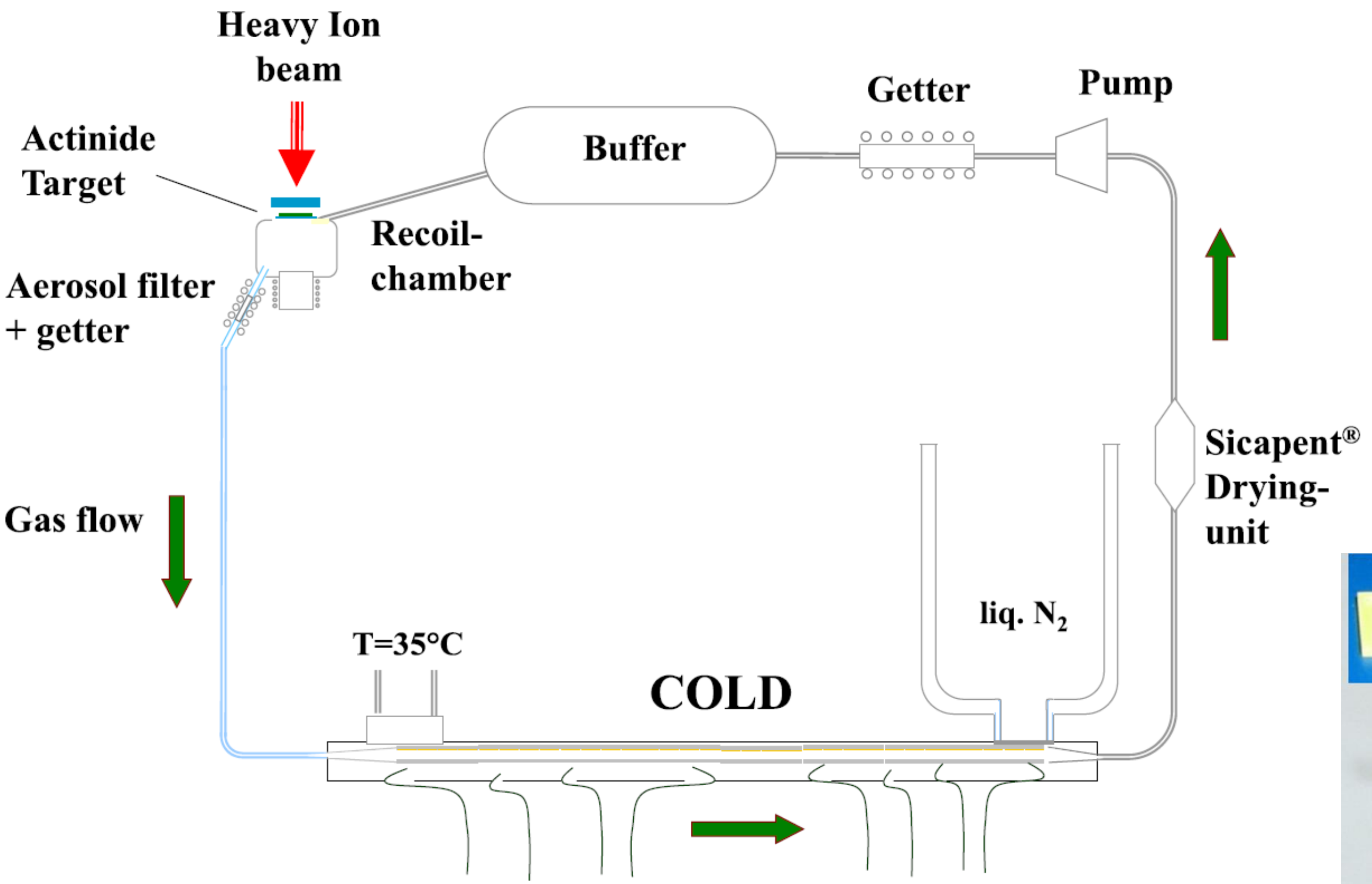
$$\tau = \tau_0 \cdot e^{-\frac{\Delta H_{ads}}{R \cdot T}}$$

R: Gas constant; T: column temperature; τ_0=characteristic time of oscillation of the column material; e.g., SiO_2: $2.2 \cdot 10^{-13}$ s

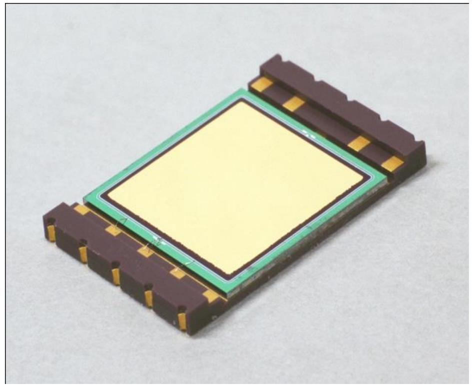
Gas phase chromotography

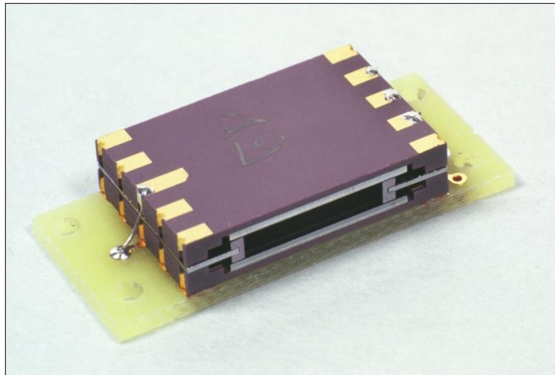


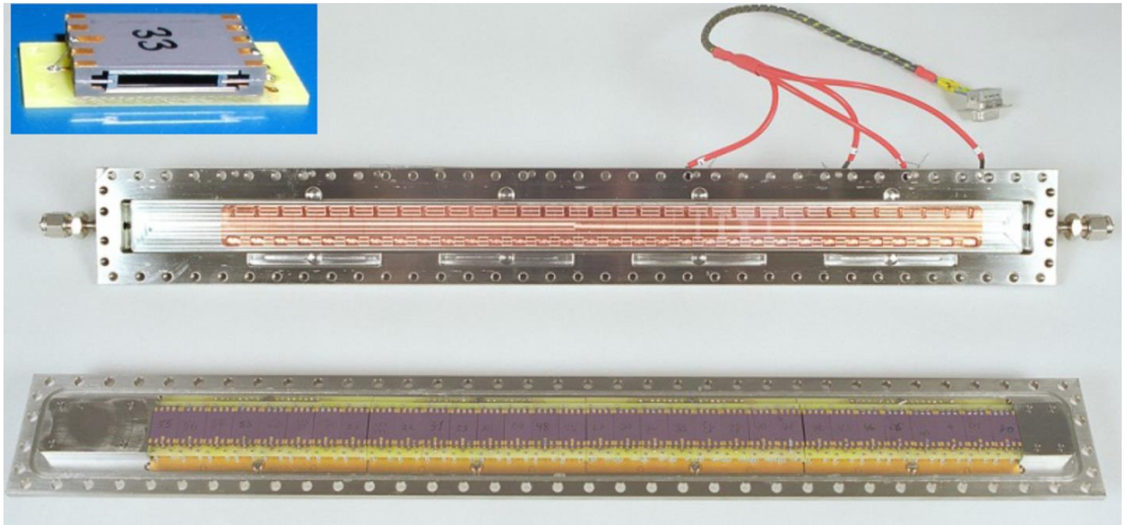
Experimental setup for Cn (Z=112) chemistry (PSI,FLNR)



Cryo-On-Line Detector

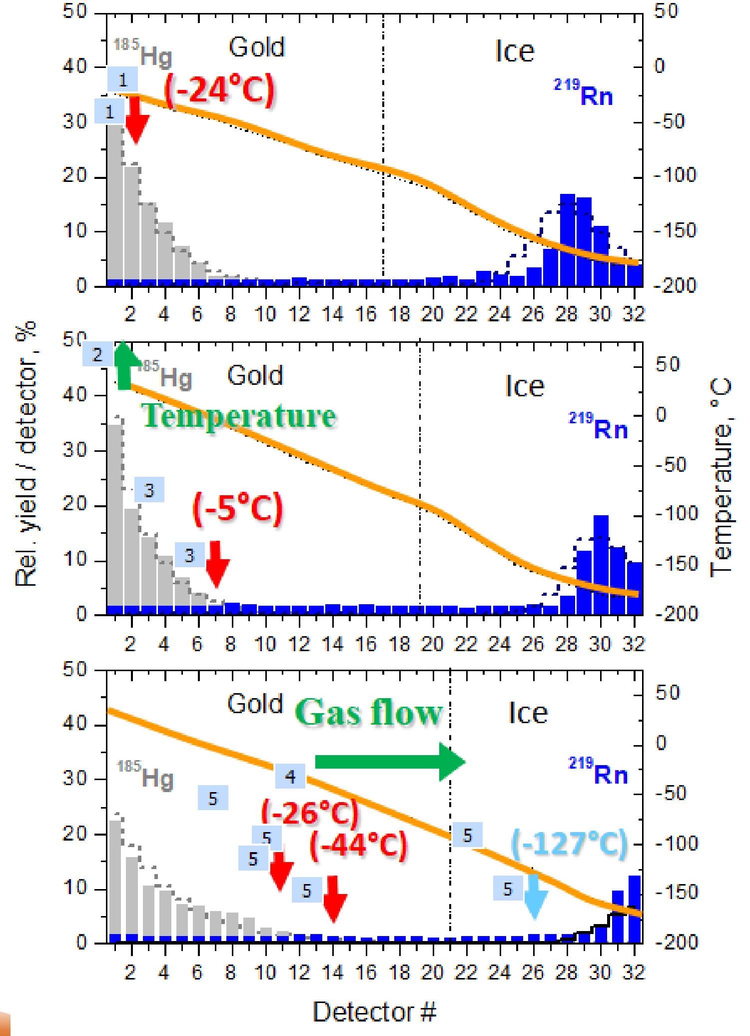


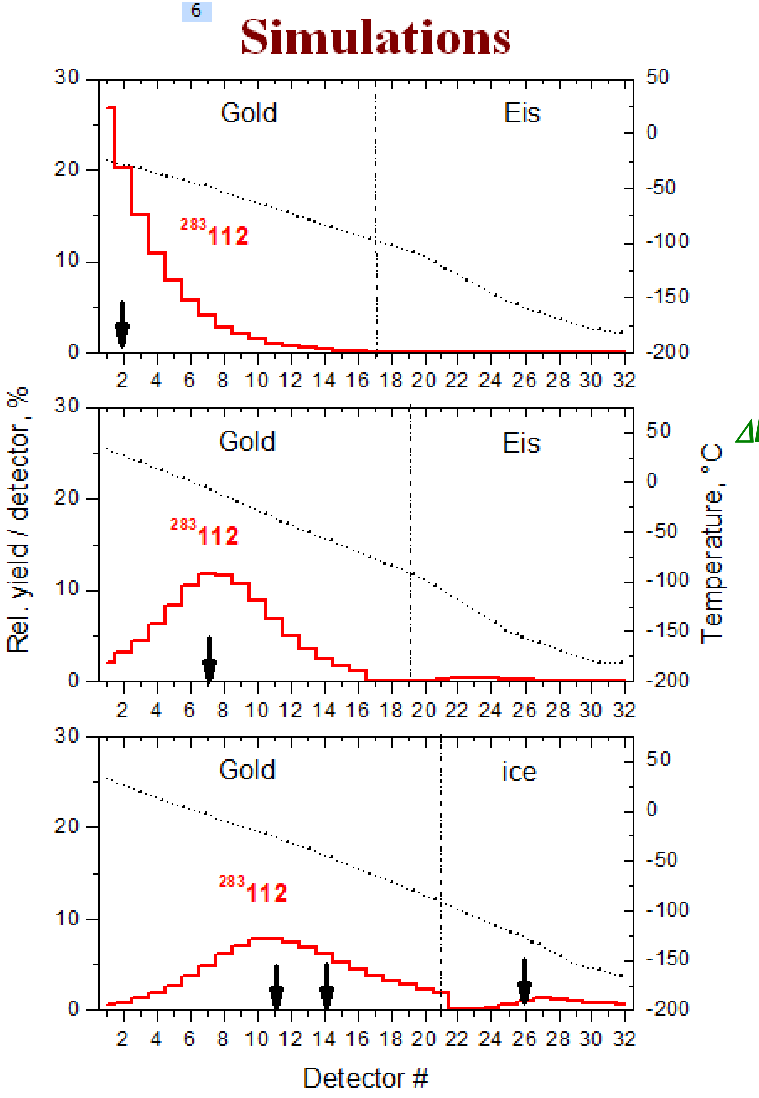


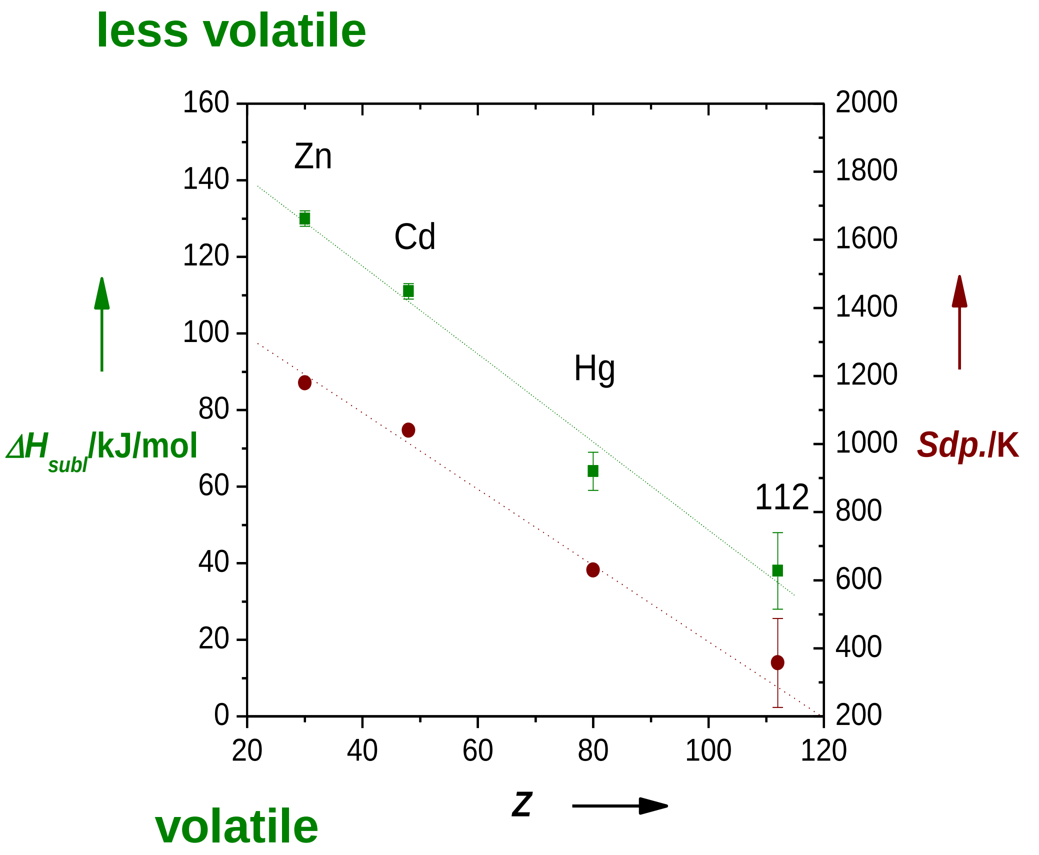


A. Türler et al., Nucl. Phys. A 944 (2015)

Volatility of Cn (Z=112)







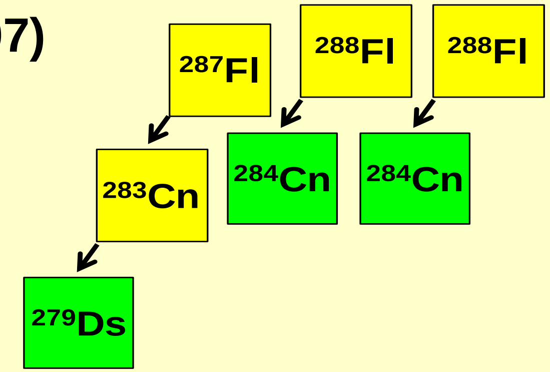
Cn keeps the trend in group 112

→ 5 Atoms required

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Fl (Z=114) chemistry experiments

PSI/Dubna (2007)
35 days

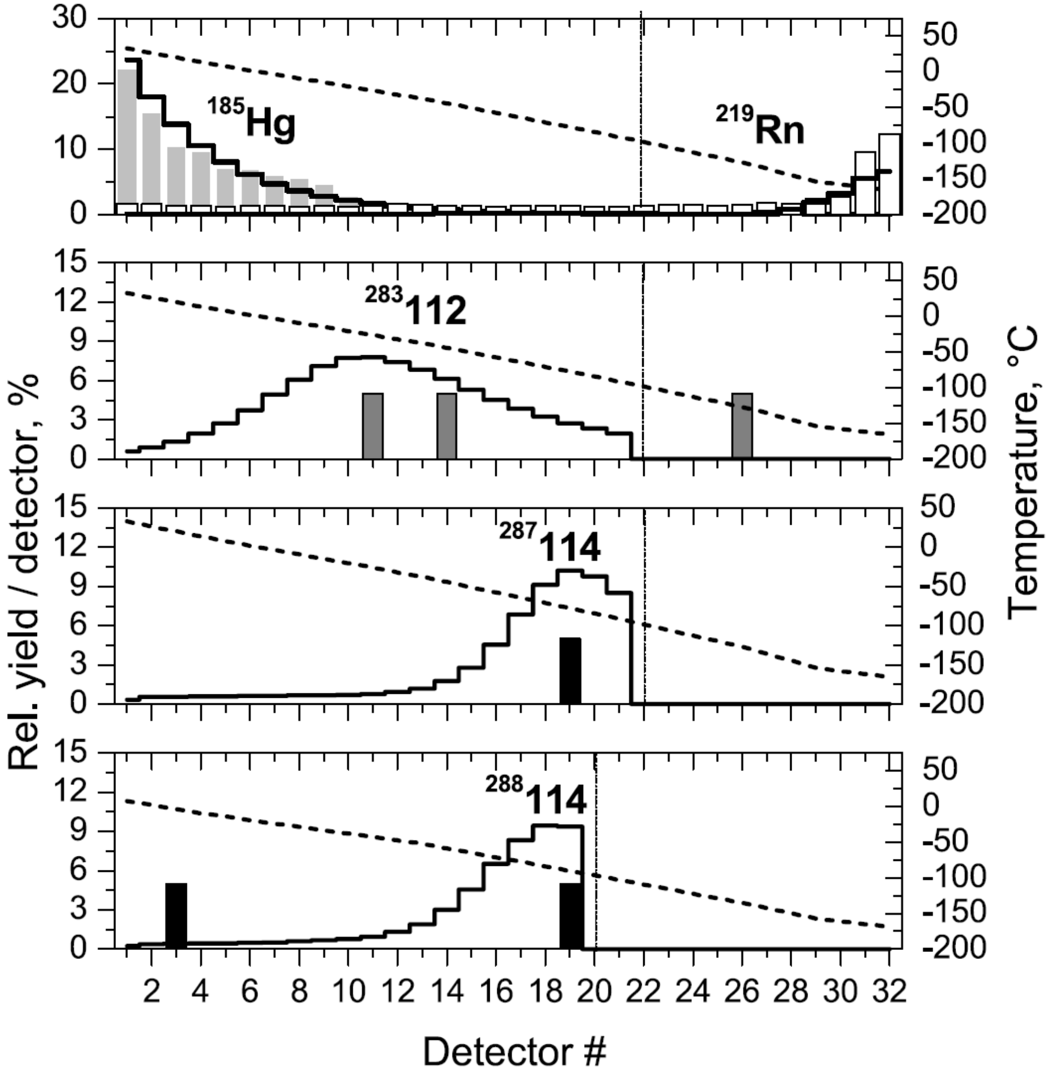


Conclusion: physisorption bond with Au

R. Eichler et al., Radiochim. Acta 98 (2010) 133

$$-\Delta H_{ads}(Au)$$

Theory	Experiment
Pb > **114** ≅ Hg **> 112**	Hg **> 112 > 114**

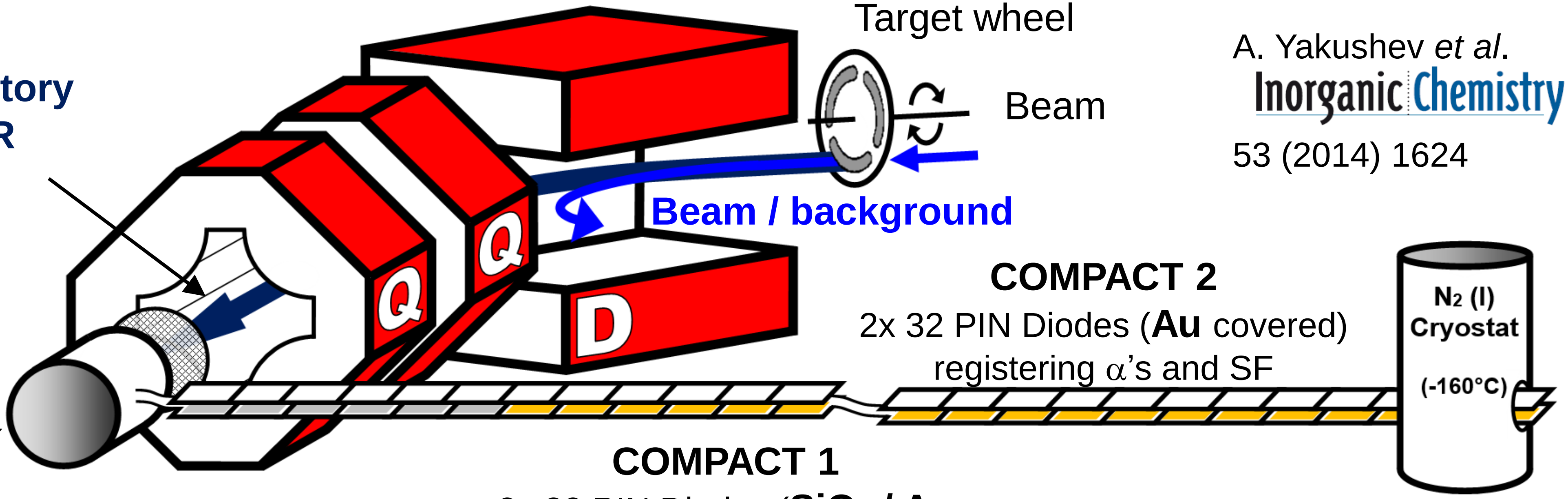


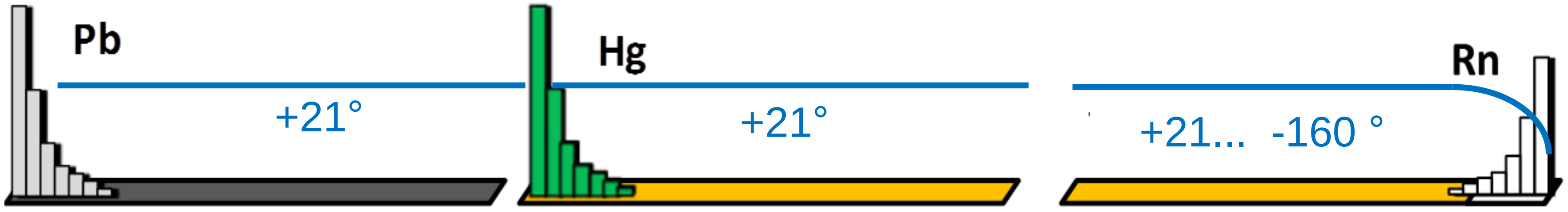
R. Eichler et al Angew. Chem. 120 (2008) 3306

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TransActinide Separator and Chemistry Apparatus – TASCA

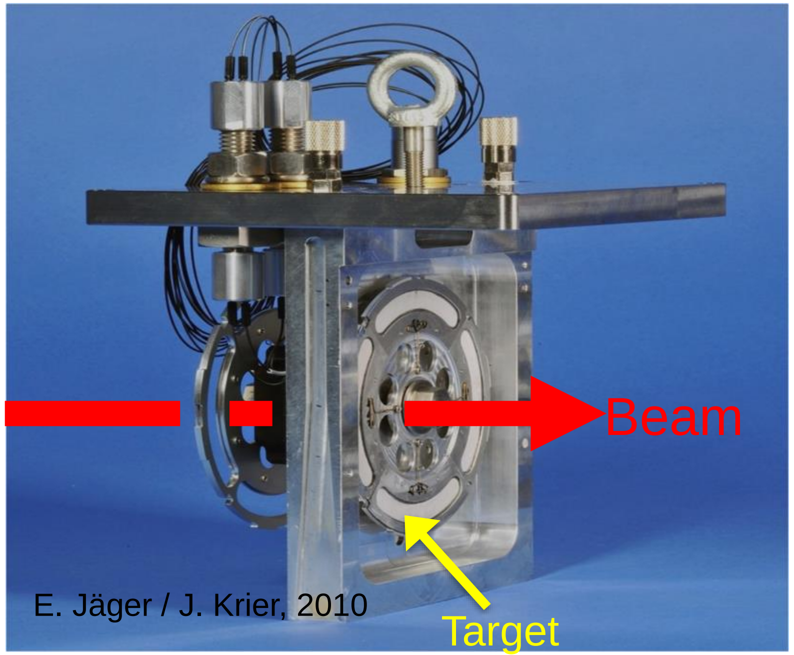
A. Yakushev *et al*. Inorganic Chemistry 53 (2014) 1624

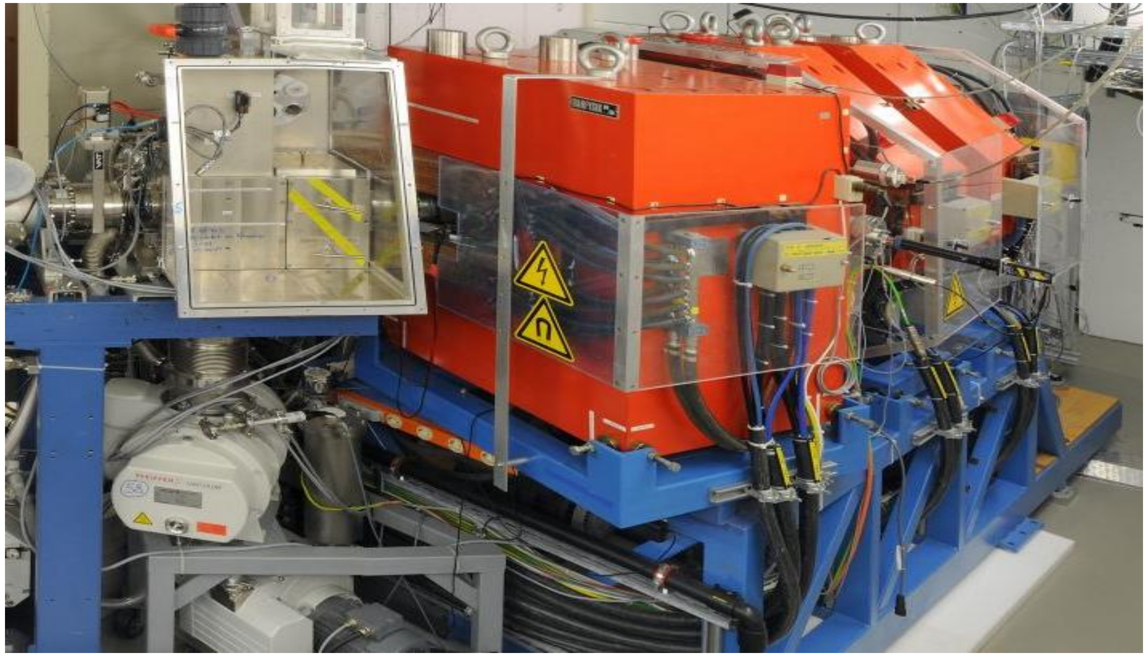


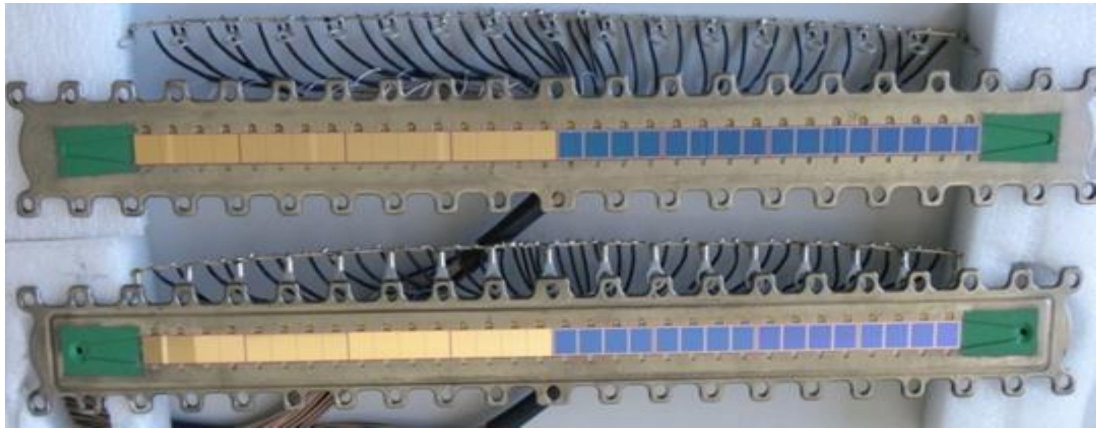


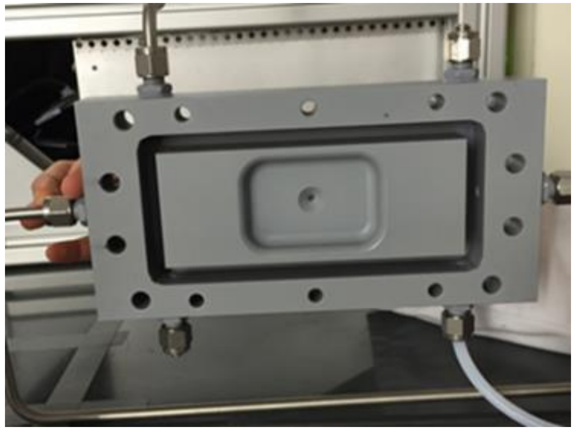
L. Lens *et al*. Radiochim. Acta 106 (2018) 949

*T*rans*A*ctinide *S*eparator and *C*hemistry *A*pparatus – *TASCA*





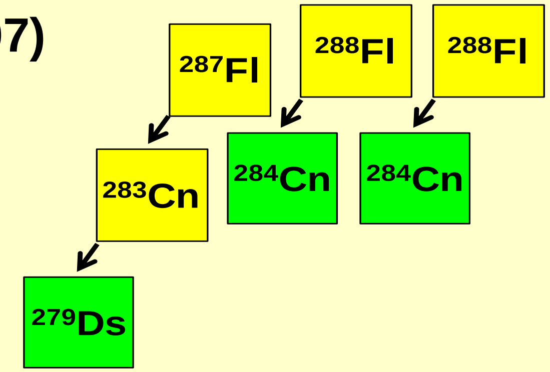




HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Fl (Z=114) decay chains from chemistry experiments

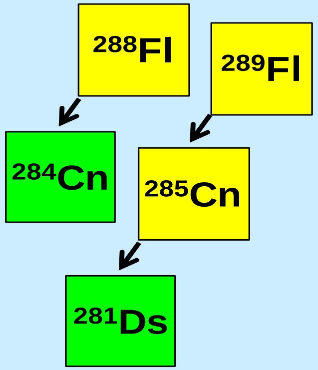
PSI/Dubna (2007)
35 days



Conclusion: physisorption bond with Au

R. Eichler *et al.*, RCA (2010)

GSI (2009)
28 days



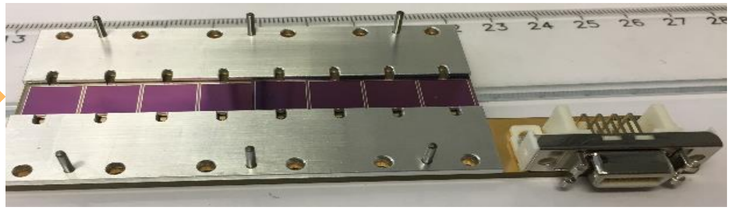
Conclusion: metallic bond with Au

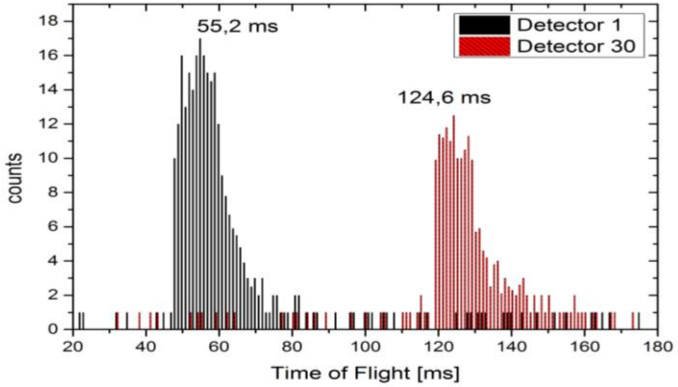
A. Yakushev *et al.*, Inorg. Chem. (2014)

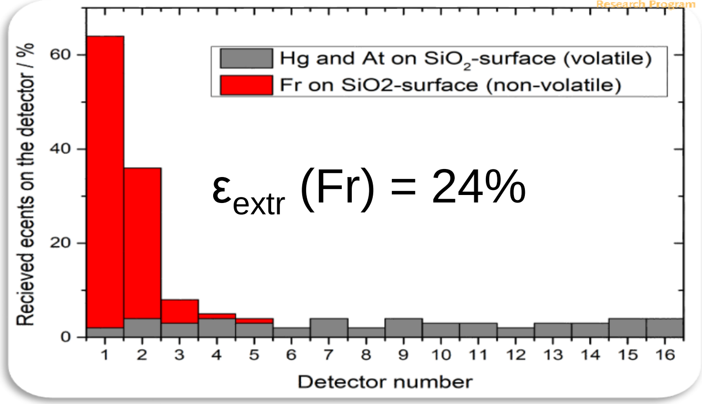
Beyond Mc: Preparations for chemistry with ^{116}Lv and ^{117}Ts

First test experiments: Coupling of BGC with COMPACT and miniCOMPACT

He
50 mbar







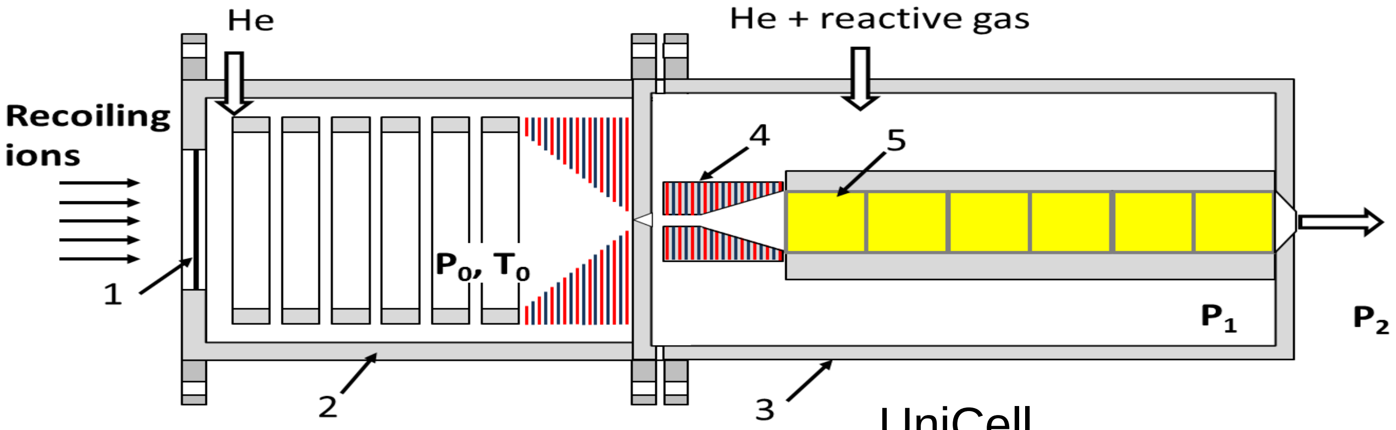
Old „SHIP“ Buffer gas cell

miniCOMPACT

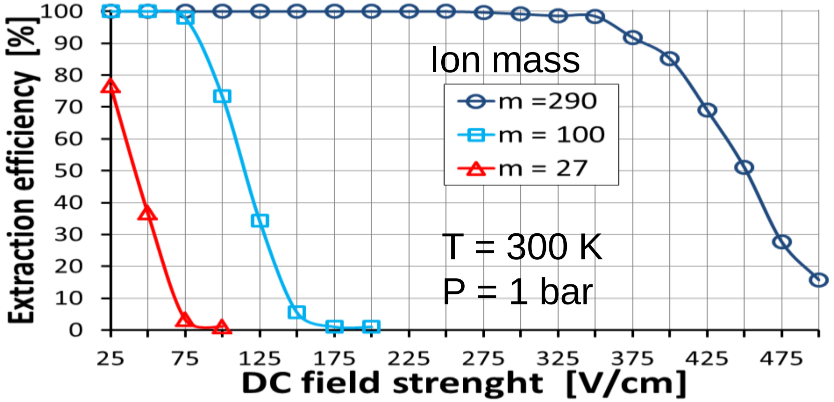
≈ 50 ms extraction time

S. Götz *et al.*, NIM A 165090 (2021)
S. Götz et al., NIM B 507 (2021) 27-35

High-pressure UniCell project for faster extraction and higher efficiency



UniCell



V. Varentsov, A. Yakushev, NIM A 940 (2019)

Chemistry is possible
with single atoms

Literature:

Schädel, Matthias, and Dawn Shaughnessy, eds.
The chemistry of superheavy elements. Springer Science & Business Media, 2013.