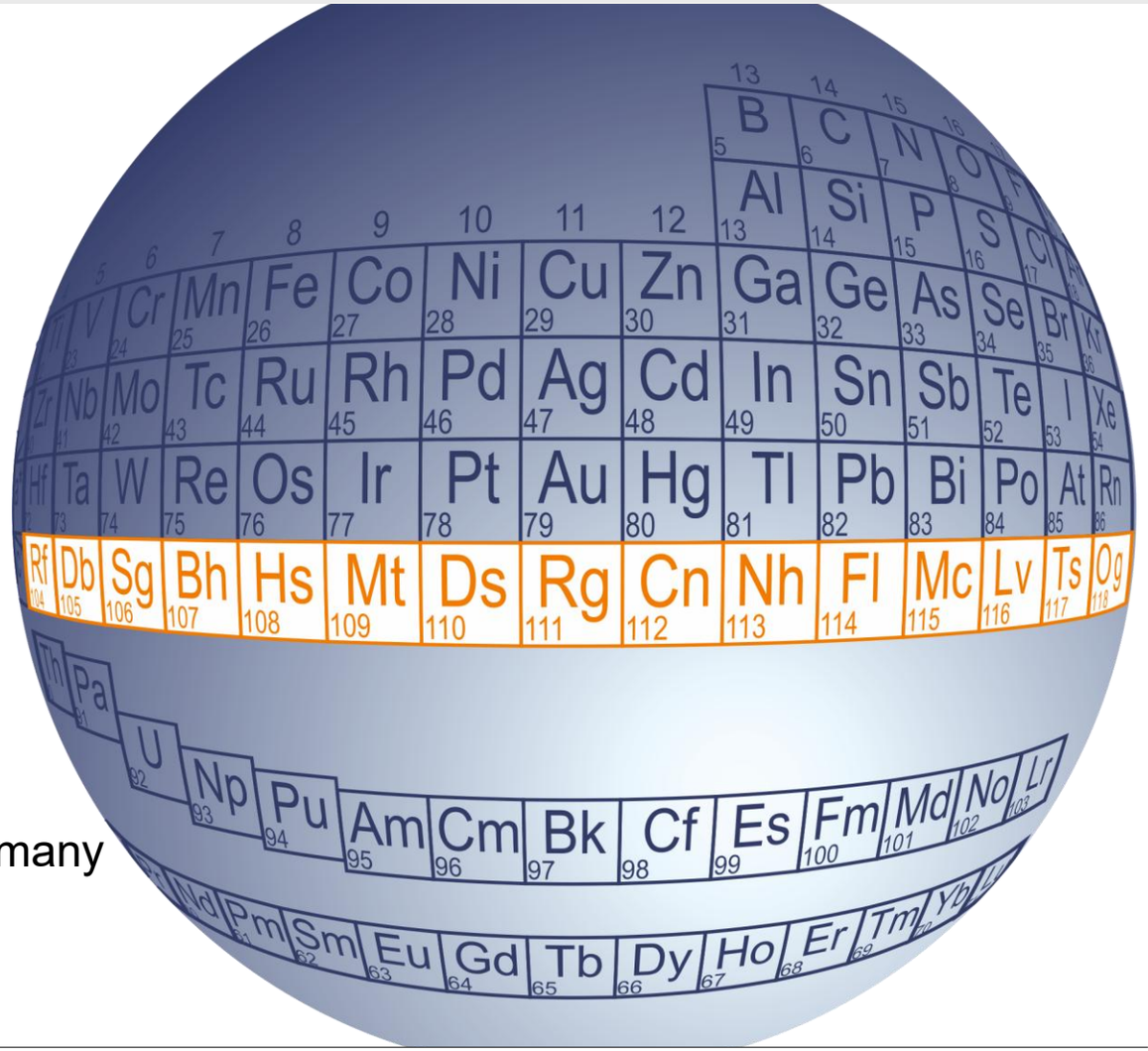
www.superheavies.de
duellmann@uni-mainz.de

Experimental chemical studies of the heaviest elements



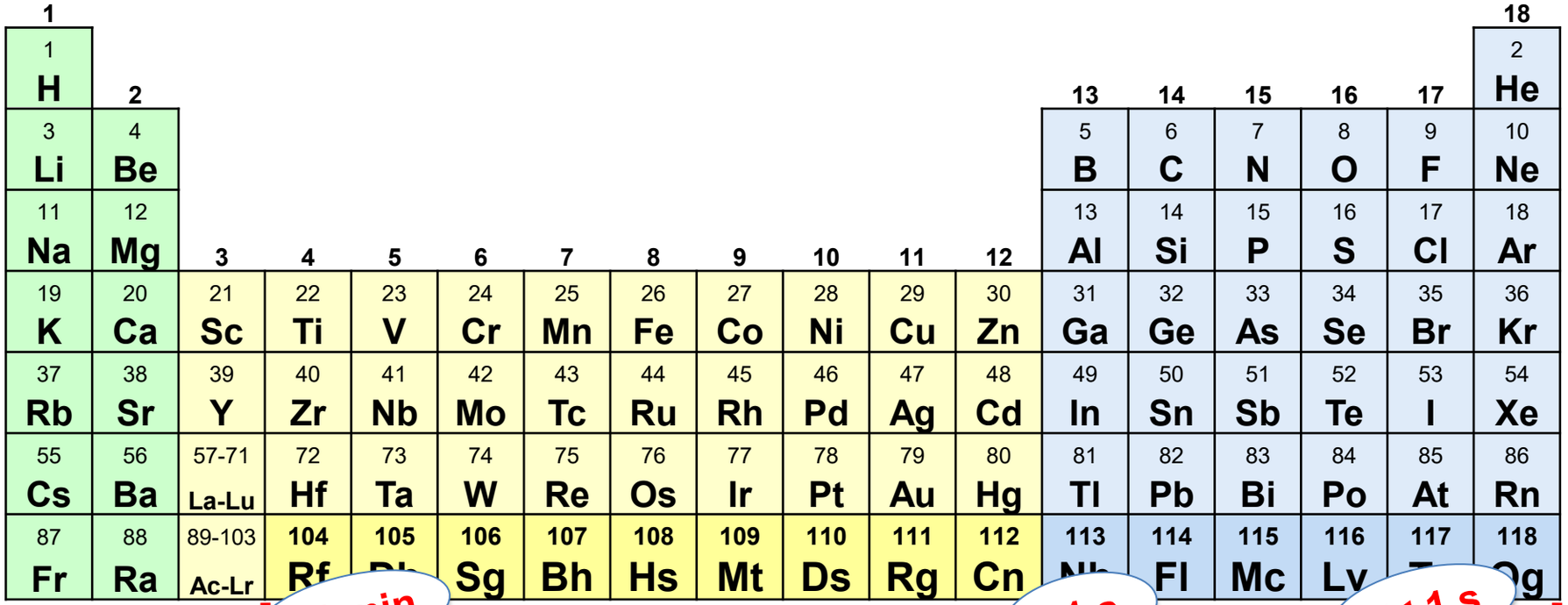
Christoph E. Düllmann

Johannes Gutenberg University Mainz, Mainz, Germany
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
Helmholtz Institute Mainz, Mainz, Germany

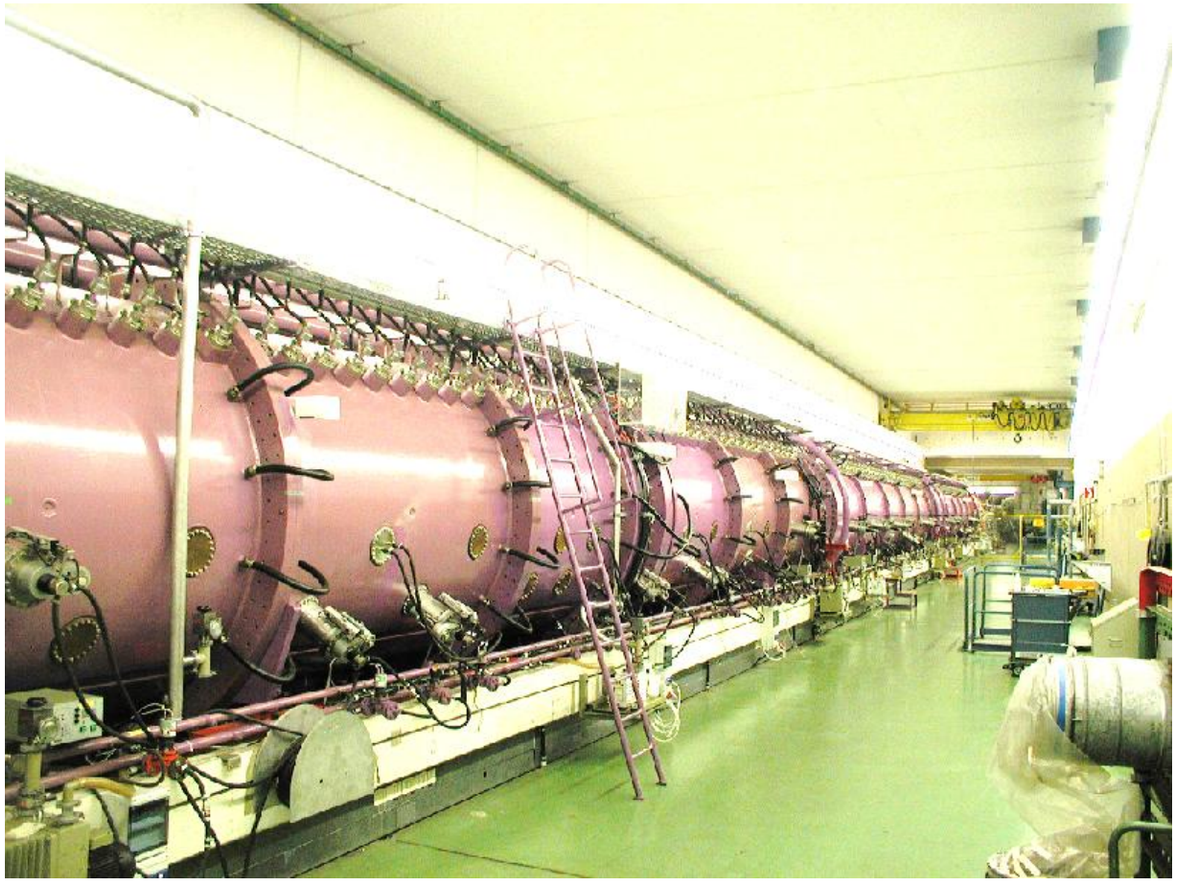


Workshop on the Physics and Chemistry of the Heaviest Elements
ECT* Trento, Italy, September 14-18, 2026

The periodic table 2026

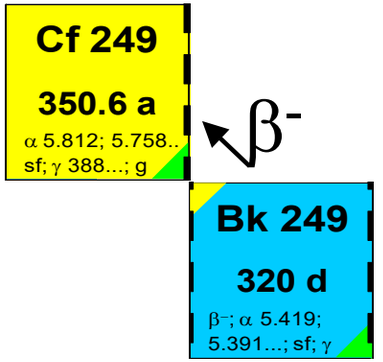


UNILAC accelerator at GSI Darmstadt



Actinide targets from JGU Mainz Nuclear Chemistry





12 mg
(700 GBq)
^{249}Bk

J. Runke *et al.*, J. Radioanal. Nucl. Chem. 299 (2014) 1081

57 La	Targets on thin foils								67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102	103

~1 h

tons mg / μg / pg 50 atoms min^{-1}

The periodic table 2026

Alkali metals

Noble gases

1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

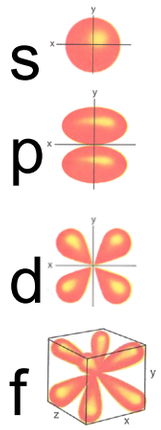
Influence of relativity on atomic and chemical properties

Three relativistic effects, due to finite speed of light, which is approached by electrons near highly charged atomic nucleus

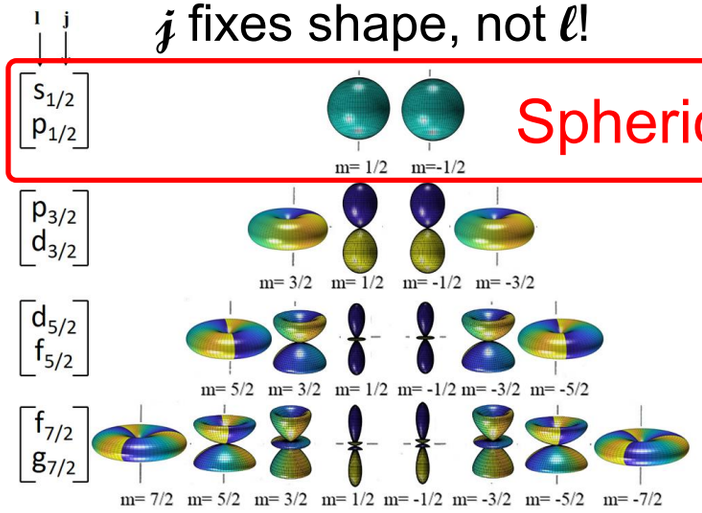
Mass of relativistic electrons in SHE is up to two times their rest mass

Non-relativistic vs. relativistic orbitals

ℓ fixes shape



j fixes shape, not ℓ!



Spherical $p_{1/2}$ orbital !

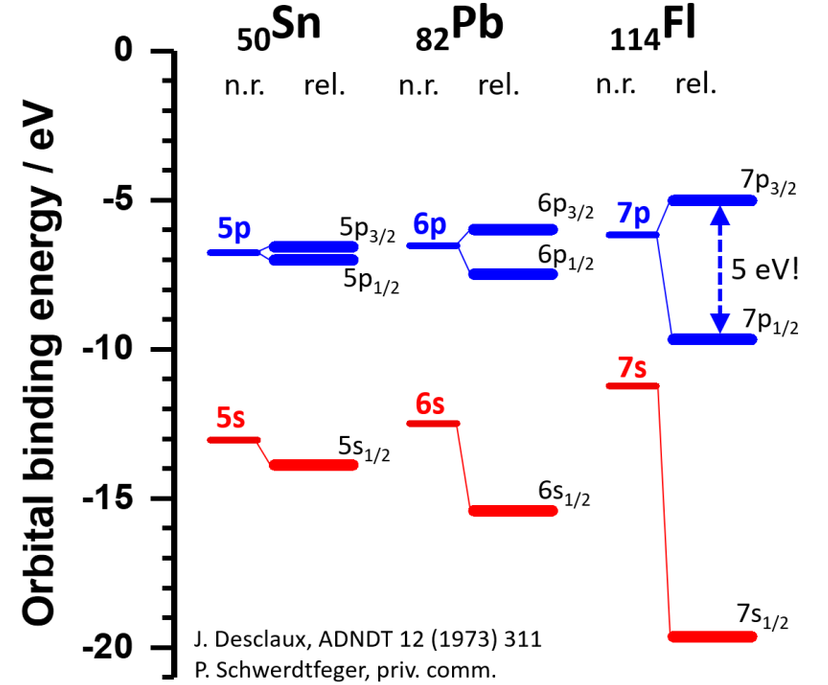
O.L. Keller, Radiochim. Acta 37 (1984) 169
adapted from H. White, Phys. Rev. 38 (1931) 513.
Spinor rendering: S. Knecht%

1) Direct effect: $s_{1/2}$; $p_{1/2}$: stabilized / contracted

2) Indirect effect: $p_{3/2}$; d; f: better shielded ⇒ destabilized / expand

3) Spin-orbit splitting: $p \rightarrow p_{1/2}/p_{3/2}$; $d \rightarrow d_{3/2}$; $d_{5/2}$;.. jj-coupling, lifts degeneracy

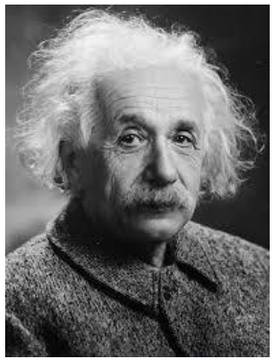
Group 14



J. Desclaux, ADNDT 12 (1973) 311
P. Schwerdtfeger, priv. comm.

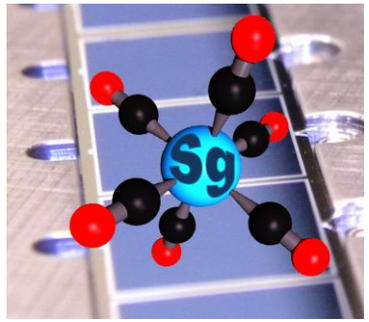
P. Pyykkö *et al.*, Acc. Chem. Res. 12 (1979) 276

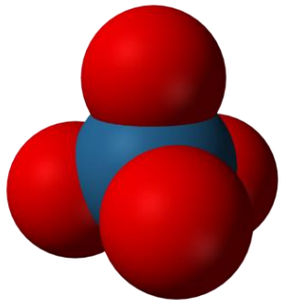
A. Einstein



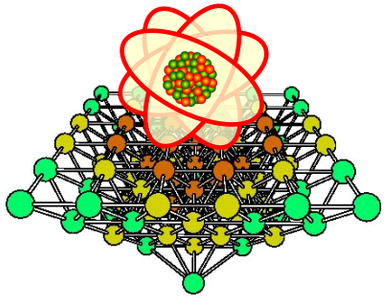
Current status of SHE chemistry

Chemical compounds





Elemental system



Following talk by A. Yakushev: Cr/Mo/W/Sg compounds

This talk: $_{113}$Nh – $_{115}$Mc

Talk by K. Hermainski later this morning: Towards $_{116}$Lv

1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be															9 F	10 Ne
11 Na	12 Mg															17 Cl	18 Ar
19	20							10								35 Br	36 Kr
			24 Cr	25 Mn	26 Fe	Co		28 Ni	Cu	Zn	31 Ga	32 Ge	33 As	34 Se			
			42 Mo	43 Tc	44 Ru						49 In	50 Sn	51 Sb	52 Te			
			74 W	75 Re	76 Os						81 Tl	82 Pb	83 Bi	84 Po			
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

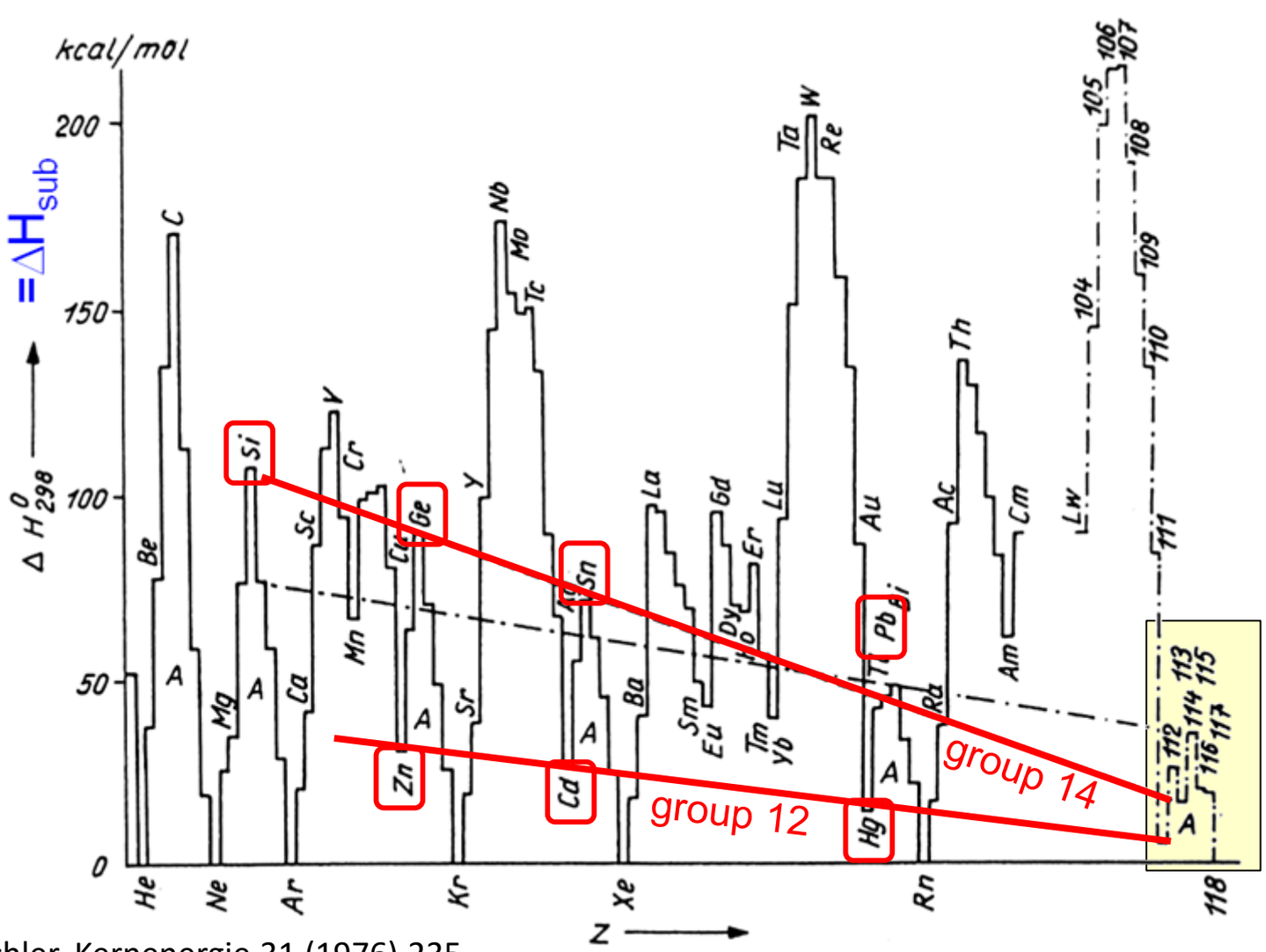
No chemical studies

No chemical studies

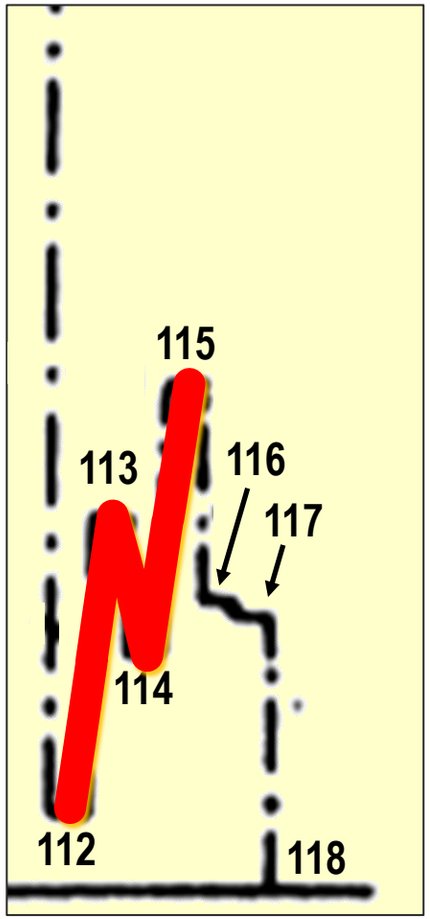
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Trends of volatility in the main groups

Enthalpy of formation of monatomic gaseous elements



B. Eichler, Kernenergie 31 (1976) 235





D. Mendelejew

Trend in group 12 experimentally confirmed:

R. Eichler *et al.*, Angew. Chem. Int. Ed. 47 (2008) 3262

The *TASCA* chemistry collaboration

GSI/FAIR Darmstadt (D)	**A. Yakushev**, M. Block, H. Brand, R.A. Cantemir, F. Giacoppo, F.P. Heßberger, A. Hübner, E. Jäger, J. Khuyagbaatar, B. Kindler, J. Krier, S. Löchner, N. Kurz, B. Lommel, P. Mošať, E. Parr, V. Pershina, S. Raeder J. Runke, M. Schädel, B. Schausten, J. Steiner, V. Varentsov, P. Wieczorek, Y. Wei, V. Yakusheva
Univ. Mainz (D)	**Ch.E. Düllmann**, D. Dietzel, A.T. Loria Basto, C. Mokry, P. Thörle-Pospiech, N. Trautmann, N. Wiehl
HIM Mainz (D)	M. Götz, S. Götz, M. Laatiaoui, P. Scharrer
HS Mannheim (D)	T. Krupp, L. Lens, U.W. Scherer, J. van de Laar
Univ. Liverpool (UK)	T. Calverly, L. Harkness-Brennan, R.-D. Herzberg, D. Judson, A. Ward
Univ. Lund (S)	D.M. Cox, P. Golubev, Y. Hrabar, D. Rudolph, A. Såmark-Roth, L.G. Sarmiento
Univ. Jyväskylä (SF)	J. Konki, P. Papadakis, J. Uusitalo
Univ. Oslo (N)	J.P. Omtvedt
RIKEN, Wako-shi (J)	H. Haba, Y. Komori
JAEA, Tokai (J)	M. Asai, Y. Nagame, T.K. Sato, K. Tsukada
IITR Uttarakhand (IND)	M. Maiti
SINP Kolkata (IND)	S. Lahiri
LLNL Livermore (USA)	J. Despotopulos, K.J. Moody, D.A. Shaughnessy
TAMU College Station (USA)	C.M. Folden III, K.J. Glennon, E.E. Tereshatov, M.F. Volia
ANU Canberra (AUS)	M. Dasgupta, D. Hinde, E. Williams
ITE Warsaw (PL)	J. Kulawik, M. Wegrzecki
CTU Prague (CZ)	P. Bartl, J. John, M. Němec
NPI Řež (CZ)	J. Štursa, V. Zach



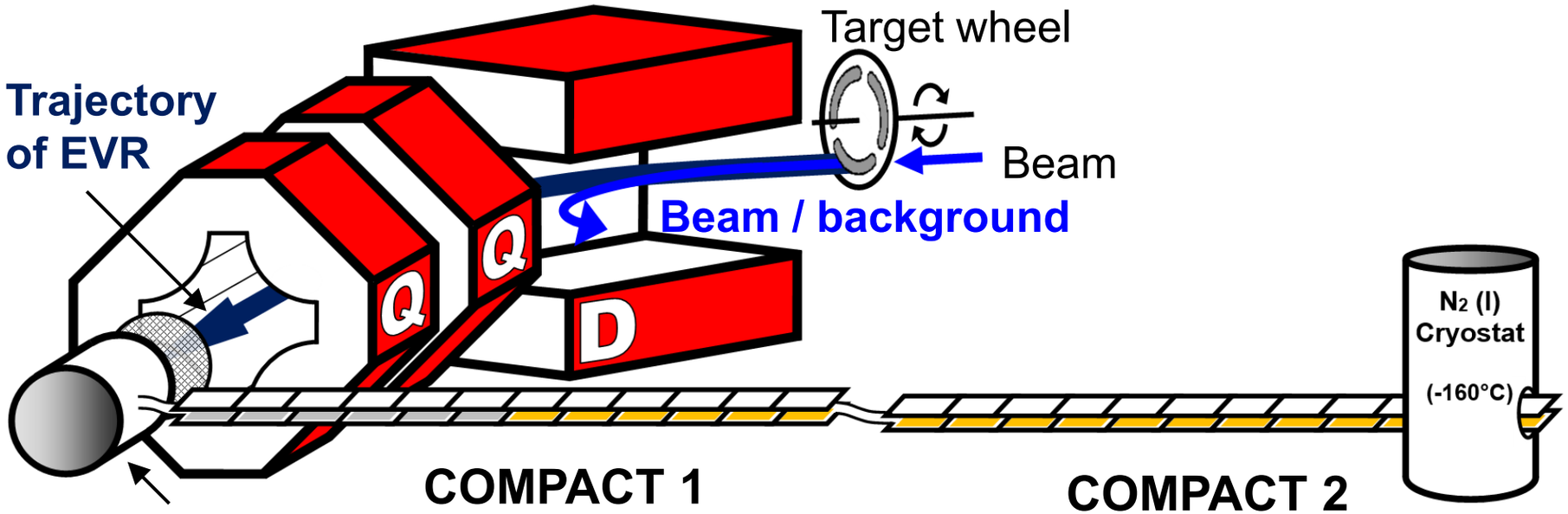
Spokesperson:
A. Yakushev

Bundesministerium für Bildung und Forschung

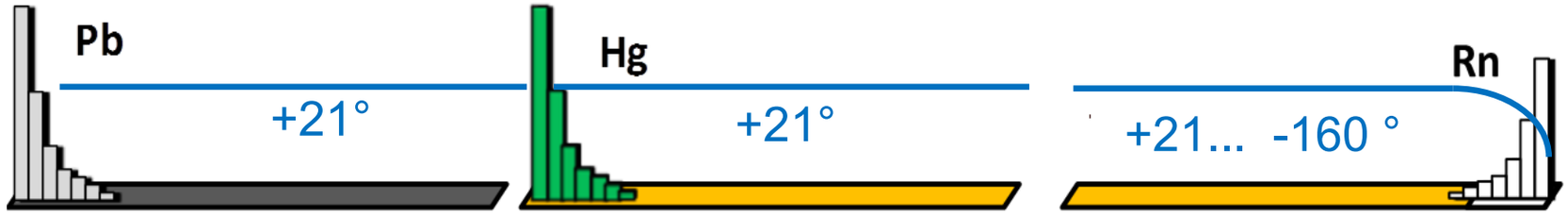
List shows members over the course of many years

Experimental setup: chemistry behind recoil separator

TransActinide Separator and Chemistry Apparatus – TASCA



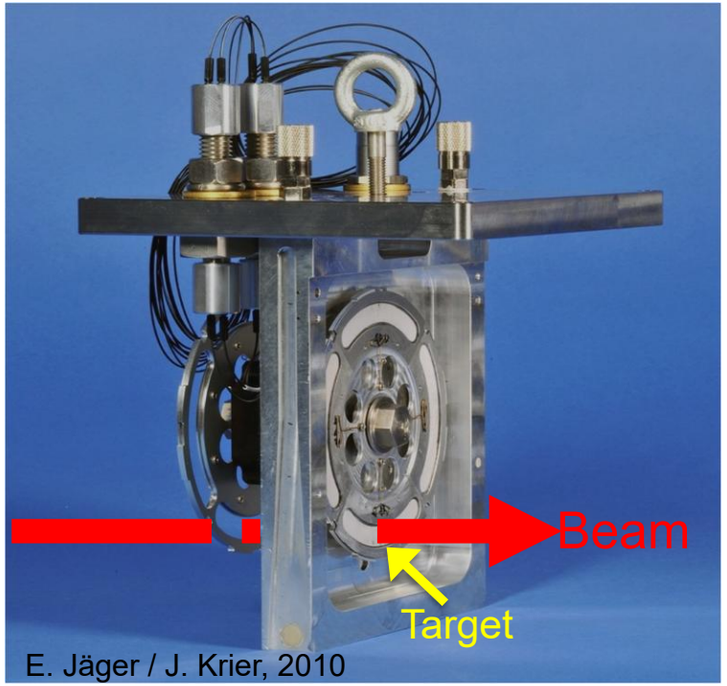
A. Yakushev *et al.*
Inorganic Chemistry
53 (2014) 1624

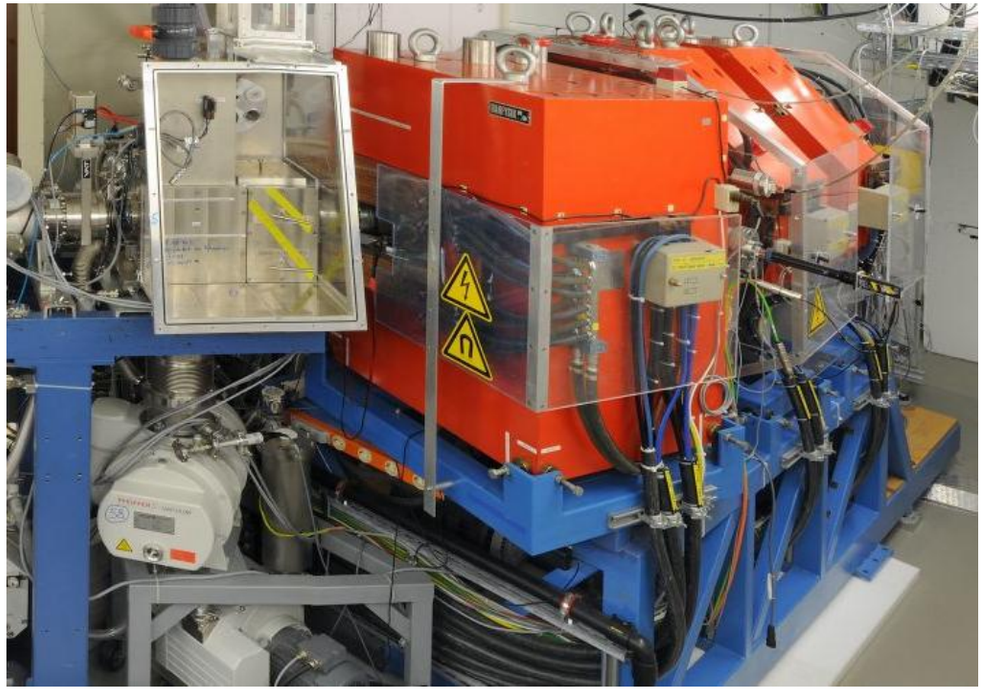


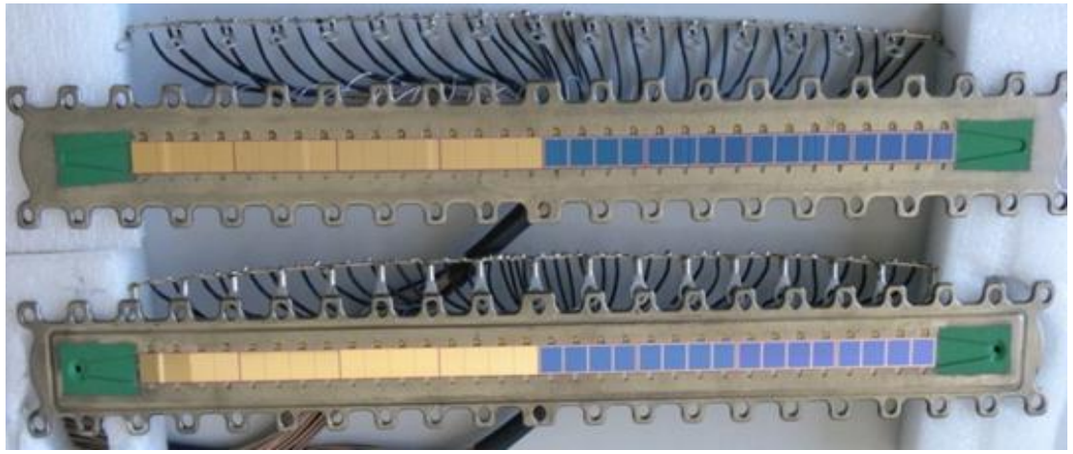
L. Lens *et al.*
Radiochim. Acta 106 (2018) 949

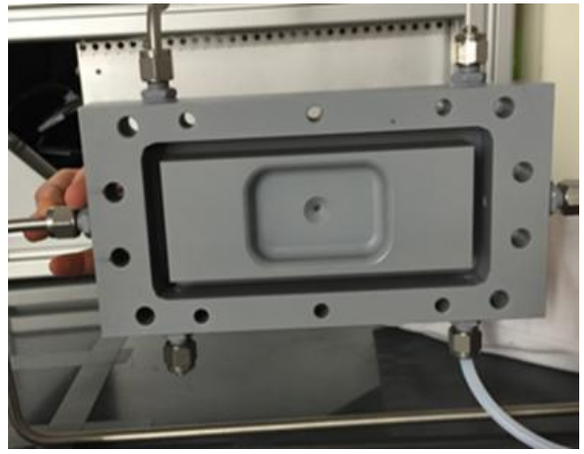
Experimental setup

TransActinide Separator and Chemistry Apparatus – TASCA









Theoretical background

1975

Are elements 112, 114, and 118 relatively inert gases?

Kenneth S. Pitzer

Department of Chemistry and Inorganic Materials Research Division of the Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 14 April 1975)

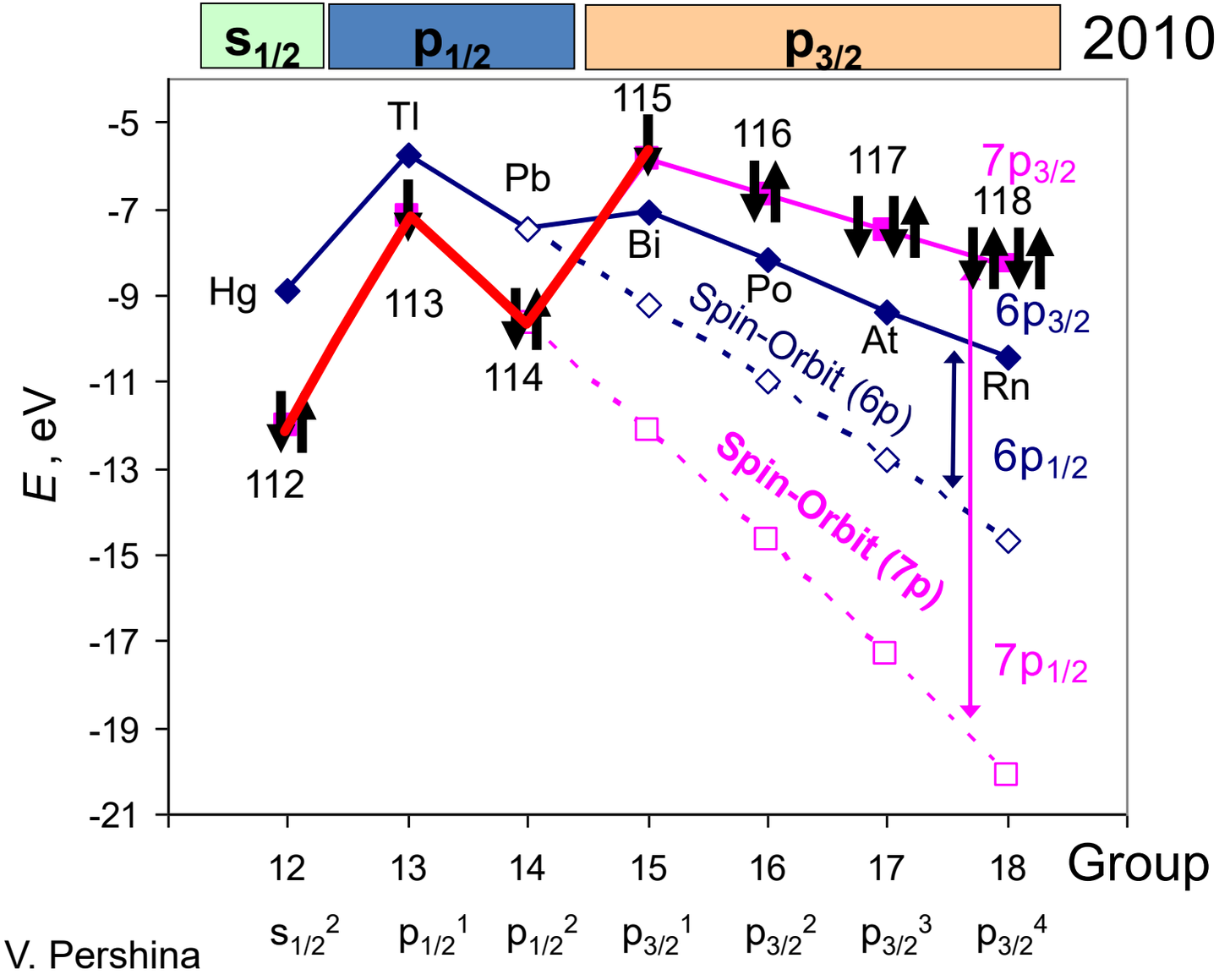
The Journal of Chemical Physics, Vol. 63, No. 2, 15 July 1975 1032

Electron configuration:

112: $7s^2 6d^{10}$

114: $7s^2 7p_{1/2}^2$

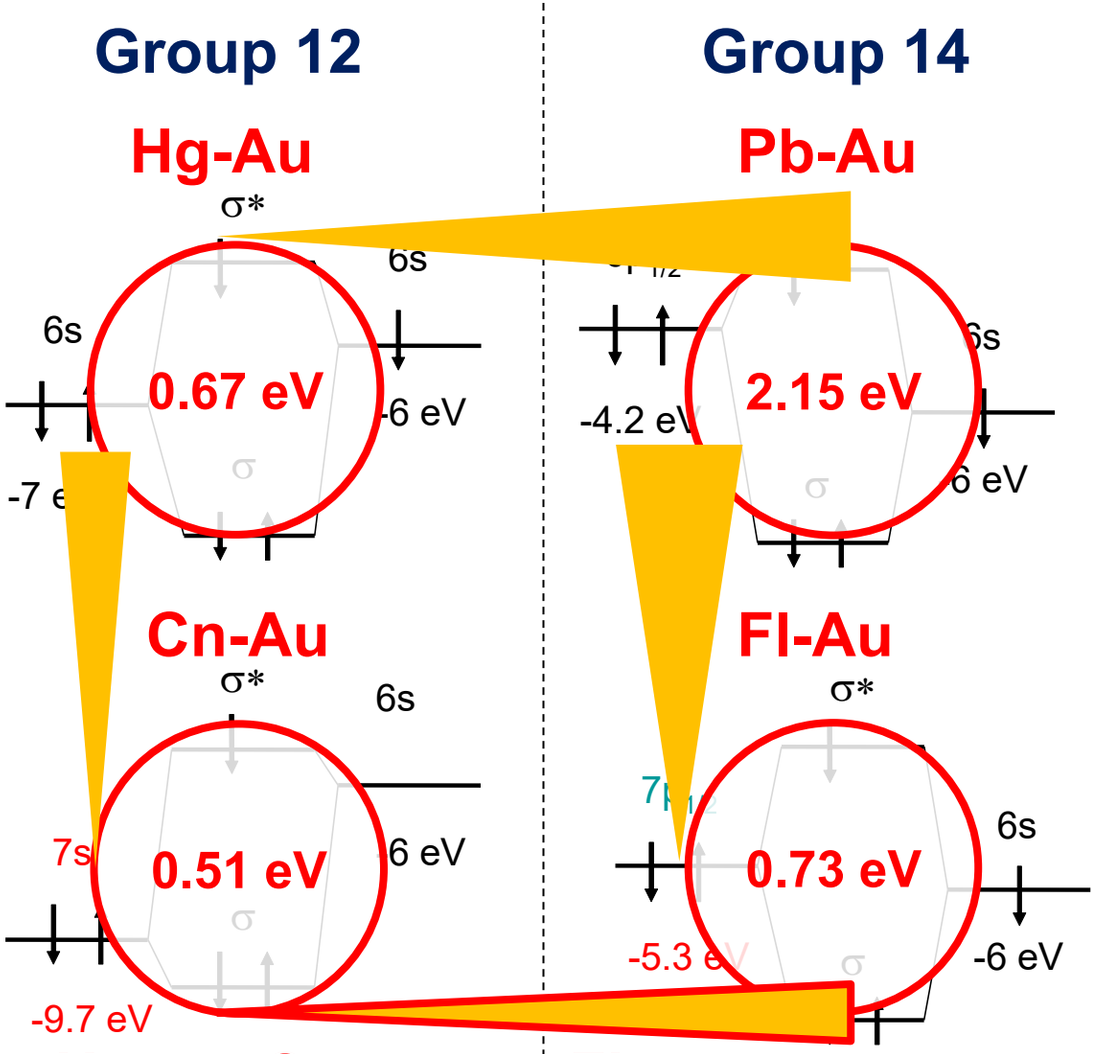
118: $7s^2 7p^6$



V. Pershina

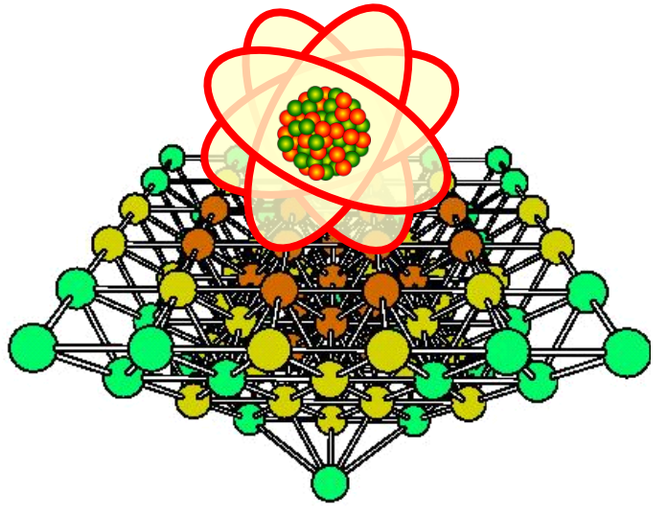
Reactivity: the „inert“ groups 12 and 14

Theory – Gen. I: M-Au Bonding (Dimer)



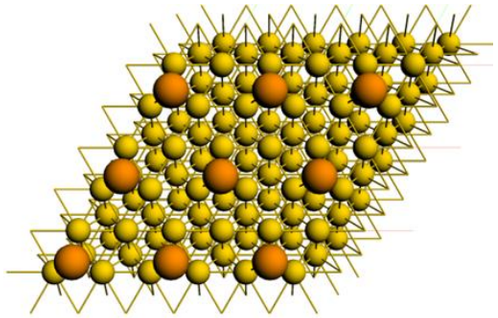
Hg-Au, Cn-Au and Fl-Au comparabe

Gen II: M on Au_n cluster



Trends from M-Au to M-Au_n preserved!

Gen III: Periodic codes



V. Pershina

Reactivity in groups 12 – 15

Predictions of adsorption of Cn, Nh, Fl and Mc on Au(111) and SiO_2 surface

ADF BAND calculations
- Spin-Orbit interaction
- best basis sets
- relaxation effects
- full geometry optimization

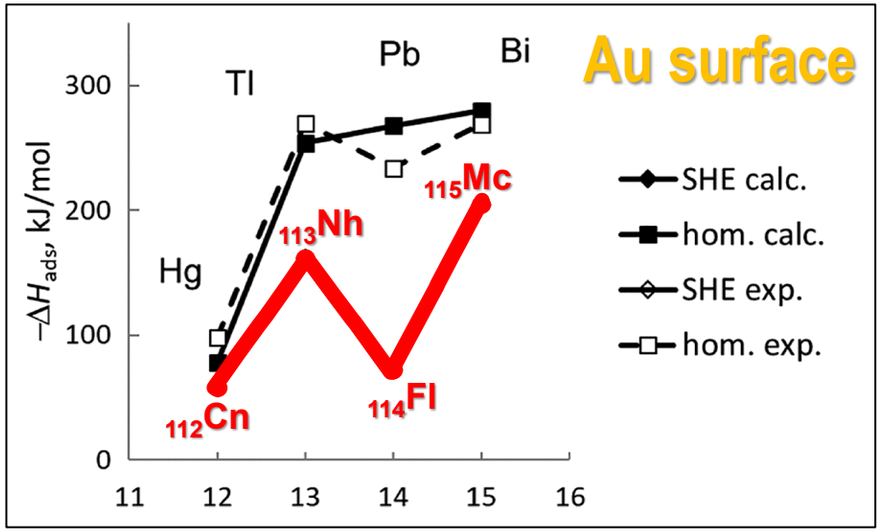
V. Pershina and M. Iliaš
Inorg. Chem. 57 (2018) 3948
Dalton Trans. 51 (2022) 7321
Inorg. Chem. 60 (2021) 9796
Inorg. Chem. 61 (2022) 15910

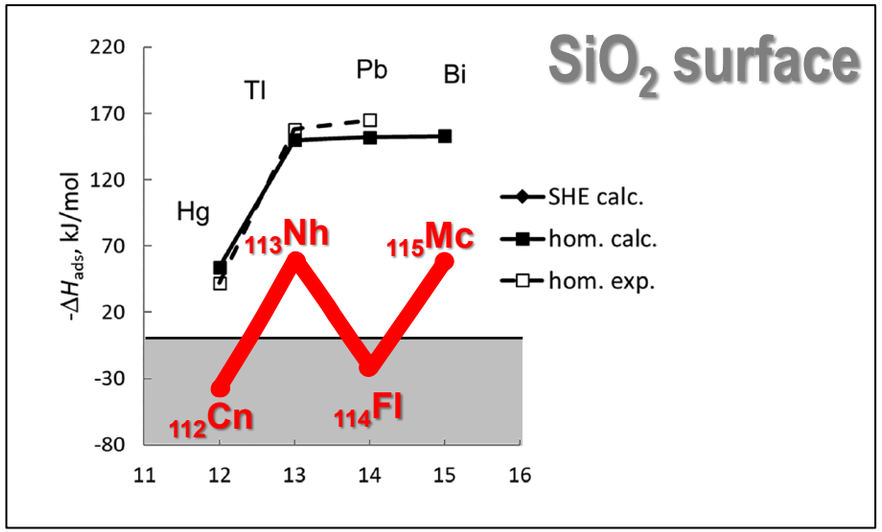
VASP calculations

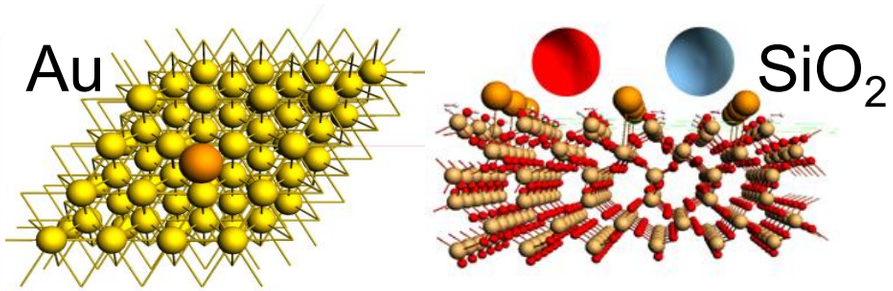
L. Trombach *et al.*,
PCCP 21 (2019) 18048

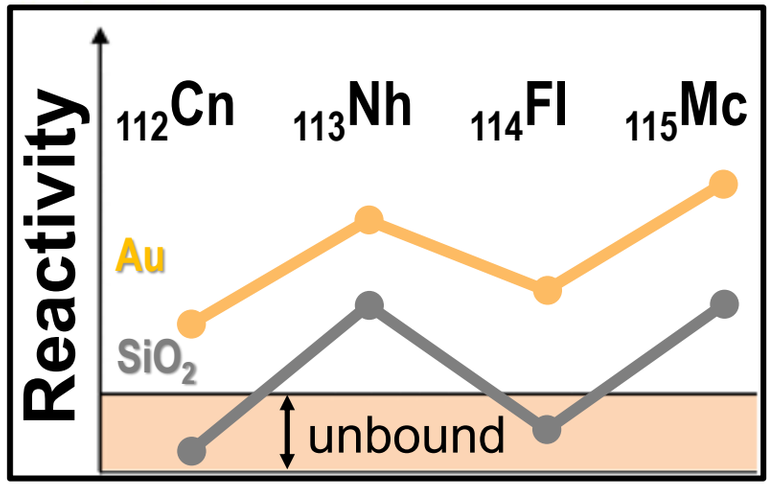
Solid state calcs.

E. Florez *et al.*,
J. Chem. Phys 167, 064304 (2022)









Expectation:
-All elements adsorb on Au
-Only Nh and Mc adsorb on SiO_2

Known isotopes from fusion of ^{48}Ca with actinides

Target **Product**

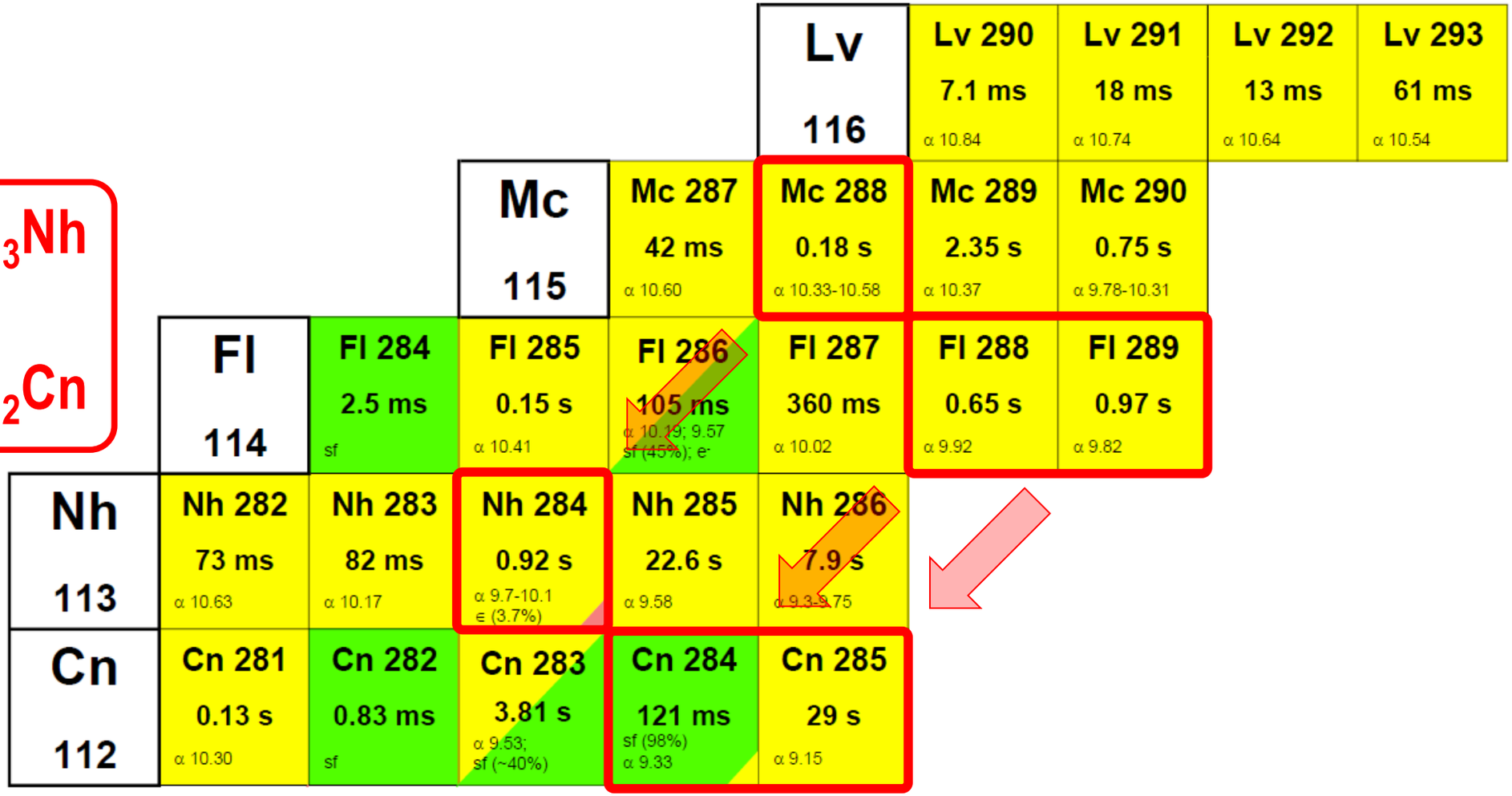
$^{248}Cm \rightarrow {}_{116}Lv$

$^{243}Am \rightarrow {}_{115}Mc \xrightarrow{\alpha} {}_{113}Nh$

$^{244}Pu \rightarrow {}_{114}Fl \xrightarrow{\alpha} {}_{112}Cn$

($^{237}Np \rightarrow {}_{113}Nh$)

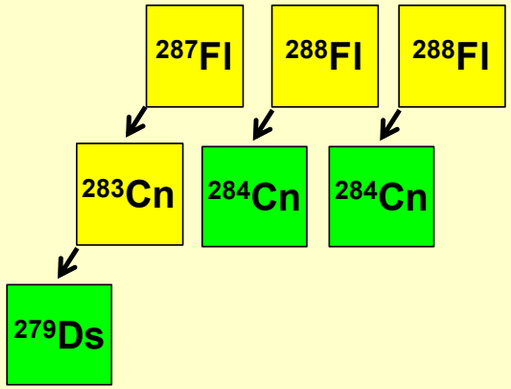
($^{238}U \rightarrow {}_{112}Cn$)



- Element 114 – Flerovium Fl

Fl decay chains from chemistry experiments

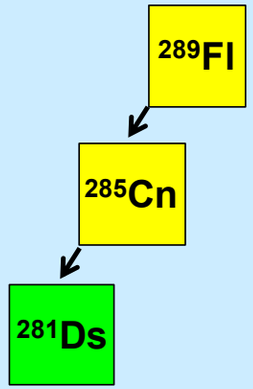
PSI/Dubna (2007)
35 days



Conclusion: physisorption bond with Au

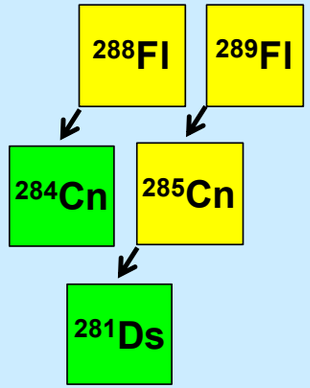
R. Eichler *et al.*, RCA (2010)

GSI (2014)
12 days



A. Yakushev *et al.*, Front. Chem. (2022)

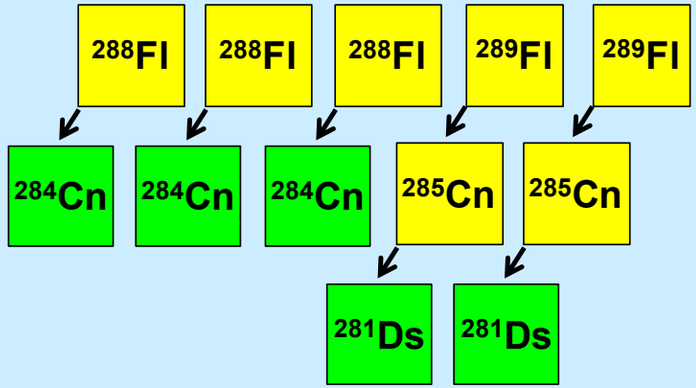
GSI (2009)
28 days



Conclusion: metallic bond with Au

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

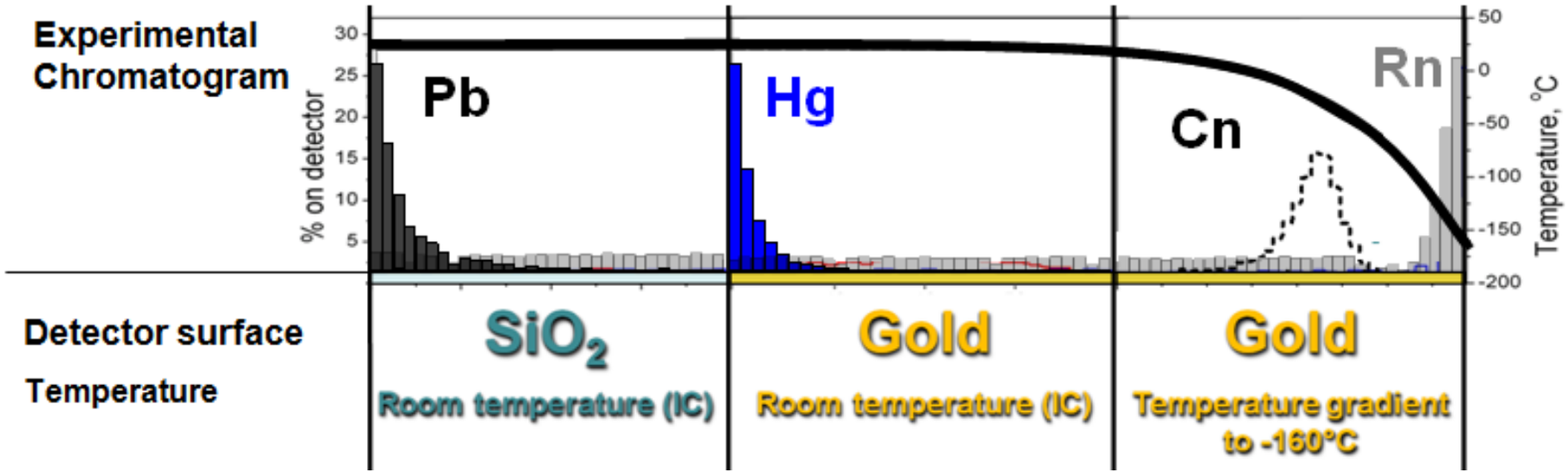
GSI (2015)
31 days



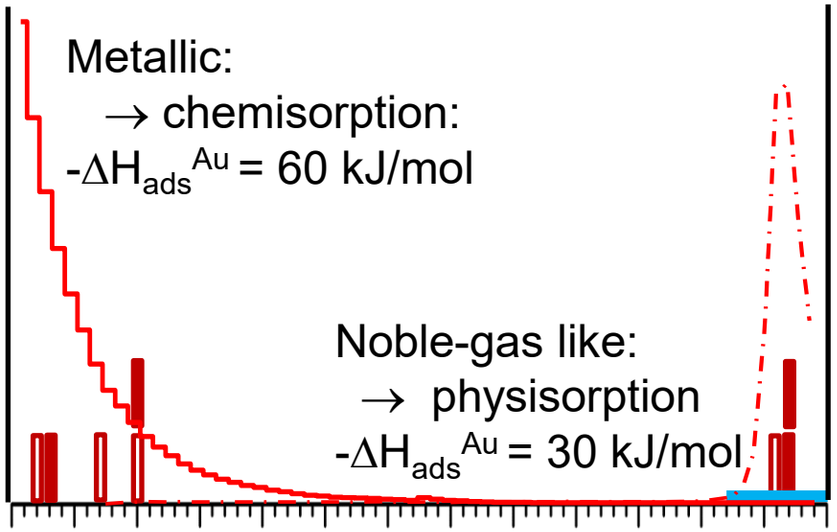
A. Yakushev *et al.*, Front. Chem. (2022)

Deposition Patterns: Metals vs. Noble Gas

TransActinide Separator and Chemistry Apparatus – TASCA



Summarized GSI Fl experiments (2009 / 2014 / 2015)



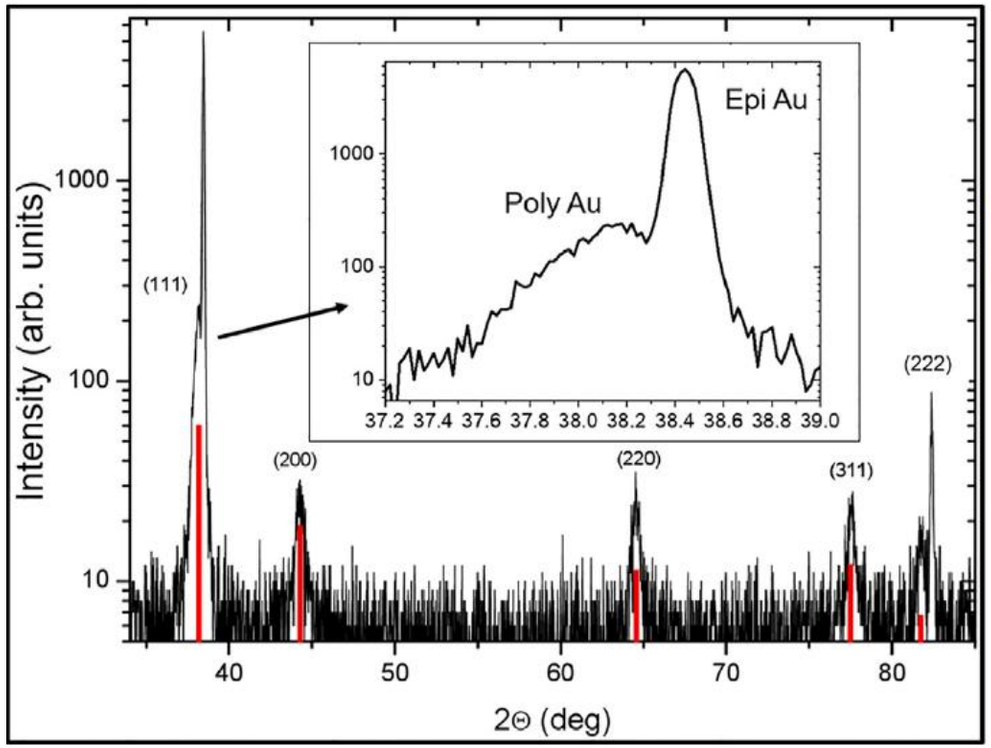
^{288}Fl

^{289}Fl

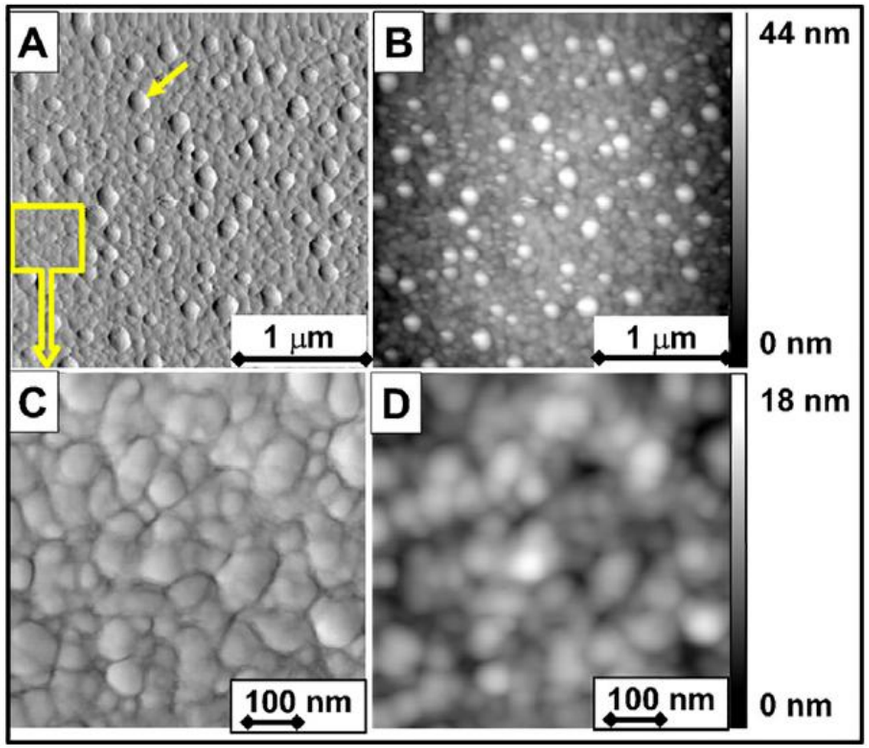
Two different Fl species?
→ considered unlikely for Fl, for which molecule formation is not readily expected.

Analytics of detector surface

XRD study



AFM study



Au layer is
-inhomogeneous
-far from Au(111)

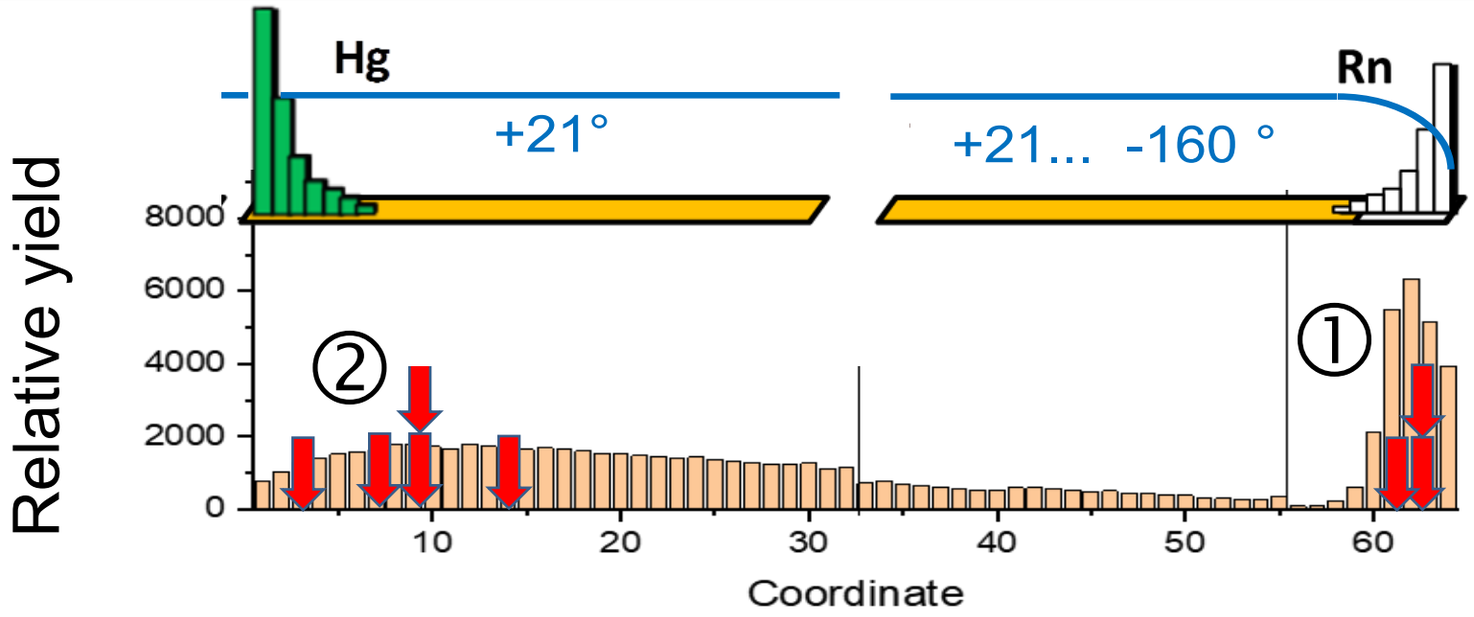
Polycrystalline plus epitaxial Au
(simulation – red line)

Fine grains (~ 20-50 nm)
and larger islands (~ 100 nm)

Acknowledgement: Inst. Physics, JGU Mainz

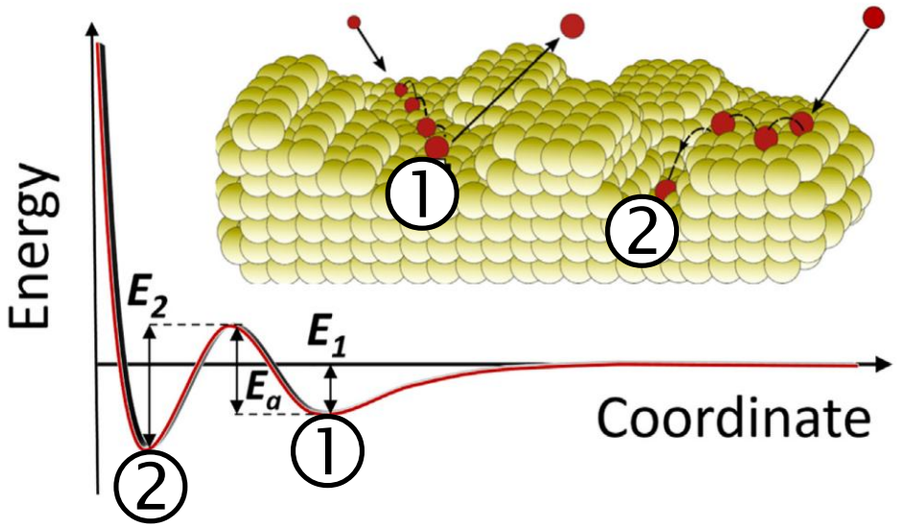
Acknowledgement: Mat.Sci. department @ GSI

Interaction of Fl with an inhomogeneous Au surface



Data from 2009 – 2016 (3 runs):
8 atoms

Two peaks corresponding to two different Fl species is considered unlikely



Fl encounters the inhomogeneous Au surface, and…

-at **weakly interacting site**, desorption may occur, leading to transport untill **adsorption by van-der Waals occurs** (peak ①)

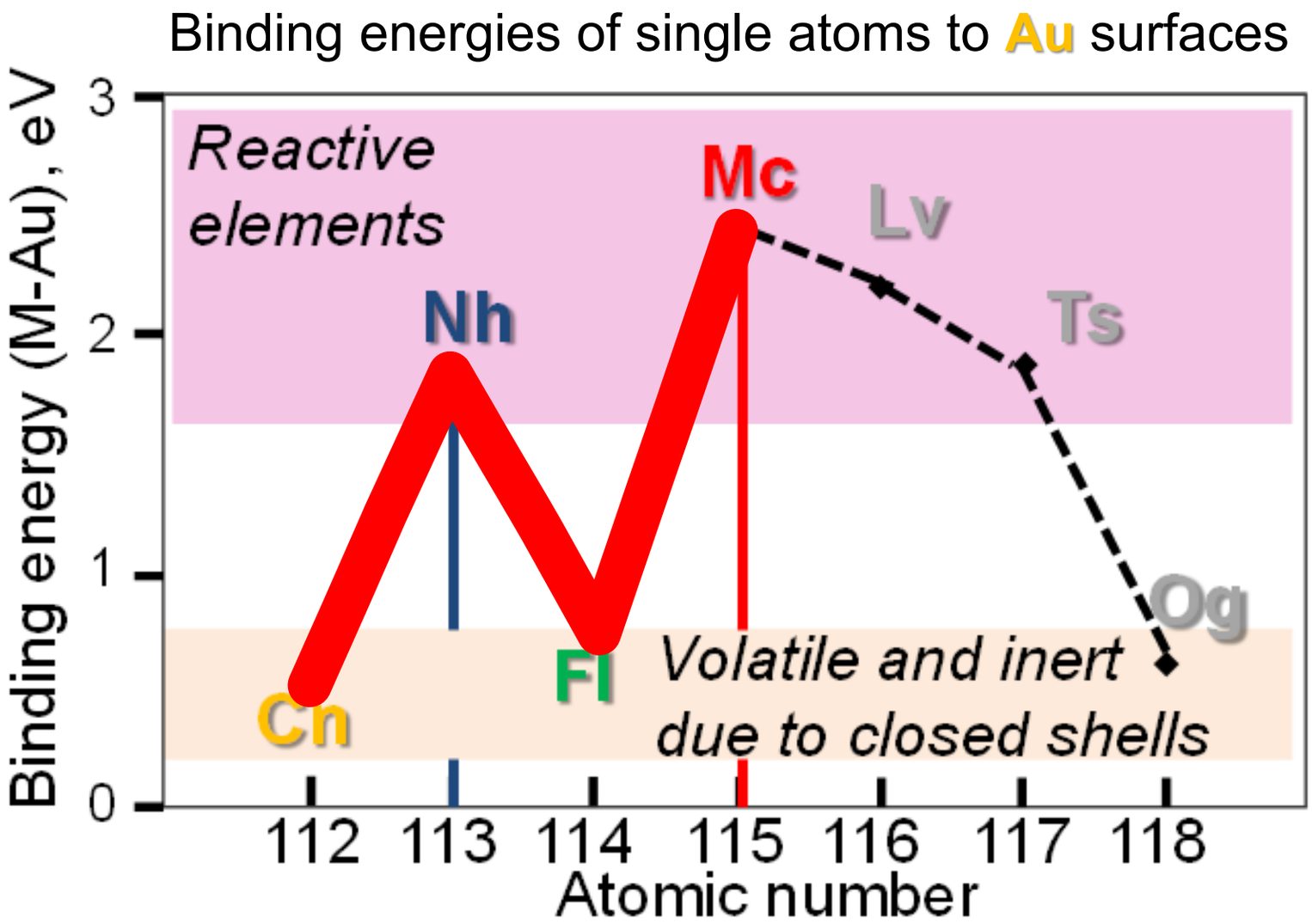
-diffusion may lead to **strongly reactive site**, where the atom is reatined due to formation of a **Fl-metal bond** (peak ②)

Flerovium is a weakly reactive metal, not a noble gas

A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635

- Element 113 – Nihonium Nh
- Element 115 – Moscovium Mc

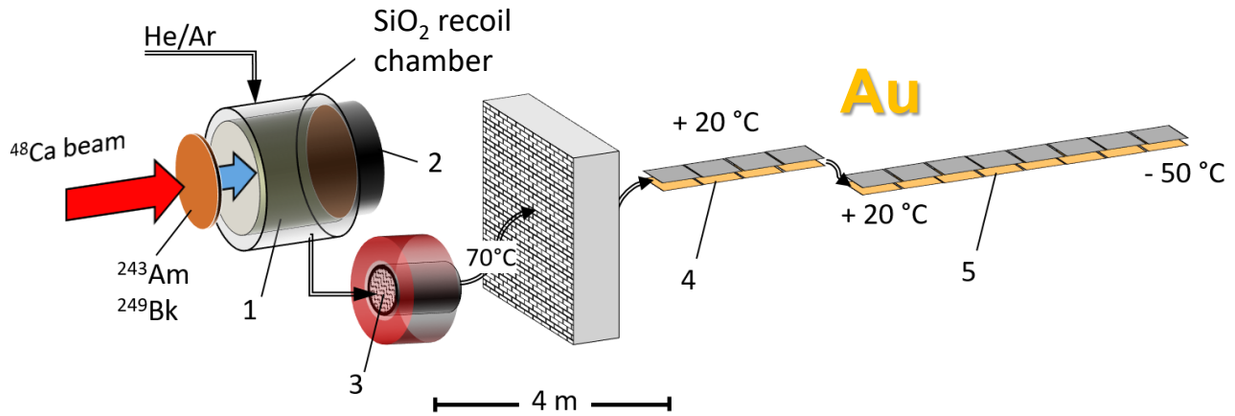
From Cn and Fl on the way towards Og



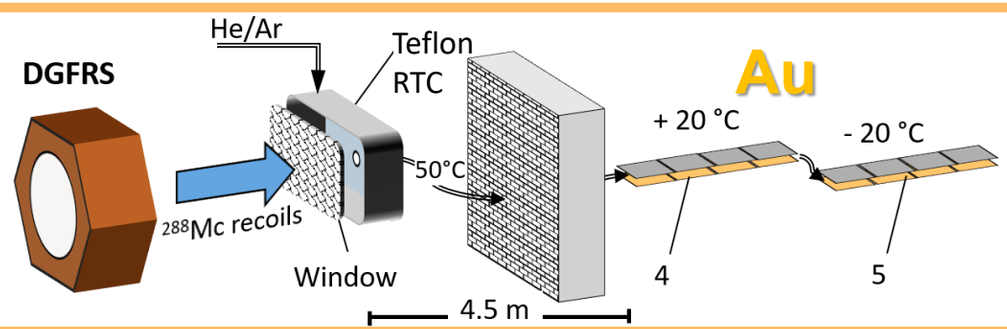
V. Pershina and M. Ilias

Past attempts on element 113 – nihonium

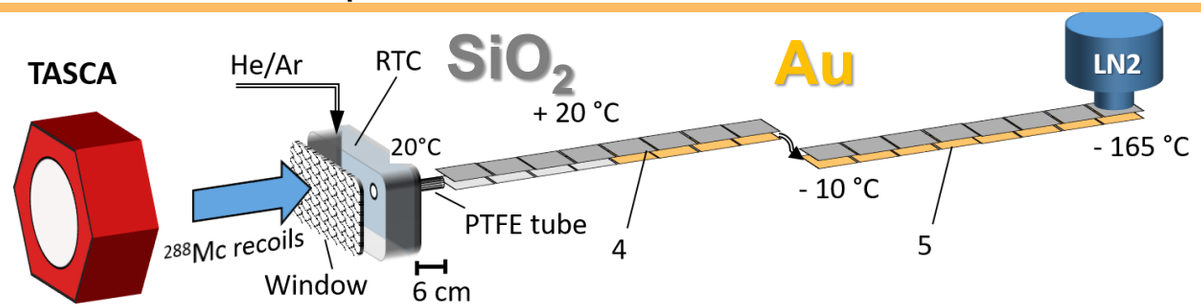
Exp. 1
FLNR Dubna
No separator



Exp. 2
FLNR Dubna
Behind DGFRS



Exp. 3
GSI Darmstadt
Behind ***TASCA***



5 events on Au @ RT
$-\Delta H_{ads}$(Au) > 60 kJ/mol

S.N. Dmitriev *et al.*,
Mend. Comm. 24, 253 (2014).

FLNR joint interpretation of both exps.:
Exp. 1: NhOH formation in SiO_2 chamber
Exp. 2: elemental Nh
(Aksenov *et al.*, Eur. Phys. J. A, 2017)

0 events @ DGFRS
$-\Delta H_{ads}$(PTFE) > 45 kJ/mol

N.V. Aksenov *et al.*,
Eur. Phys. J. A 53, 158 (2017).

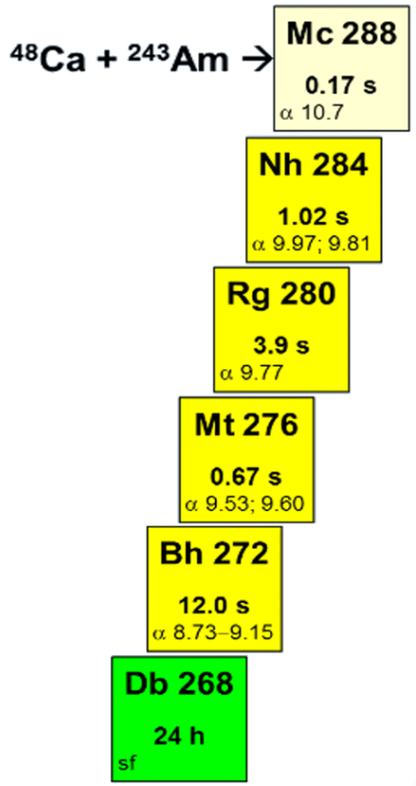
0 events @ TASCA
$-\Delta H_{ads}$(PTFE) > 50 kJ/mol

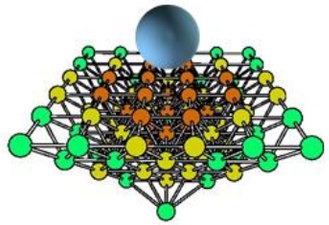
A. Yakushev *et al.*, Front. Chem. 9, 1002 (2021).

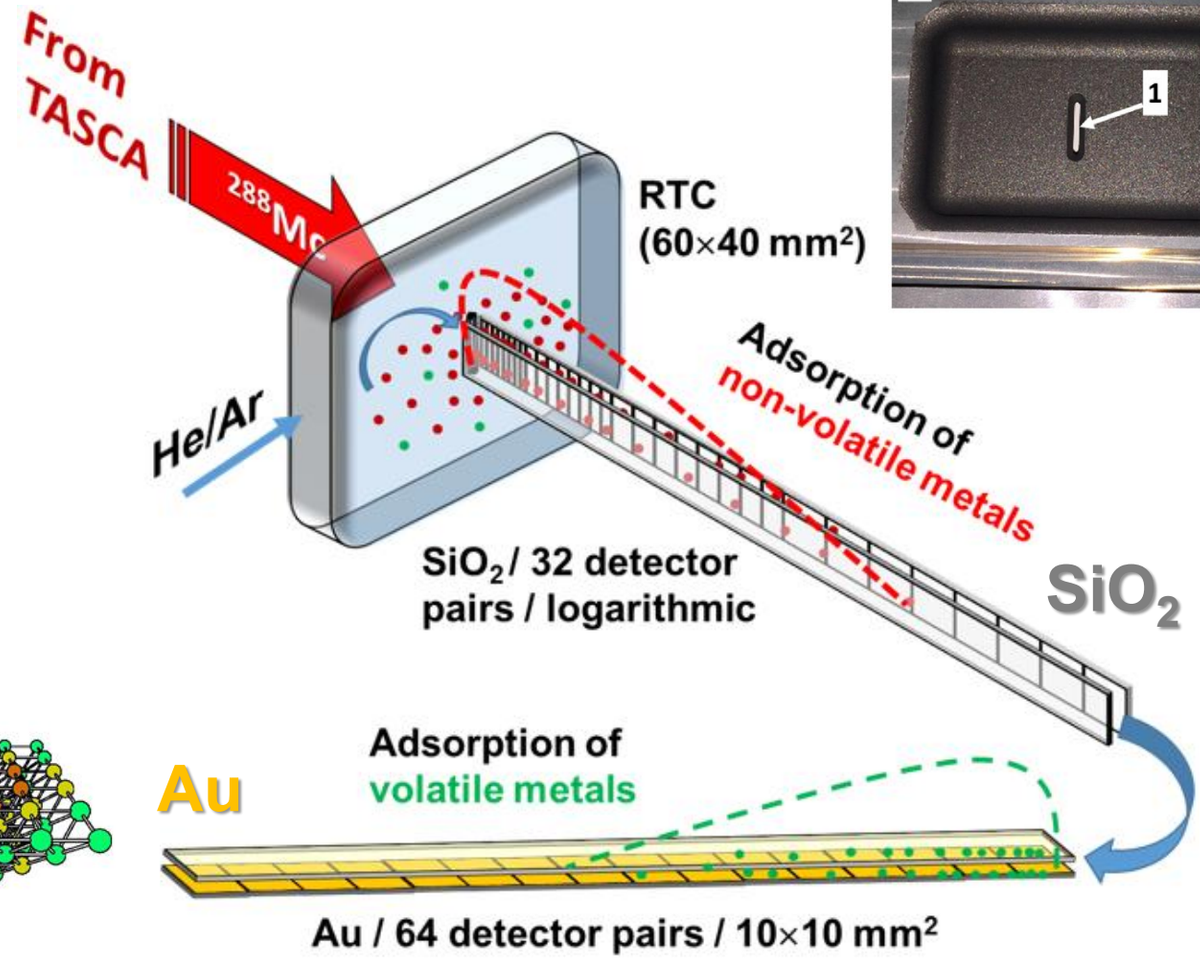
GSI conclusion:
Nh reactivity high → avoid any transport line!

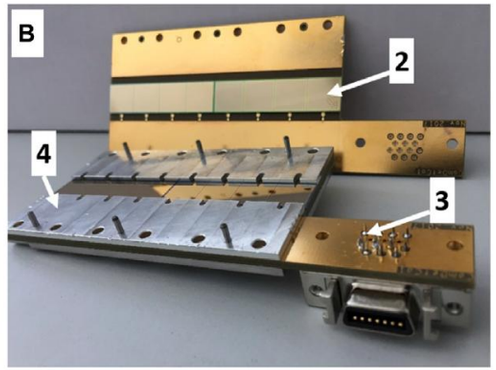
Elements 113 and 115: $^{243}Am(^{48}Ca,3n)^{288}Mc \rightarrow {}^{284}Nh$

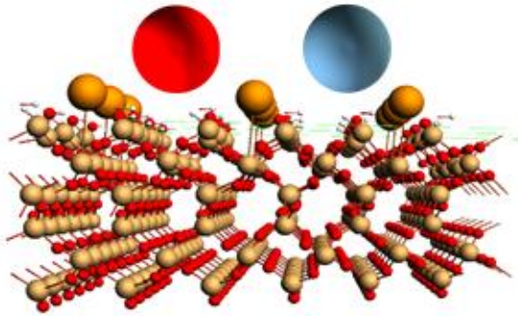
Direct coupling of miniCOMPACT to the RTC (no transport tube)







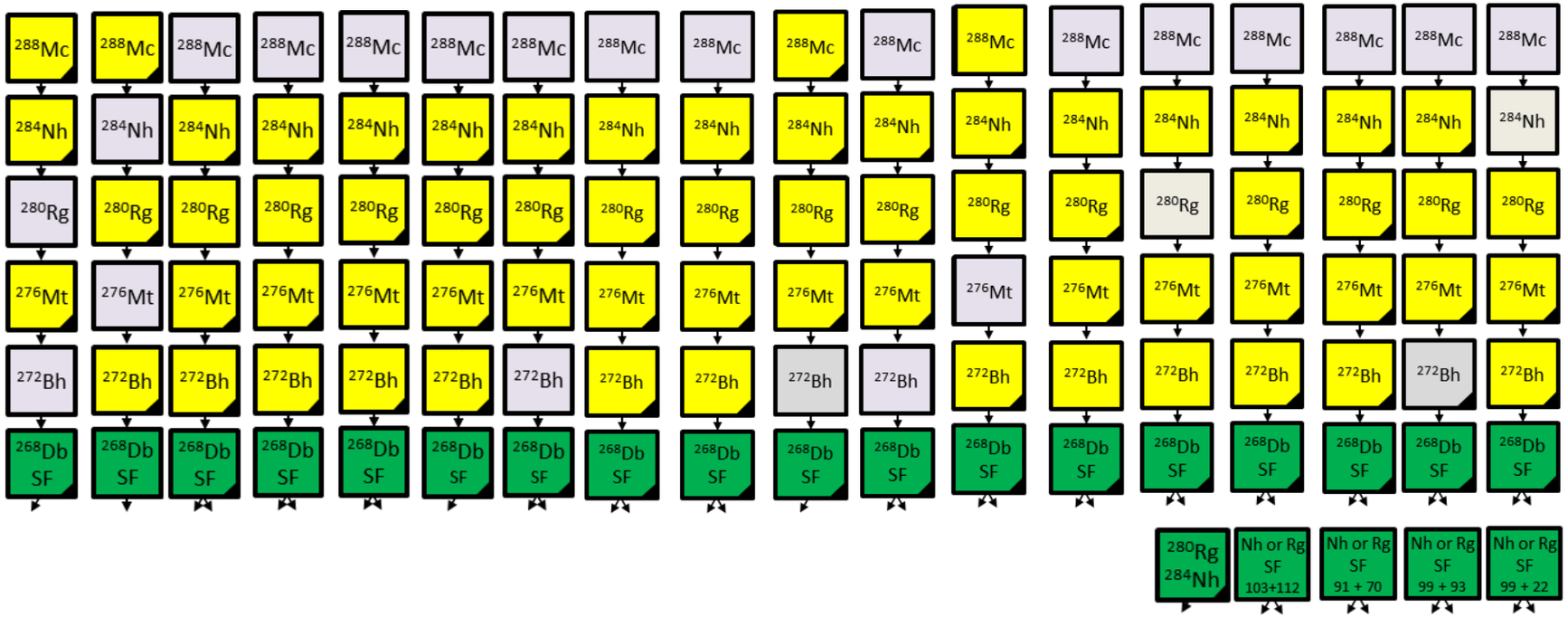




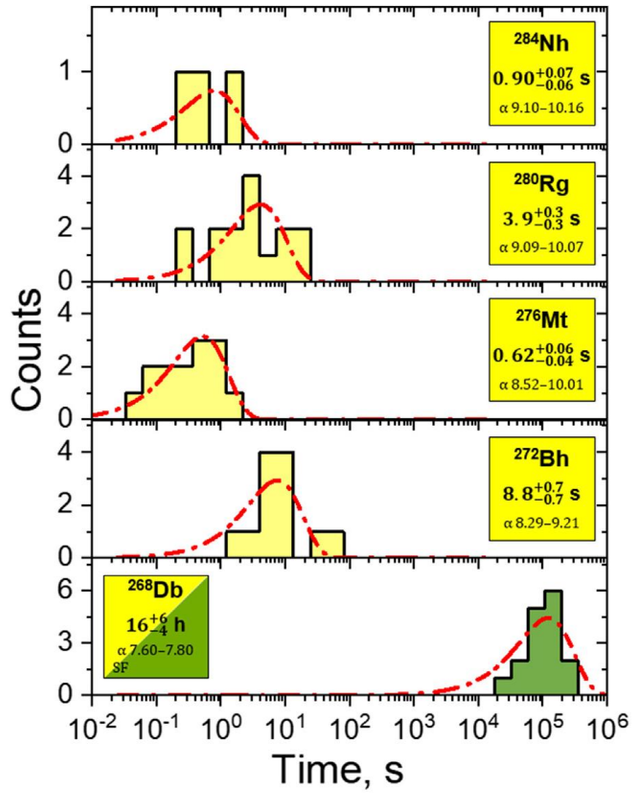
A. Yakushev *et al.*, Front. Chem. 9 (2021) 753738

Elements 113 and 115: $^{243}Am(^{48}Ca,3n)^{288}Mc \rightarrow {}^{284}Nh$

18 decay chains & 5 fissions in 2 months of beamtime



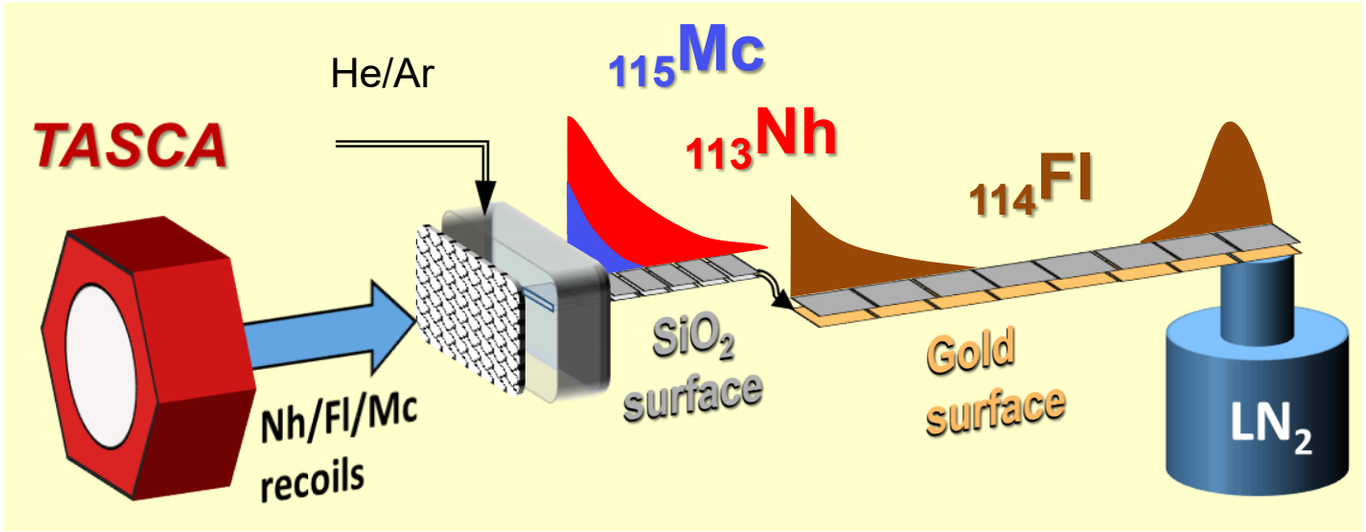
Nuclear data



A. Yakushev *et al.*, Front. Chem. 12 (2024) 1474820

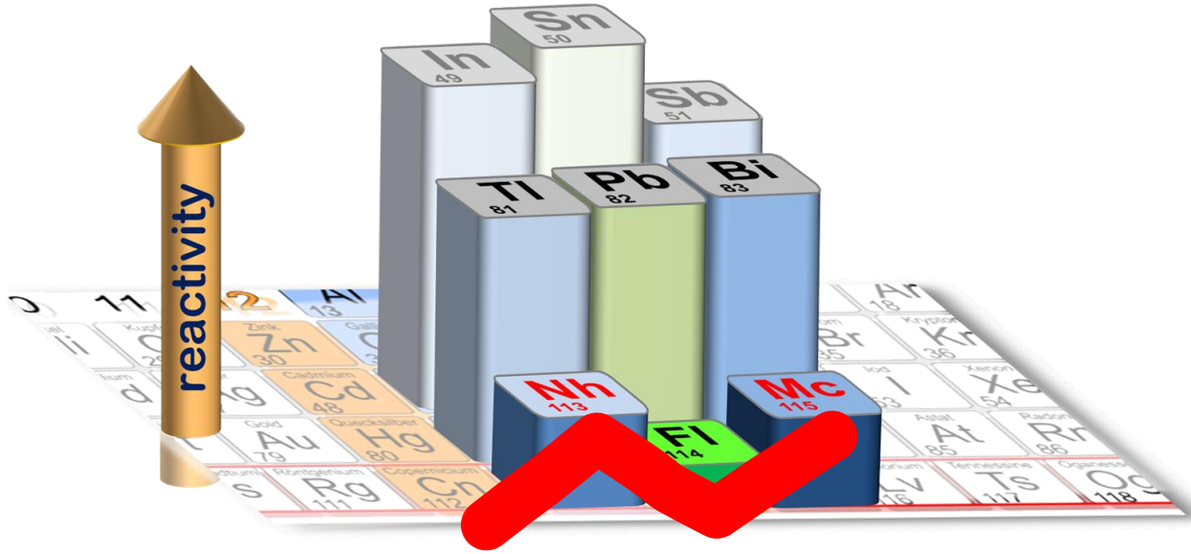
The heaviest chemically studied elements

Deposition of Nh, Fl, and Mc on SiO_2 and Au



A. Yakushev *et al.*, Front. Chem. 12 (2024) 1474820

Reactivity trends in groups 13-15



Bar height: $-\Delta H_{ads}$ on SiO_2

A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635

$7p_{1/2}$ subshell closure in $_{114}$Fl experimentally confirmed

Outlook beyond $_{115}$Mc

$_{116}$Lv: Even the lighter homolog Po is a radioelement
Basic interest for ADS (Po formation in Pb/Bi eutectic)

$_{117}$Ts: Ligther homolog At of high interest for the life science community (TAT)
Metallic vs. halogen behavior

Zn	Ga	Ge	As	Se	Br	Kr
48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Talk by Katharina Hermainski

Today, 11:30

Known isotopes from fusion of ^{48}Ca with actinides

^{249}Cf → $_{118}$Og

^{249}Bk → $_{117}$Ls

^{248}Cm → $_{116}$Lv

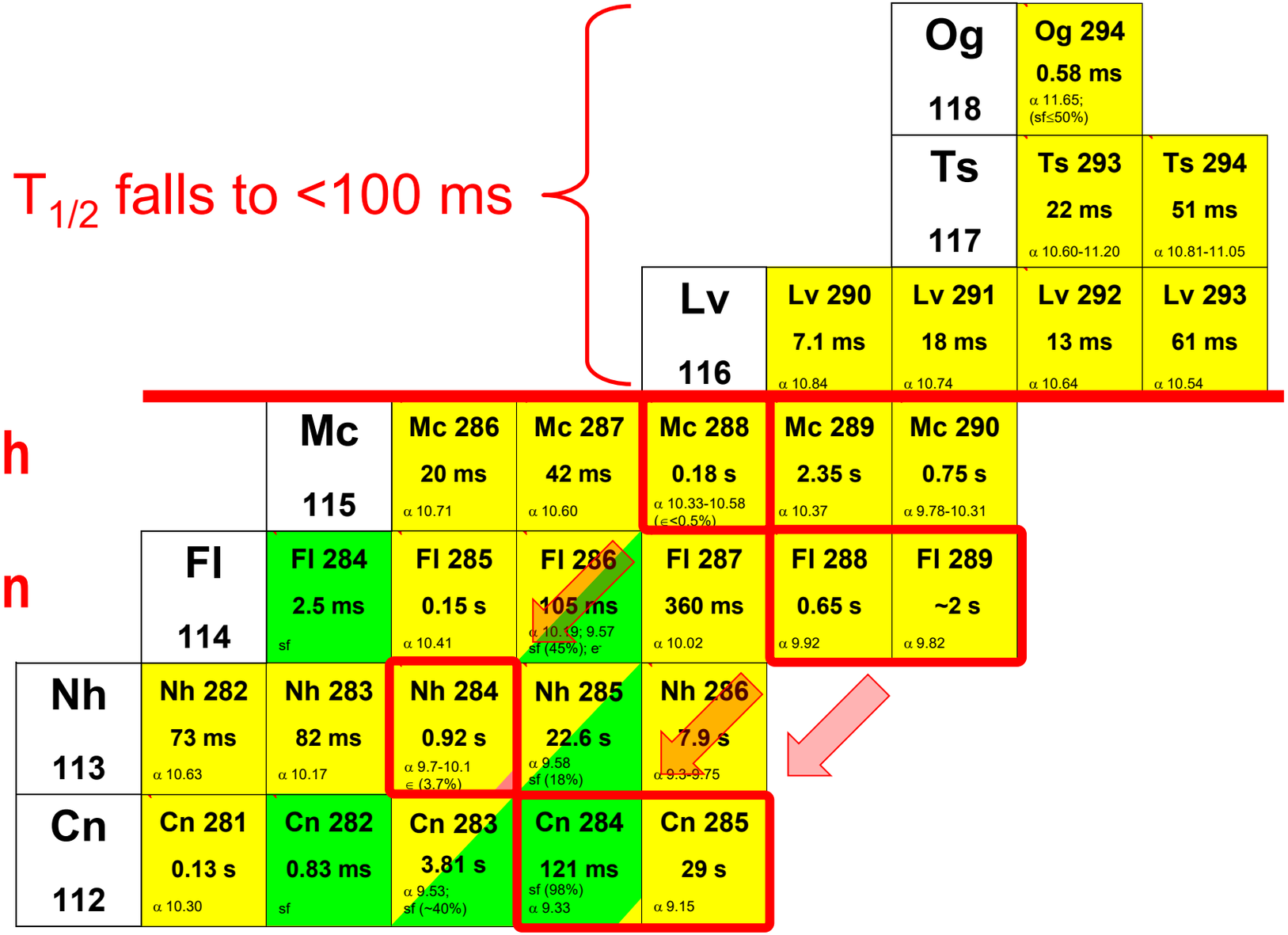
^{243}Am → $_{115}$Mc $\xrightarrow{\alpha}$ $_{113}$Nh

^{244}Pu → $_{114}$Fl $\xrightarrow{\alpha}$ $_{112}$Cn

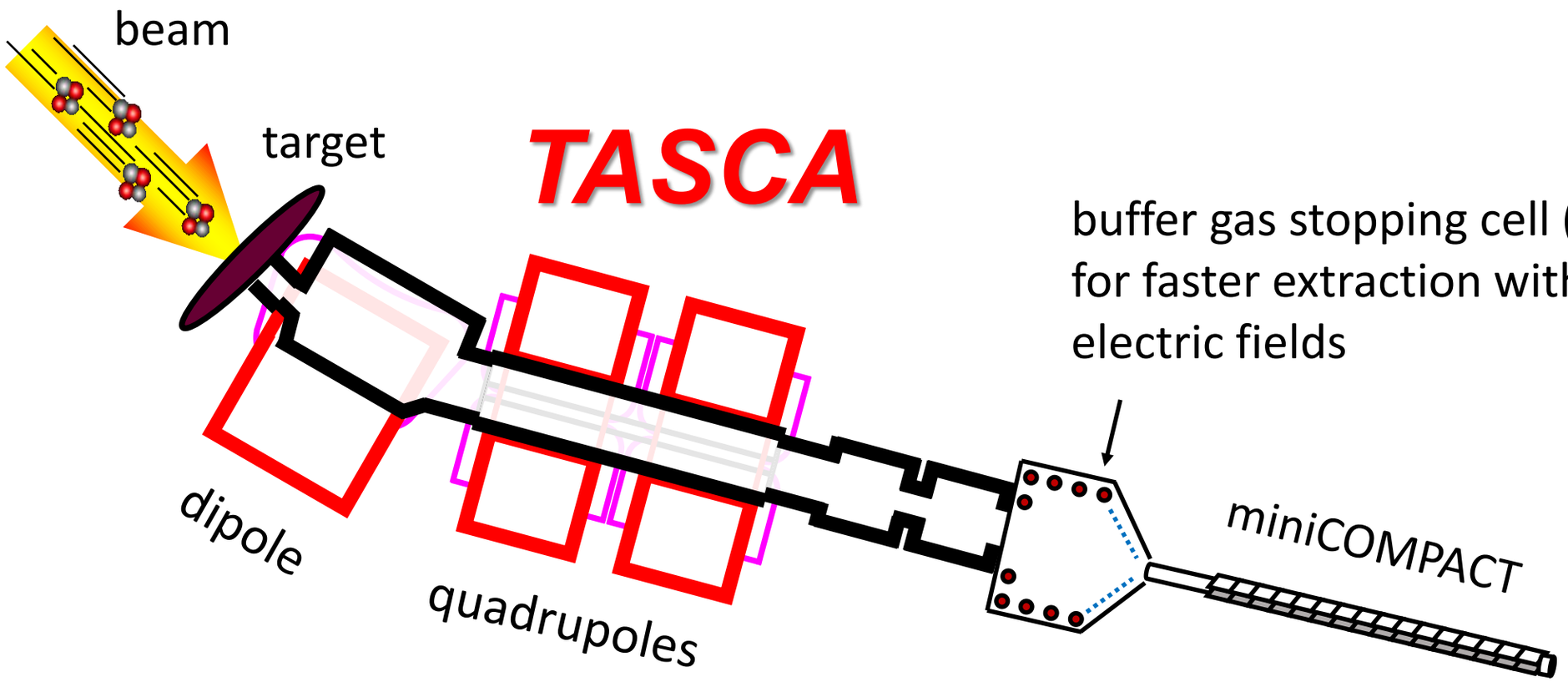
(^{237}Np → $_{113}$Nh)

(^{238}U → $_{112}$Cn)

$T_{1/2}$ falls to <100 ms



Beyond Mc: Preparing studies of $_{116}$Lv and $_{117}$Ts



buffer gas stopping cell (BGC) for faster extraction with electric fields

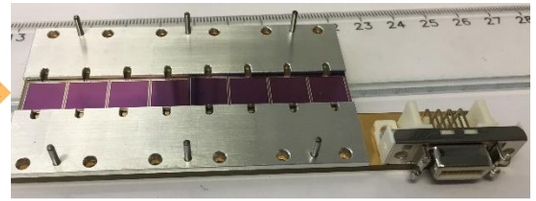
Successful tests with short-lived Hg, At, and Fr isotopes at Texas A&M Univ. and at GSI

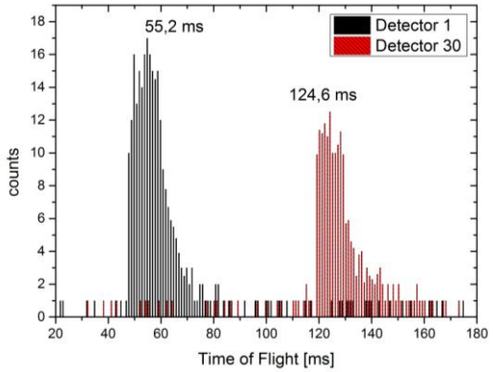
S. Götz *et al.*, Nucl. Instrum. Meth. B 507 (2021) 27

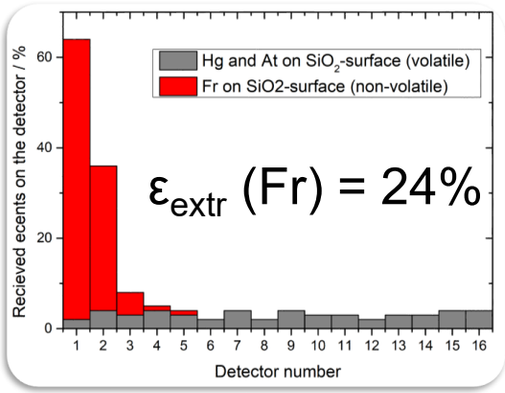
Beyond Mc: Preparing studies of ^{116}Lv and ^{117}Ts

First test experiments: Coupling of BGC with COMPACT and miniCOMPACT

He
50 mbar







Old „SHIP“
Buffer gas cell

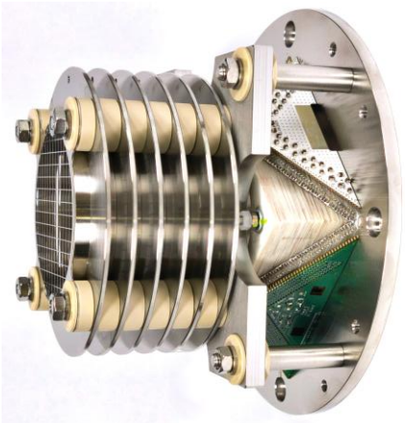
miniCOMPACT

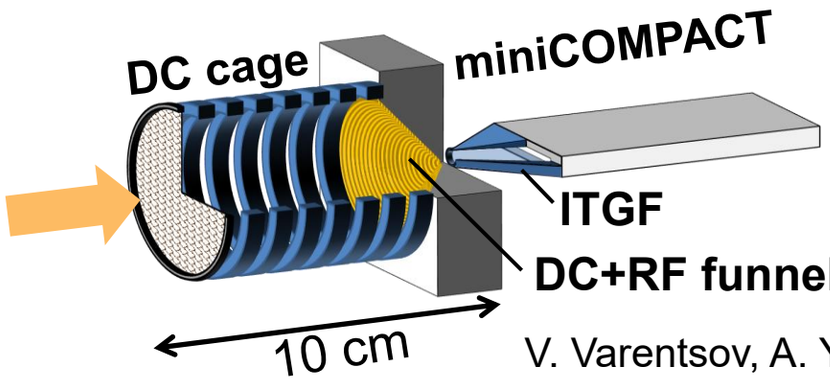
≈ 50 ms extraction time

S. Götz *et al.*, NIM A 995 (2021) 165090
S. Götz et al., NIM B 507 (2021) 27



High-pressure UniCell for faster extraction and higher efficiency





V. Varentsov, A. Yakushev, NIM A 940 (2019) 206
Y. Wei *et al.*, Nucl. Sci. Tech. 36 (2025) 187







Bundesministerium
für Bildung
und Forschung

Summary

- Chemical studies of the superheavy elements probe the structure of the periodic table
- Relativistic effects influence their electronic structure
- These lead to a sub-shell closure at $_{114}$Fl, which has been experimentally confirmed by studies of $_{113}$Nh, $_{114}$Fl, and $_{115}$Mc
- Come back after the coffee break to hear about molecular studies and the path to $_{116}$Lv