PSI Center for Nuclear Engineering and Sciences

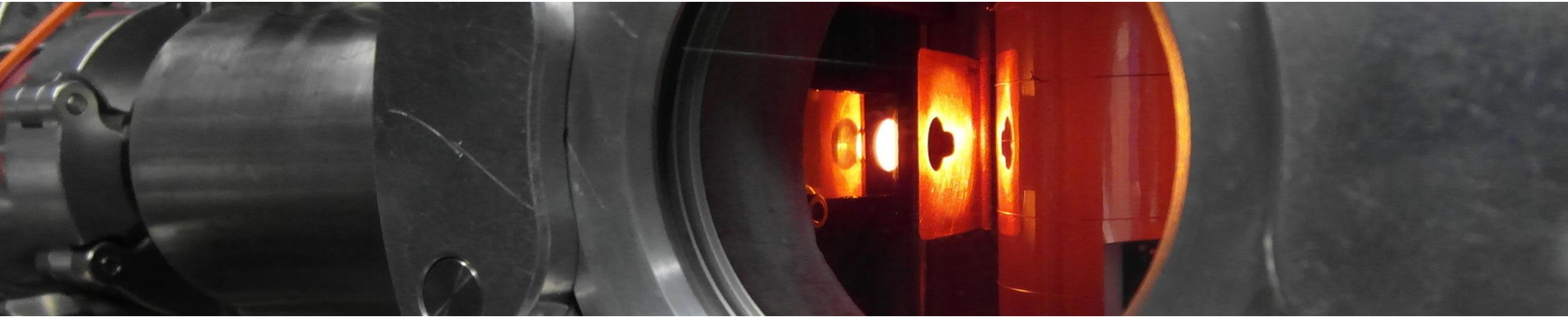
From Polonium to Nihonium

Radiochemical Research at the Paul Scherrer Institute

Patrick Steinegger (PSI / ETHZ)
European Summer School, Strasbourg, France, 01 – 05 July 2024

Agenda

1 Why do we need Radiochemistry?
2 The Laboratory of Radiochemistry
3 Radionuclide Production at PSI
4 Chemistry Experiments with Superheavy Elements
5 The Chemistry of Gen IV nuclear reactors



Why do we need Radiochemistry?

Key: atomic number
Symbol
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abridged standard atomic weight

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1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01		44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01			
		89-103 actinoids															

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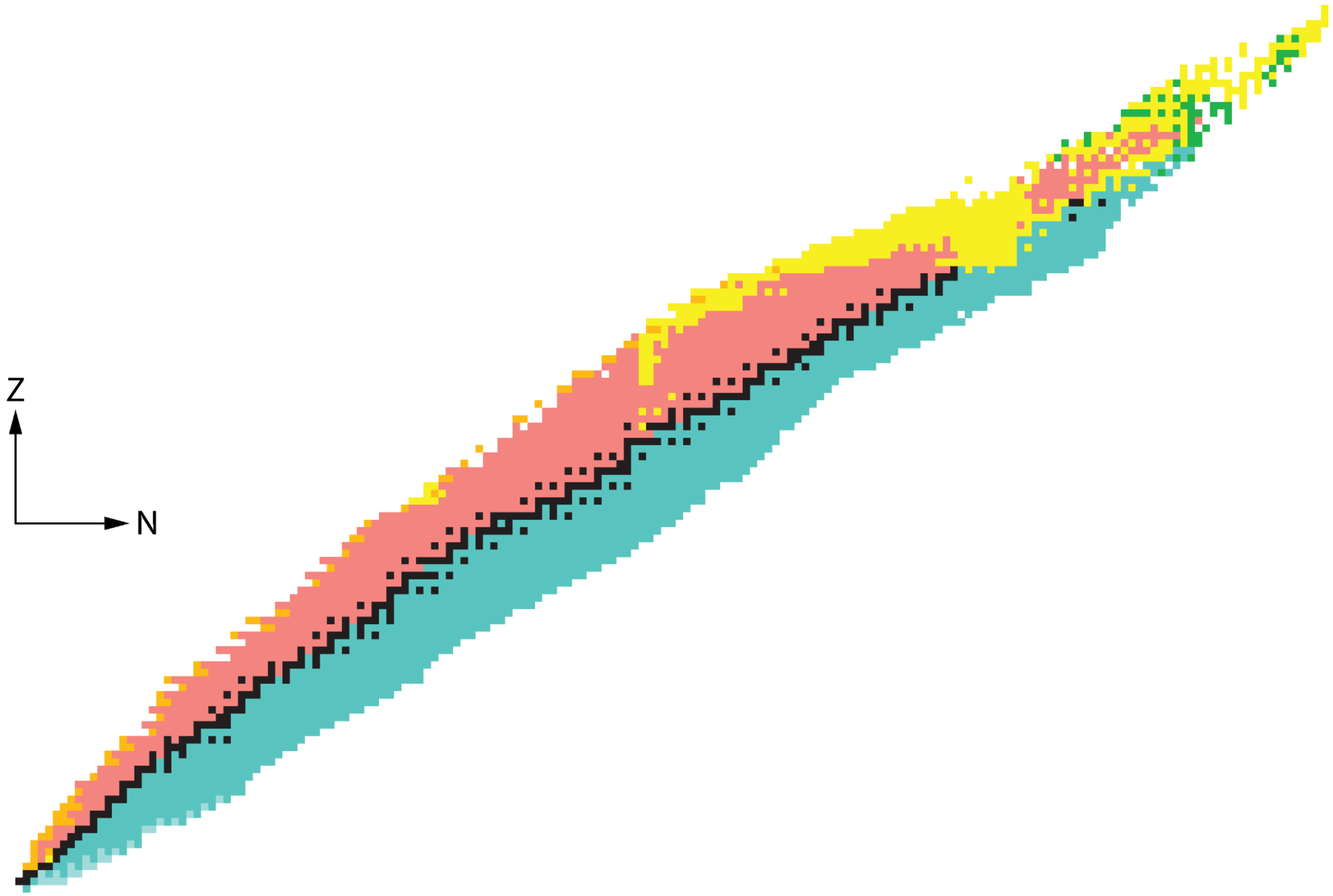
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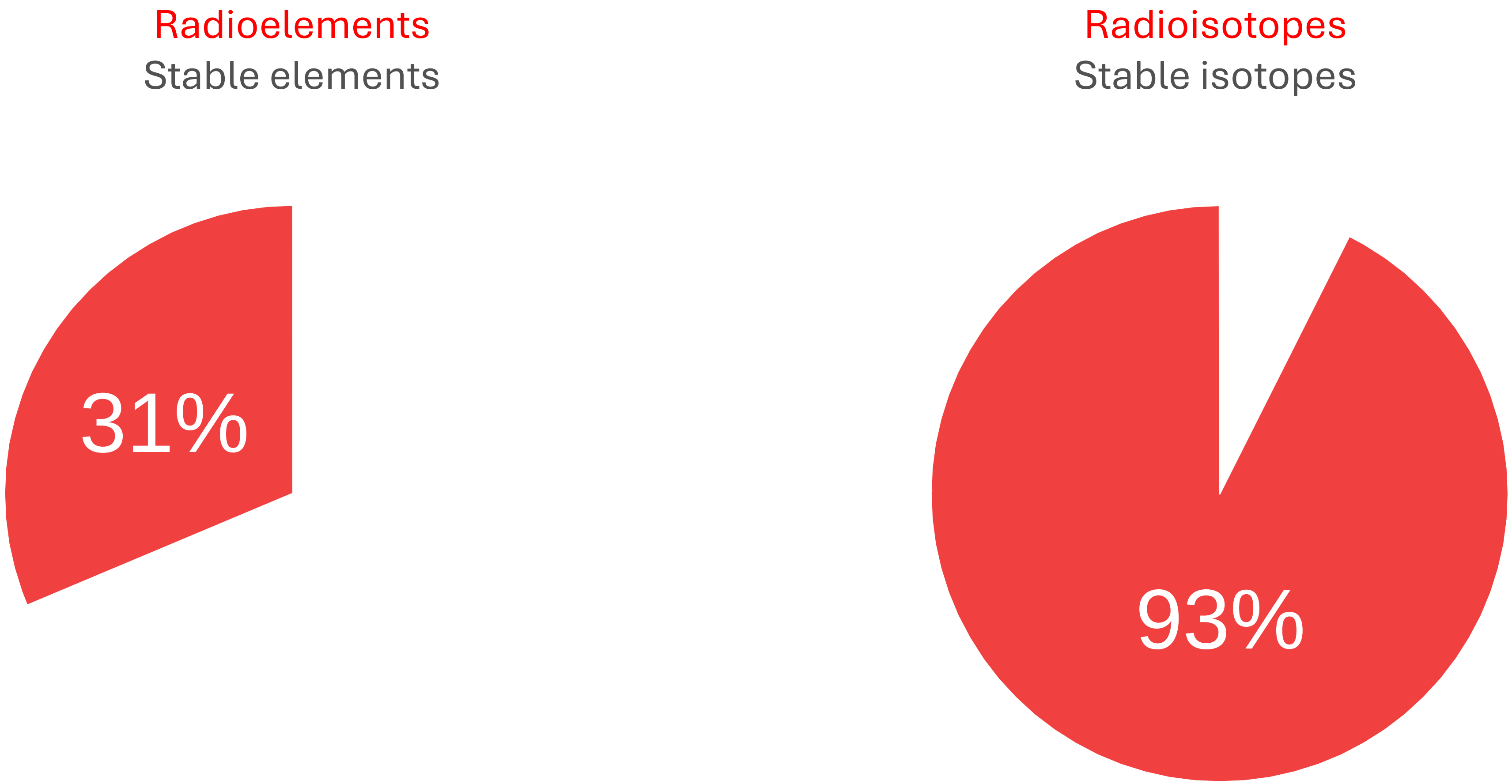

Radioelements
Stable elements
31%
Radioisotopes
Stable isotopes
93%

The Laboratory of Radiochemistry


PSI
ETH zürich
UNIVERSITÄT
BERN

The Laboratory of Radiochemistry

Postdoctoral researchers

PhD students

Prof. Dr. Robert Eichler

Sandha Keller (Admin, 80%)
Deputy lab head (tbd)

ETH zürich

HEAVY ELEMENTS
Prof. Dr. Patrick Steinegger

Dr. Rugard Dressler
Alexander Vögele
Dominik Herrmann

Jennifer Wilson (SNF)
Georg Tiebel (SNF)
Paul Dutheil (ENSI, LOG)
Michael Hofstetter (BABS)
Aleksandr Kharchenko (Uni Basel)

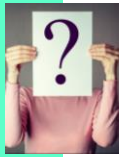
ISOTOPE & TARGET CHEMISTRY
Dr. Zeynep Talip

Dr. Jörg Neuhausen
Dr. Emilio Maugeri
Dr. Djordje Cvjetinovic
Dr. Haohan Zhang

Ivan Zivadinovic (EU, PATRICIA)
Noemi Cerboni (PSI)
Vladislav Zobnin (EU, PASCAL)
Xuandong Kou (Uni Bern)
Elizaveta Artiushova (SwissNuclear)

RADIONUCLIDE DEVELOPMENT
Dr. Nick van der Meulen

Dr. Who (CRS, BIO)
Dr. Pascal Grundler (CRS, BIO)
Colin Hillhouse (ITM)
Dr. Anzhelika Moiseeva
Dr. Maryam Mostamand

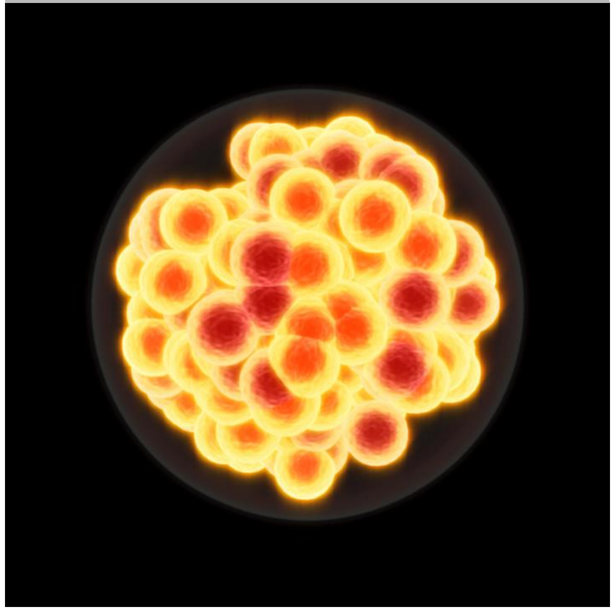


Edoardo Renaldin (Uni Bern)

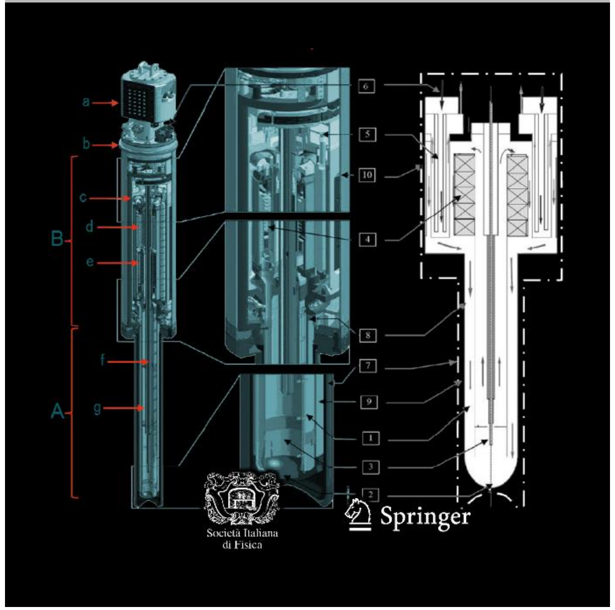
+ 2 to 3 Master- / Bachelor- / semester students

The Laboratory of Radiochemistry at PSI

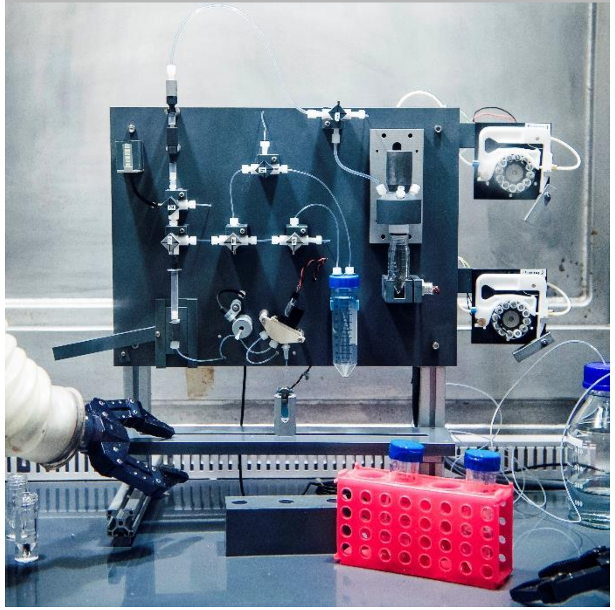
Heavy Elements



Isotope and Target Chemistry



Radionuclide Development



Pictures from: https://www.llnl.gov/; title page of the *European Physical Journal Plus* (vol. 131, no. 7, 2016) with a picture showing the MEGAPIE-target

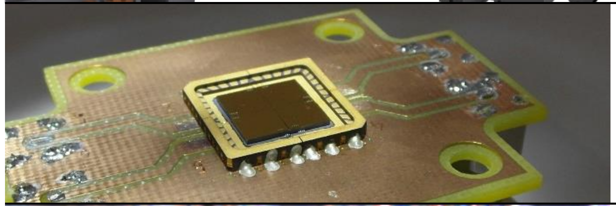
The Laboratory of Radiochemistry at PSI

Heavy Elements

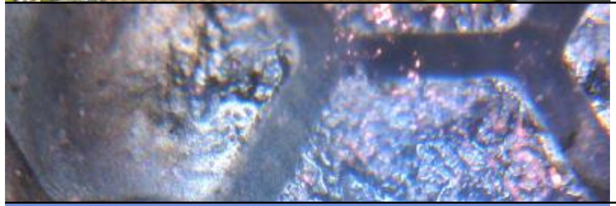
Isotope and Target Chemistry

Radionuclide Development

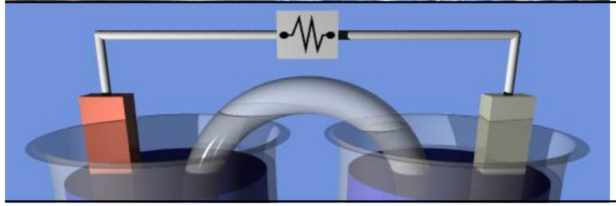
Gas adsorption chromatography with transactinide elements



Detector development for extreme conditions



Targets for heavy ion beam irradiations



Electrochemistry with transactinide elements

Daniell cell adapted from http://en.wikipedia.org

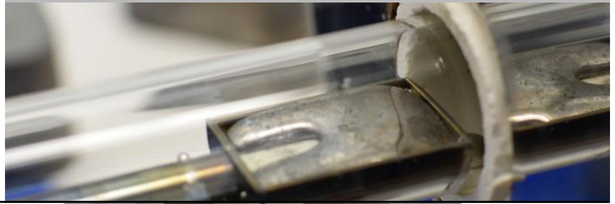
The Laboratory of Radiochemistry at PSI

Heavy Elements

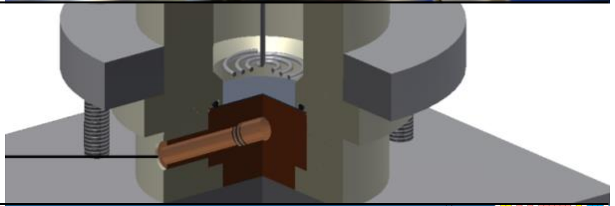
Isotope and Target Chemistry

Radionuclide Development

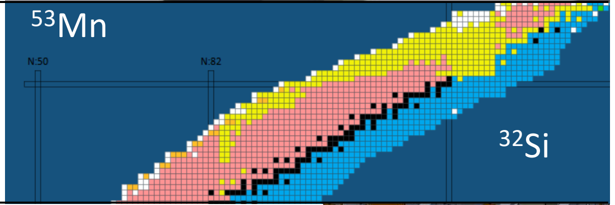
Liquid metal chemistry



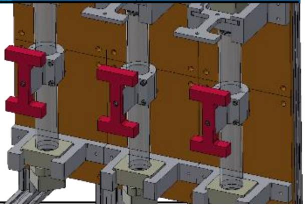
Isotope extraction and target manufacturing



Improvement of nuclear physics data



Waste treatment and isotope reclamation



The Laboratory of Radiochemistry at PSI

PSI

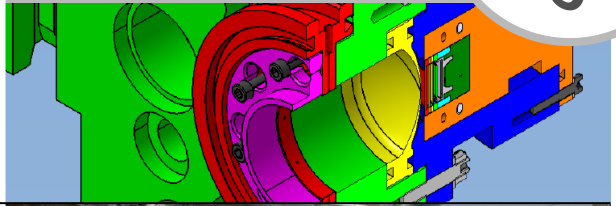
Heavy Elements

Isotope and Target Chemistry

Radionuclide Development

LRC + CRS

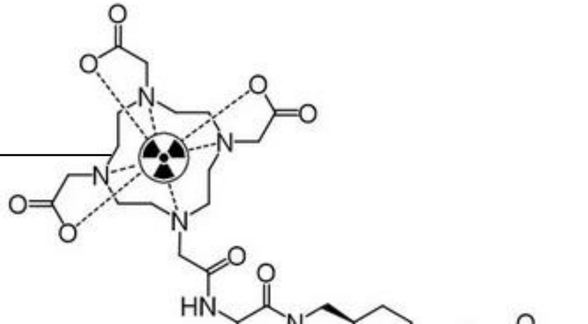
Target Development



Production of new radionuclides

Chemical separation and processing

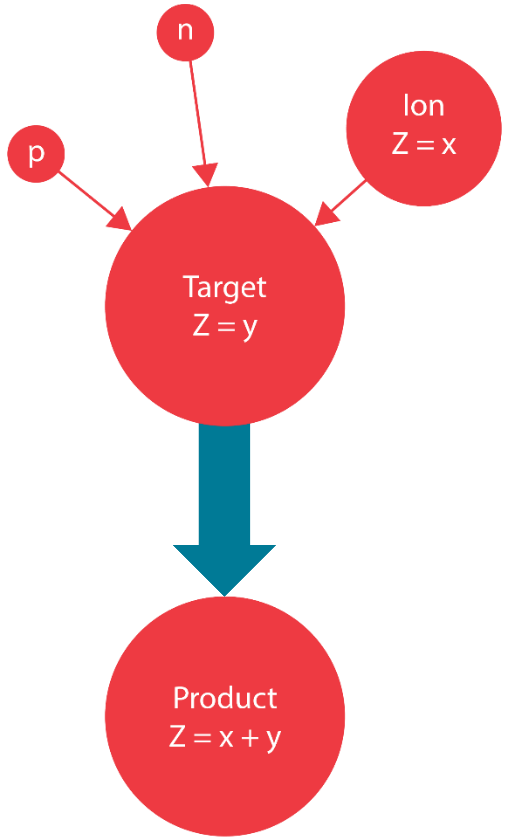
Theragnostics



https://www.radiopharmaceutical-science.ethz.ch und https://www.psi.ch/

Radionuclide Production at PSI (and elsewhere)

Radionuclide Production at PSI (and elsewhere)



> **Long-lived** radionuclides (h/d)

> **Offline** separation procedures

> **Short-lived** radionuclides (s)

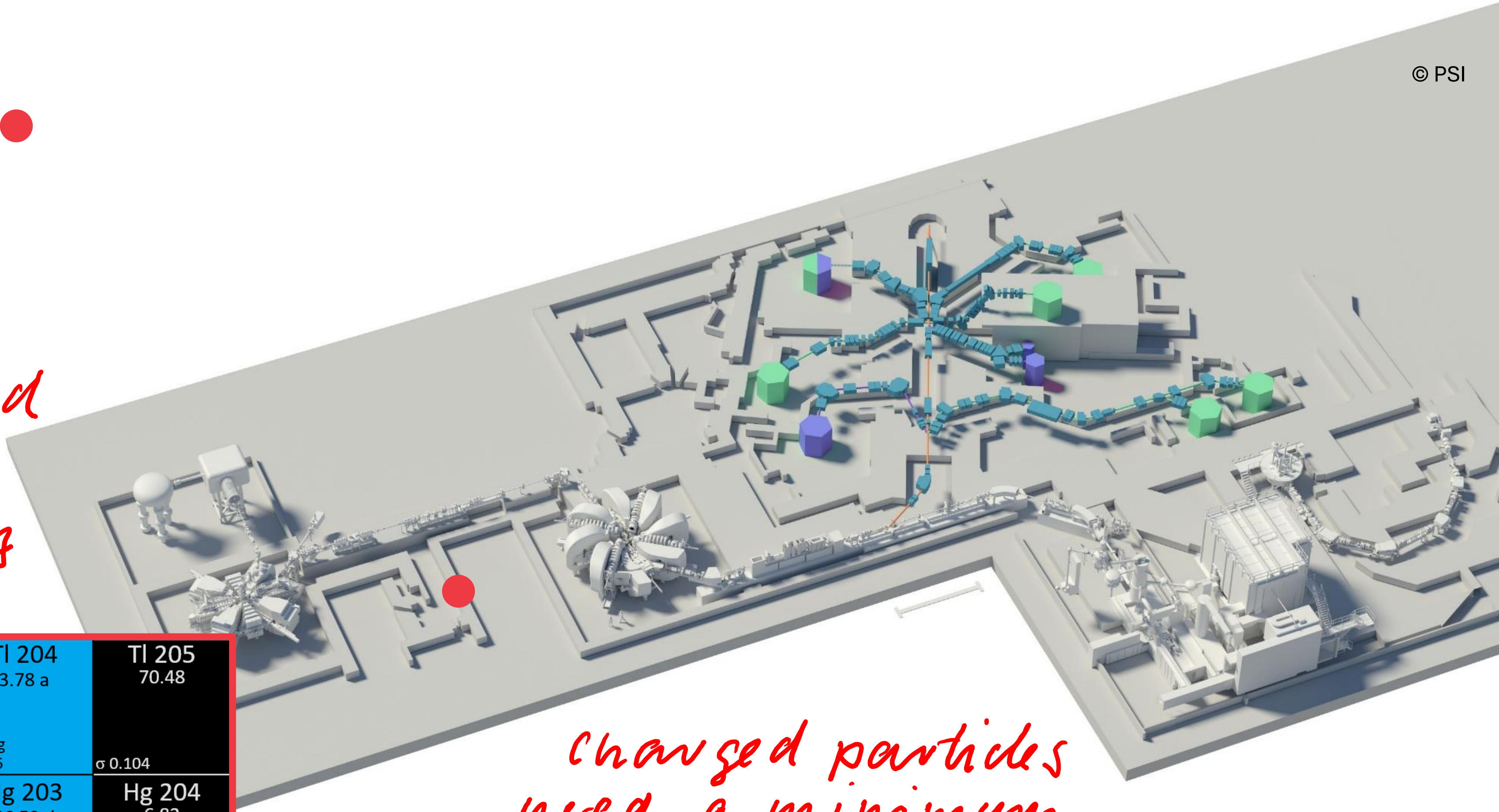
> **Online** separation procedures

Radionuclide Production at PSI

PSI

Why is our group at PSI?

- Proton irradiation (72 MeV)



number of evaporated neutrons depends on the initial energy of the proton beam

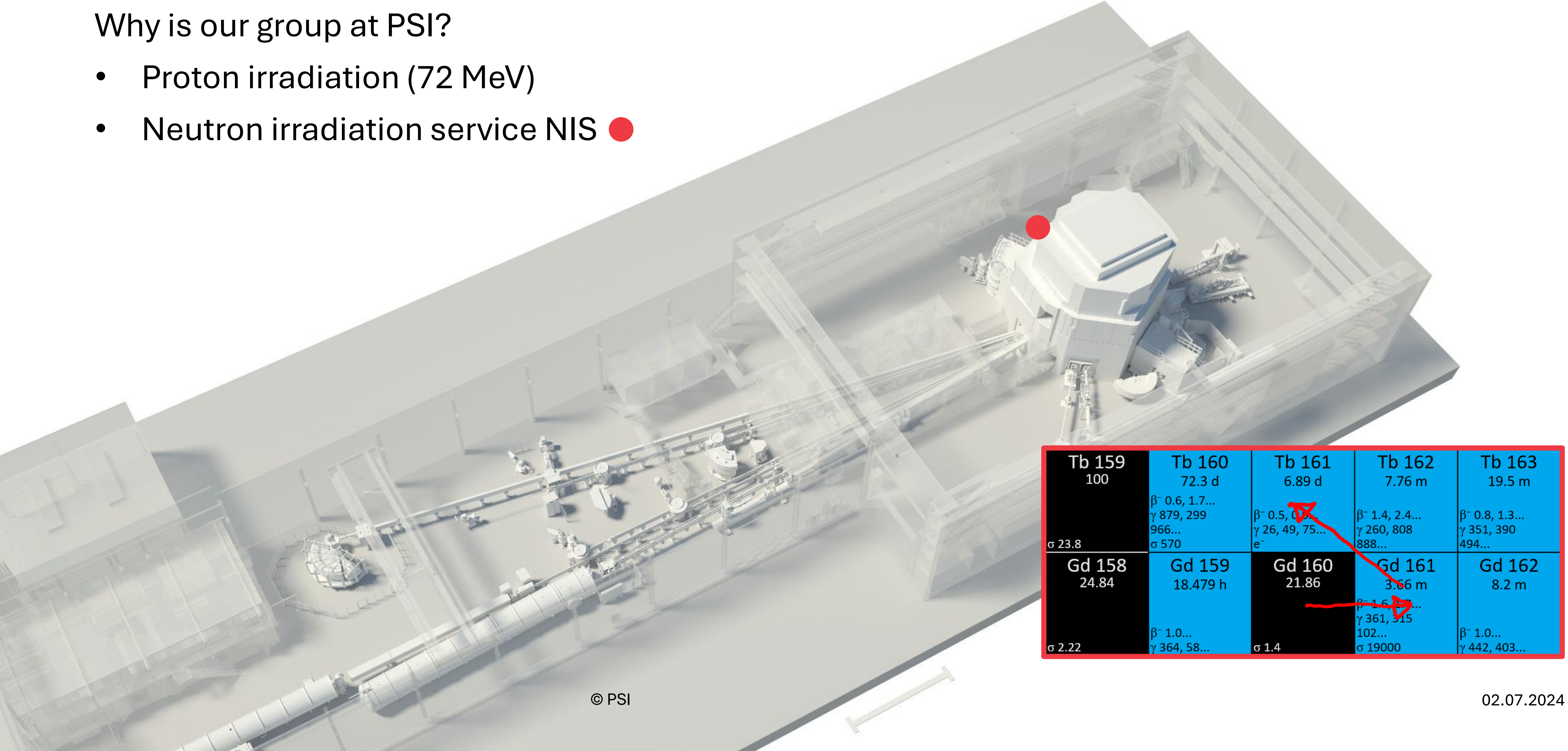
Tl 200 26.1 h ε β^+... γ 368, 1206, 579 828...	Tl 201 3.0422 d ε γ 167, 135...	Tl 202 12.23 d ε γ 440, (520...)	Tl 203 29.52 σ 11.4 $\sigma_{n,\alpha} < 0.0003$	Tl 204 3.78 a β^- 0.8 ε no γ, g σ 21.6	Tl 205 70.48 σ 0.104
Hg 199 42.67 m / 16.94 IT 374... e^- γ 158... / σ 2150	Hg 200 23.14 σ 15.0	Hg 201 13.17 σ 4.9	Hg 202 29.74 σ 4.91	Hg 203 46.59 d β^- 0.2 γ 279	Hg 204 6.82 σ 0.43

charged particles need a minimum energy to overcome the Coulomb barrier.

Radionuclide Production at PSI

Why is our group at PSI?

- Proton irradiation (72 MeV)
- Neutron irradiation service NIS



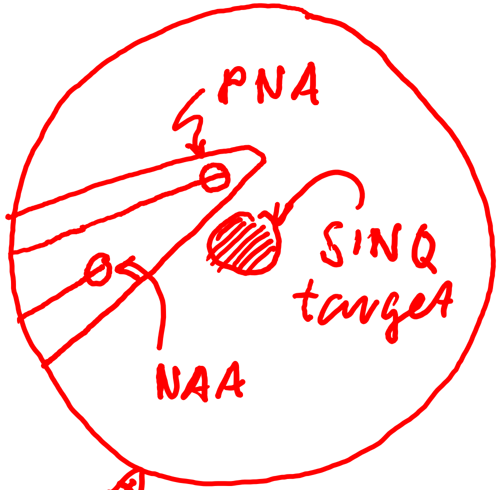
© PSI

Radionuclide Production at PSI

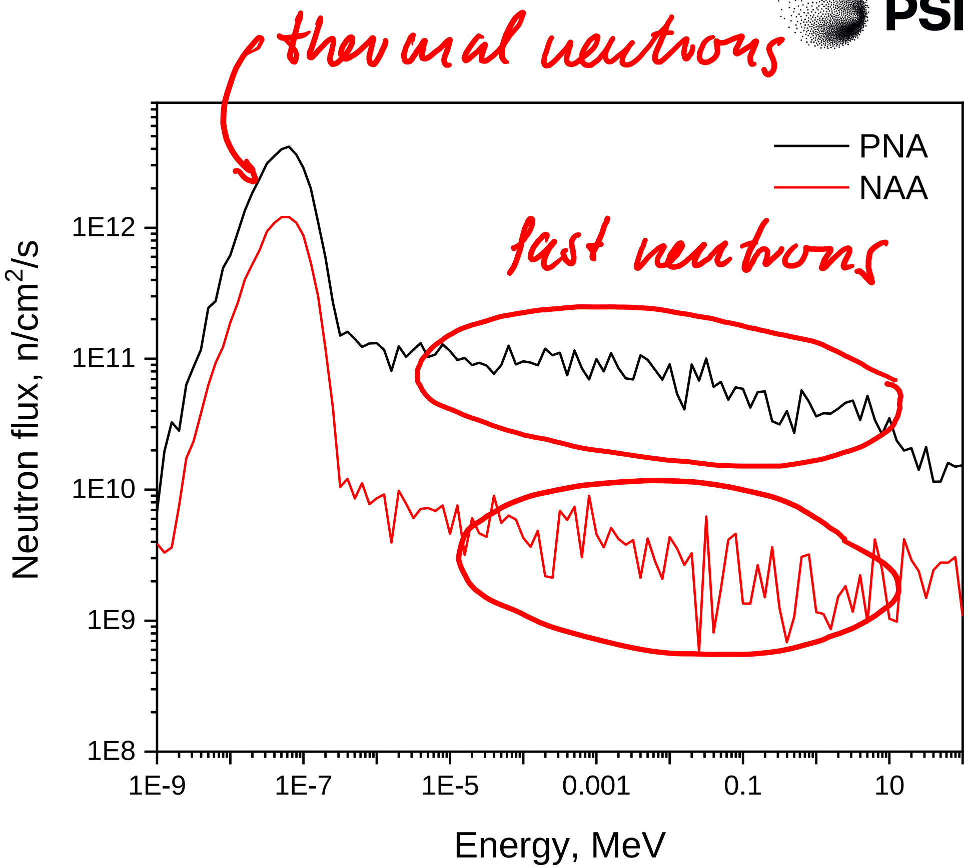
Two irradiation positions for longer irradiation times (PNA; up to 1000 h) and one for shorter irradiations (NAA; up to 2 h).

NAA

PNA



Neutron spallation source seen from top.

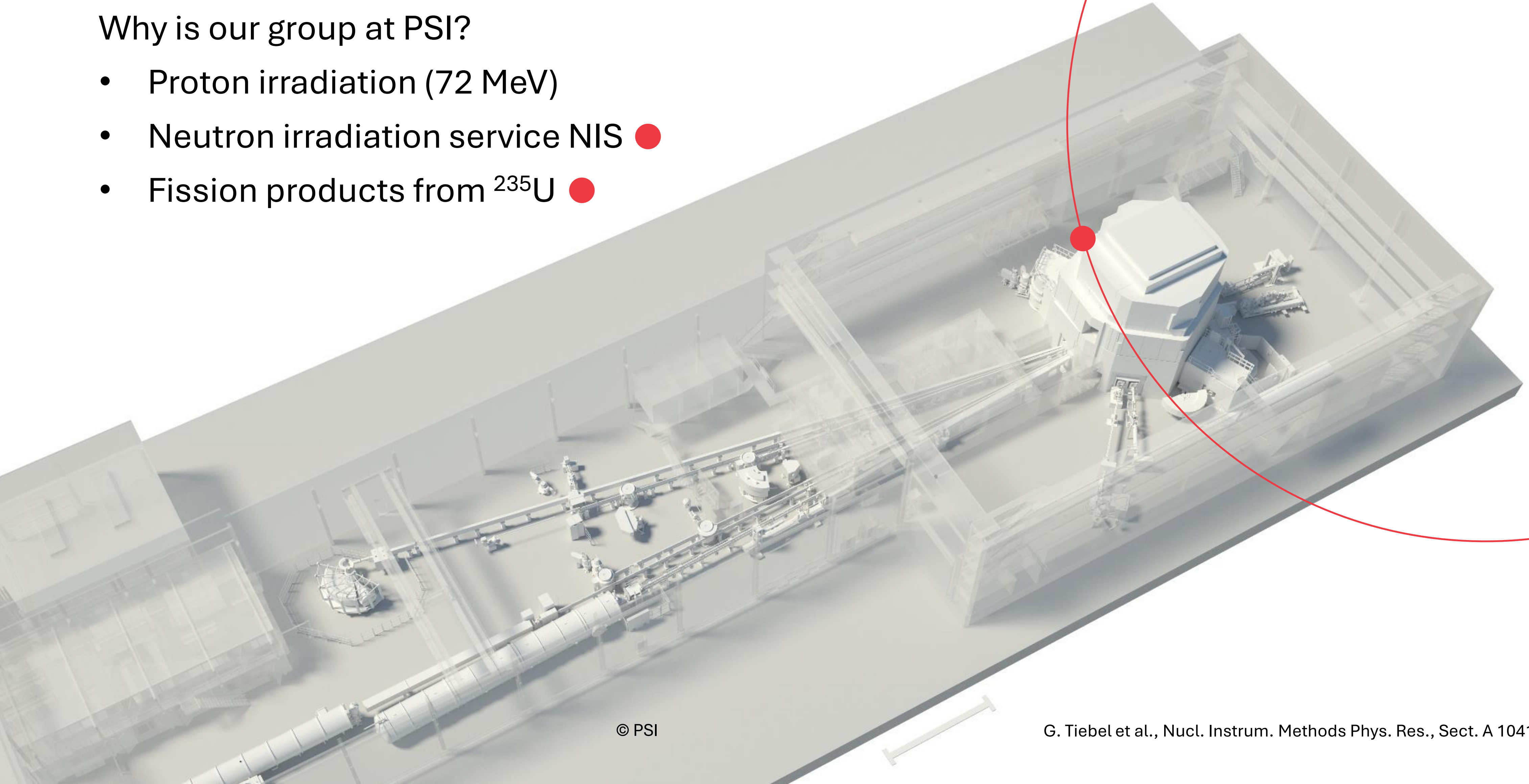


Tb 159 100 σ 23.8	Tb 160 72.3 d β⁻ 0.6, 1.7... γ 879, 299 966... σ 570	Tb 161 6.89 d β⁻ 0.5, [illegible]... γ 26, 49, 75... e⁻	Tb 162 7.76 m β⁻ 1.4, 2.4... γ 260, 808 888...	Tb 163 19.5 m β⁻ 0.8, 1.3... γ 351, 390 494...
Gd 158 24.84 σ 2.22	Gd 159 18.479 h β⁻ 1.0... γ 364, 58...	Gd 160 21.86 σ 1.4	Gd 161 3.66 m β⁻ [illegible]7... γ 361, 315 102... σ 19000	Gd 162 8.2 m β⁻ 1.0... γ 442, 403...

Radionuclide Production at PSI

Why is our group at PSI?

- Proton irradiation (72 MeV)
- Neutron irradiation service NIS
- Fission products from ^{235}U



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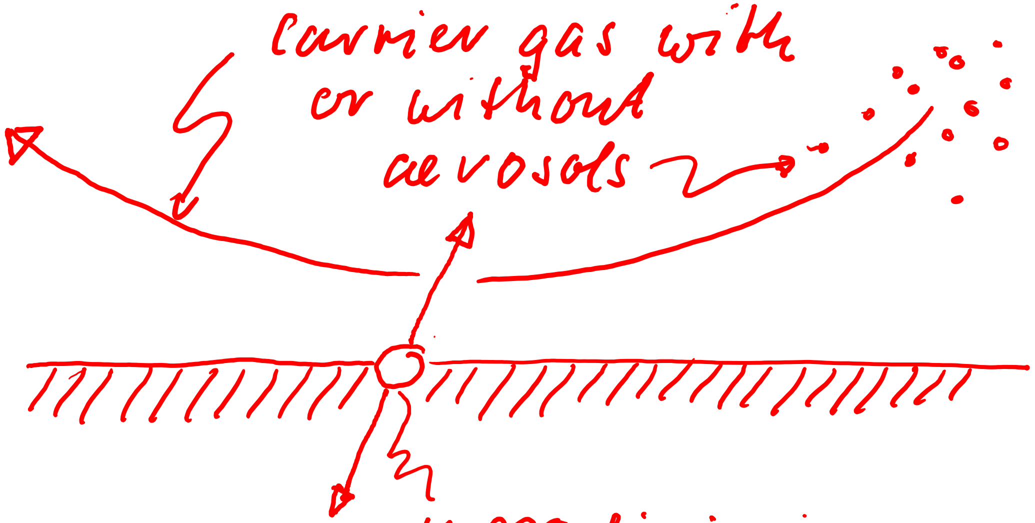
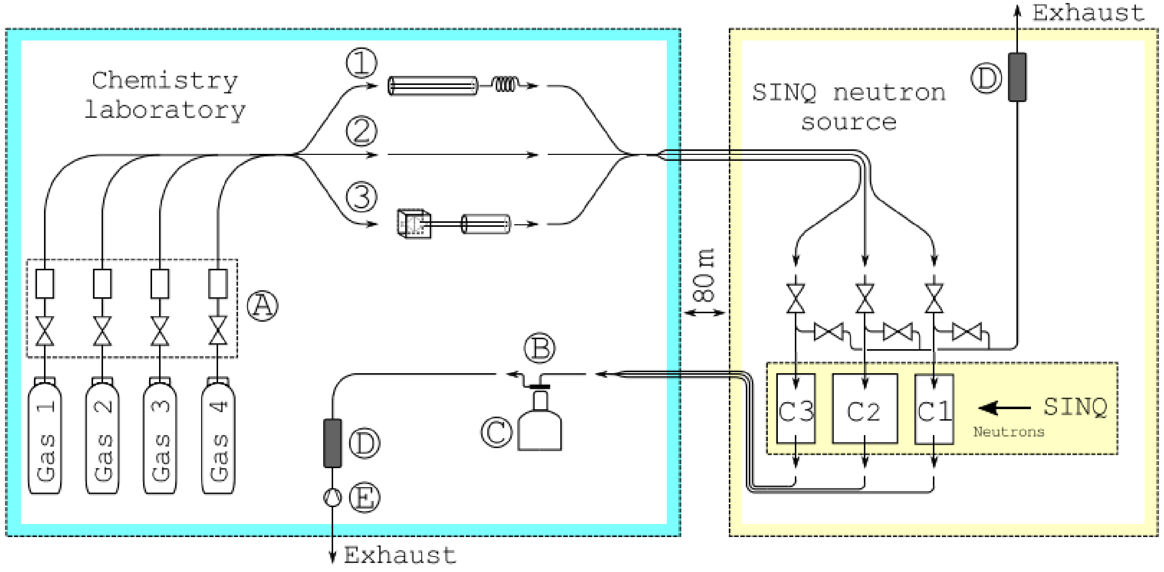
Radionuclide Production at PSI

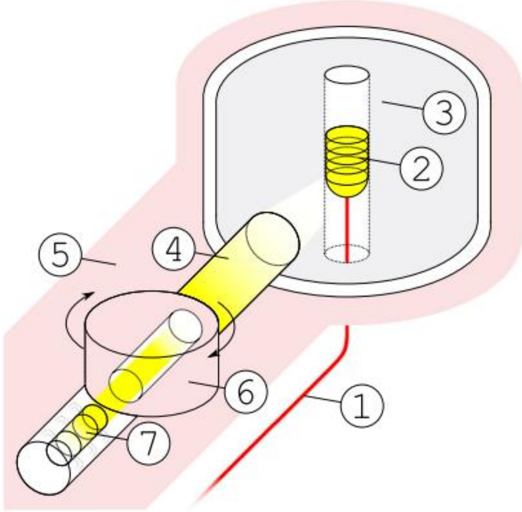
Thermal neutron-induced fission of ^{235}U

- **Volatile fission products** transported with a suitable carrier gas (e.g., N_2 or Ar).
- **Non-volatile fission products** transported with a aerosol-loaded (e.g., KCl) carrier gas.



U-235 fissioning
after capture
of thermal
neutron.





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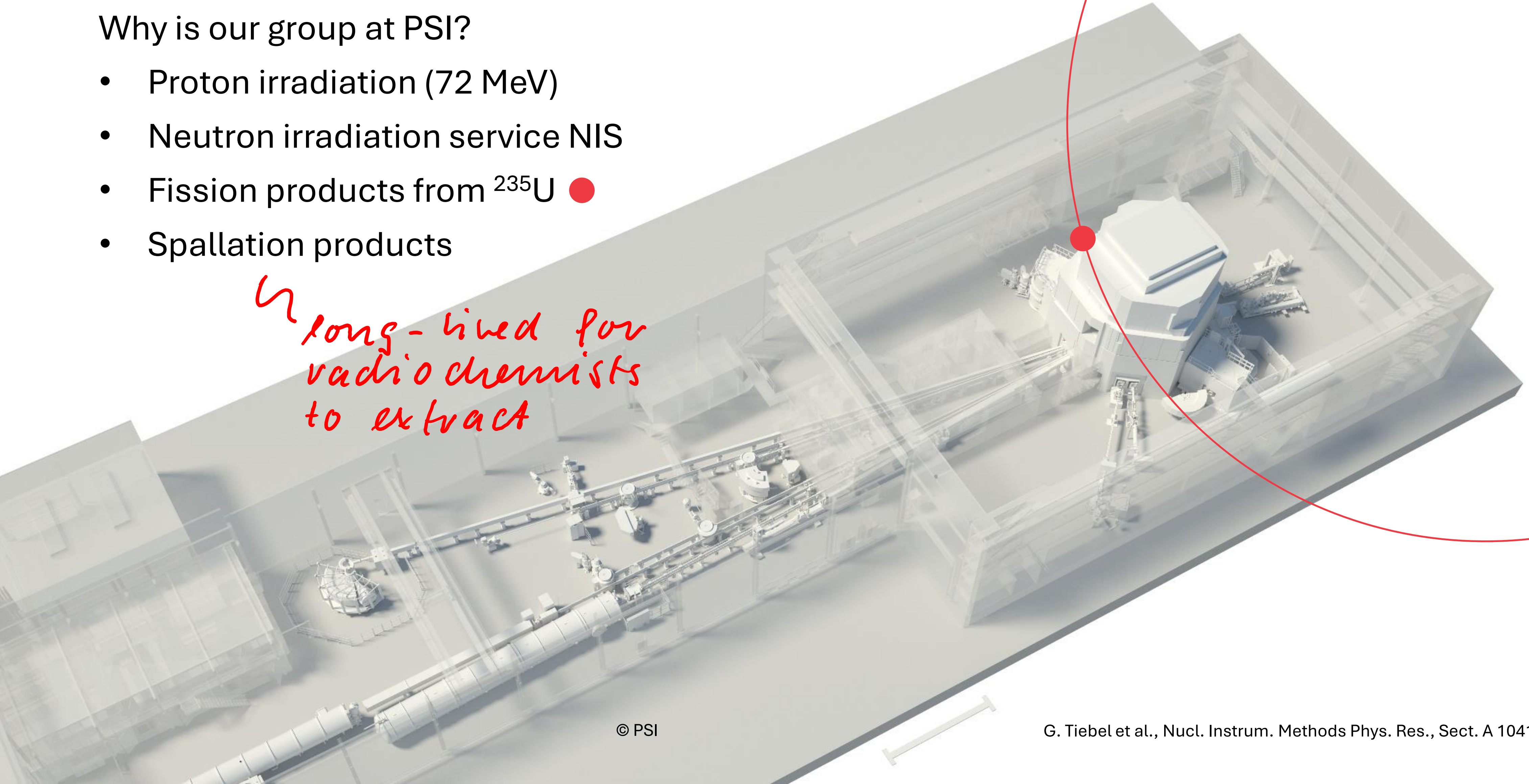
Radionuclide Production at PSI

Why is our group at PSI?

- Proton irradiation (72 MeV)
- Neutron irradiation service NIS
- Fission products from ^{235}U
- Spallation products

↳ long-lived for radiochemists to extract



G. Tiebel et al., Nucl. Instrum. Methods Phys. Res., Sect. A 1041 (2022) 167360

Chemistry Experiments with Superheavy Elements

250.000 €

What name was given to the chemical element with atomic number 110 in 2003?

A Darmstadtium

B Bonnium

C Oldenburgium

D Frankfurtium

250.000 €

What name was given to the chemical element with atomic number 110 in 2003?

A Darmstadtium

B Bonnium

C Oldenburgium

D Frankfurtium

Key: atomic number
Symbol
name
abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.

Relativitic effects

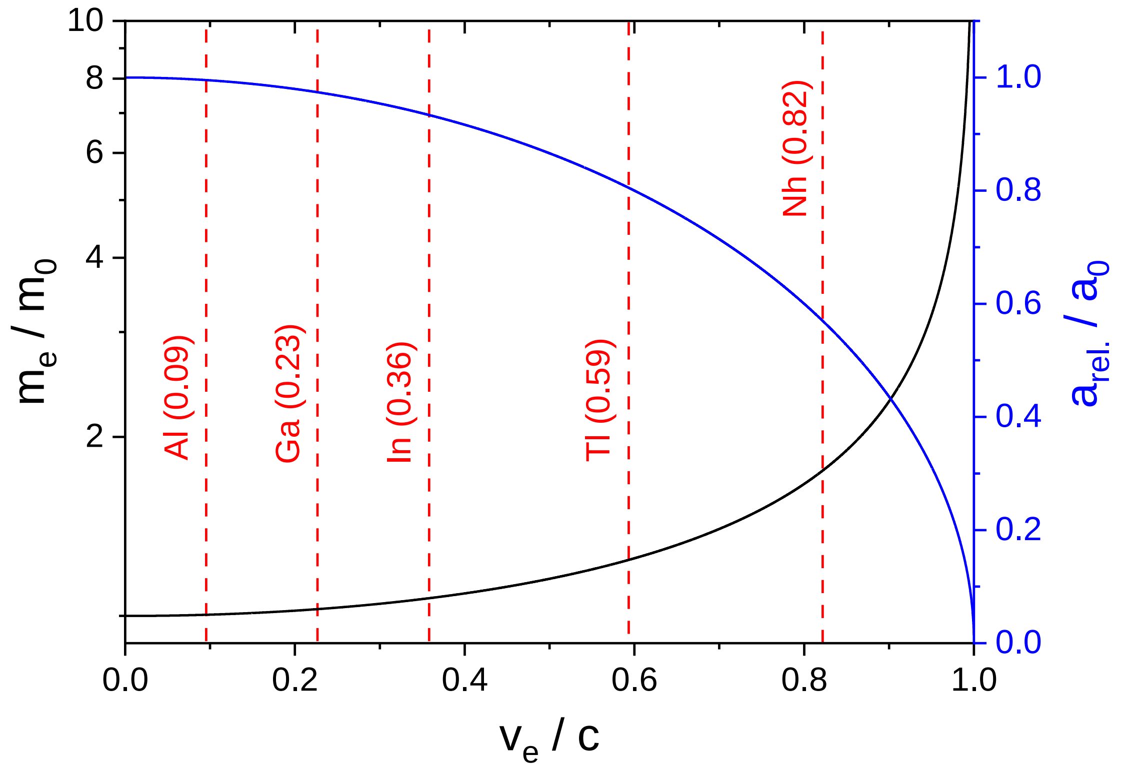
$E = mc^2$

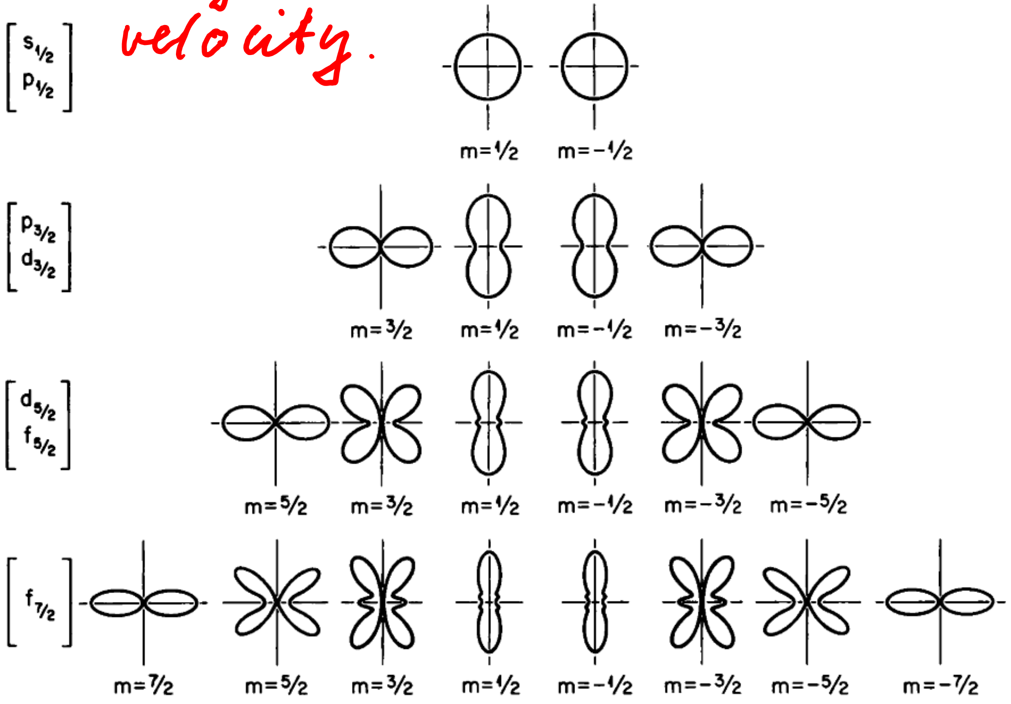
Group 13 of the periodic table and the influences of relativistic effects (ns-Orbitals).

$$m_e = \frac{m_0}{\sqrt{1-\left(\frac{v_e}{c}\right)^2}}$$

$$a_0 = n^2 \cdot \frac{4 \cdot \pi \cdot \epsilon_0 \cdot \hbar^2}{Z^2 \cdot m_e \cdot e^2}$$

electron "gains" mass due to its higher velocity.



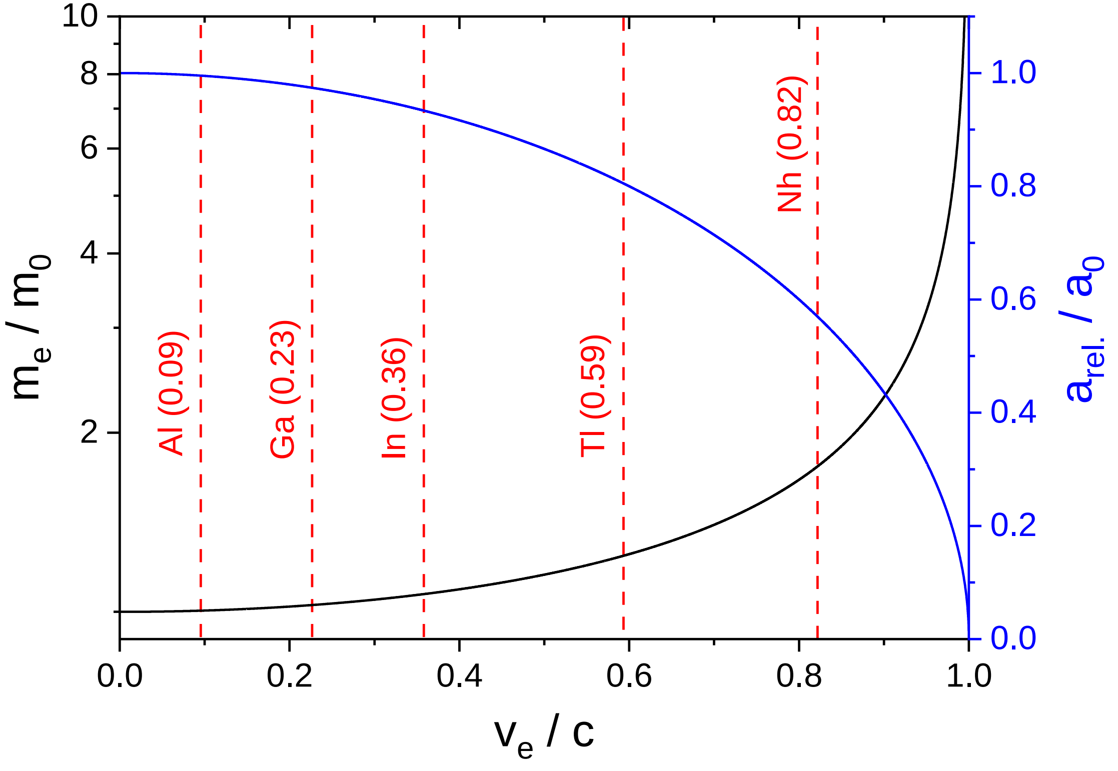


[Adapted from H. E. White, Phys. Rev. (1931)]

Orbital pictures: O. L Keller, Radiochimica Acta 37 (1984)

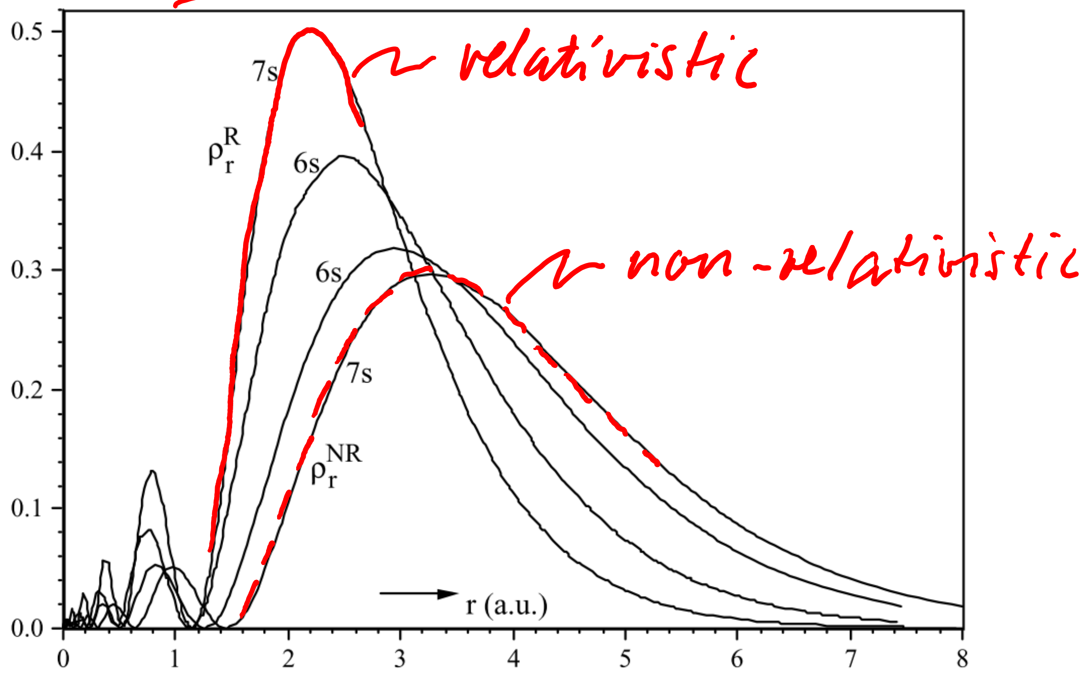
Relativitic effects

Group 13 of the periodic table and the influences of relativistic effects (ns-Orbitals).



We differentiate between different relativistic effects; these are:

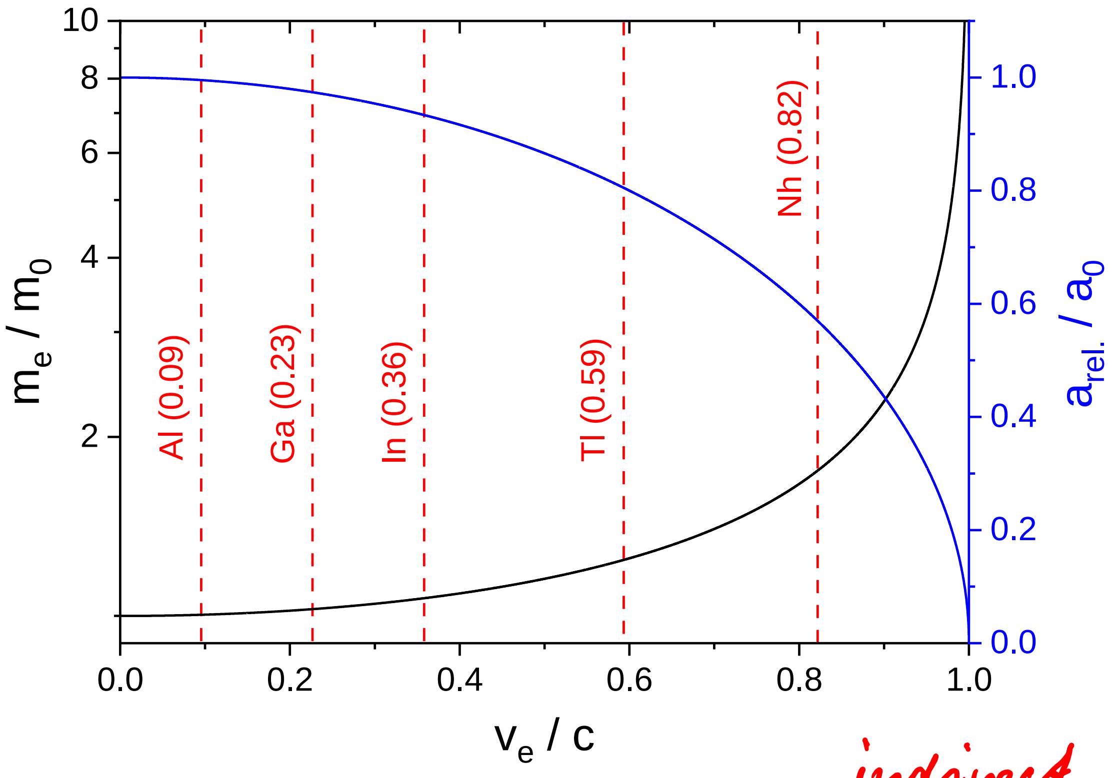
direct relativistic effects



Graph (right side): P. Schwerdtfeger, Heteroatom Chemistry 13(6) (2002)

Relativitic effects

Group 13 of the periodic table and the influences of relativistic effects (ns-Orbitals).



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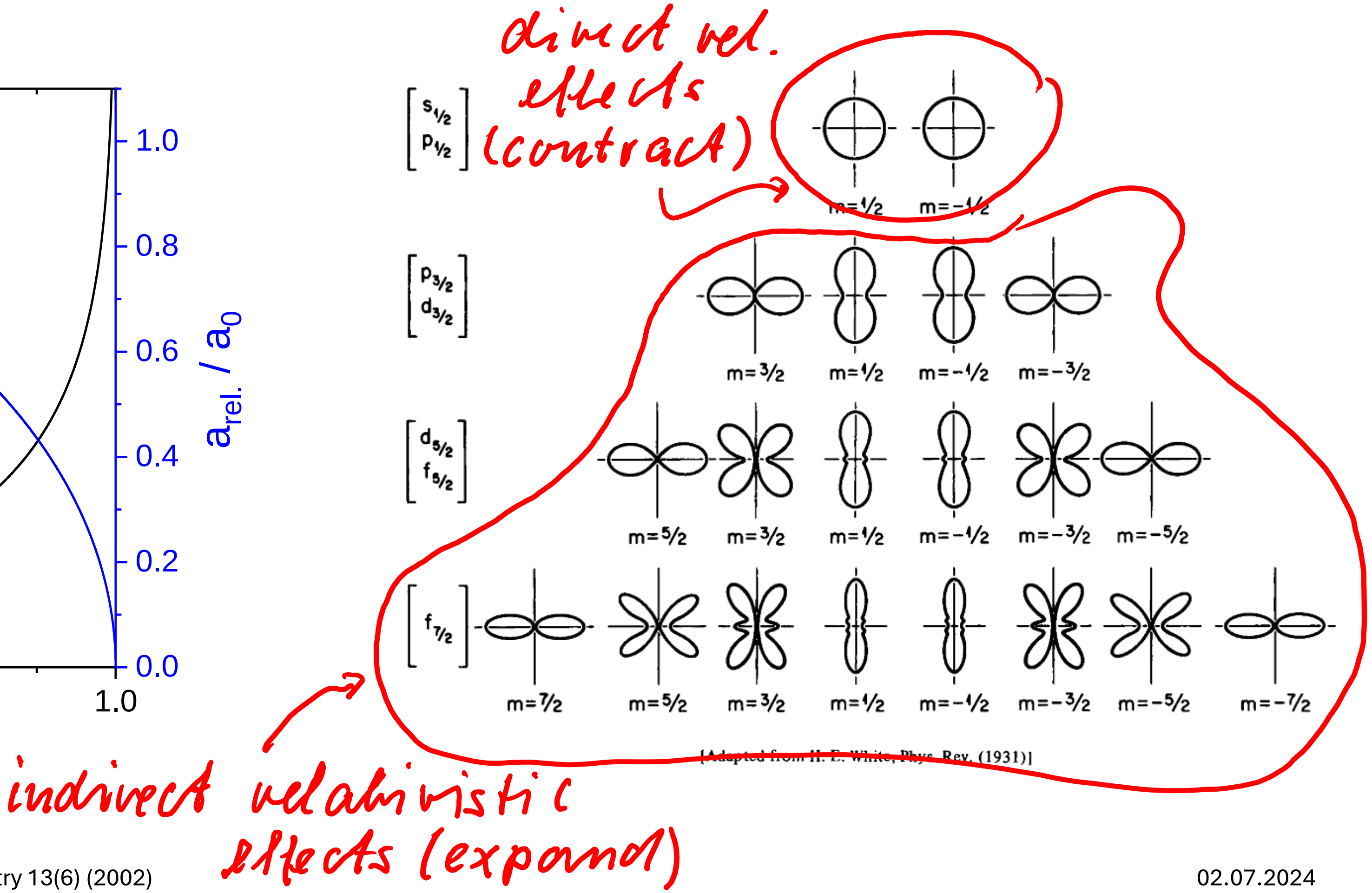
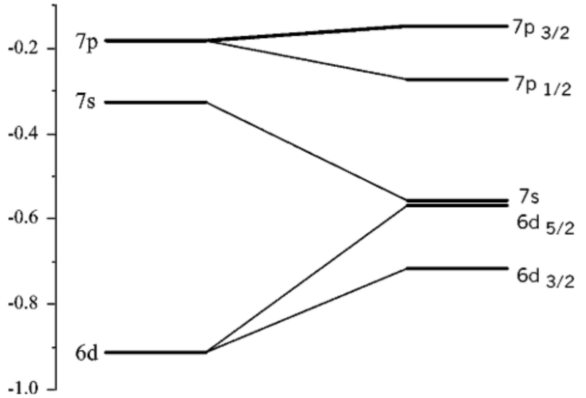
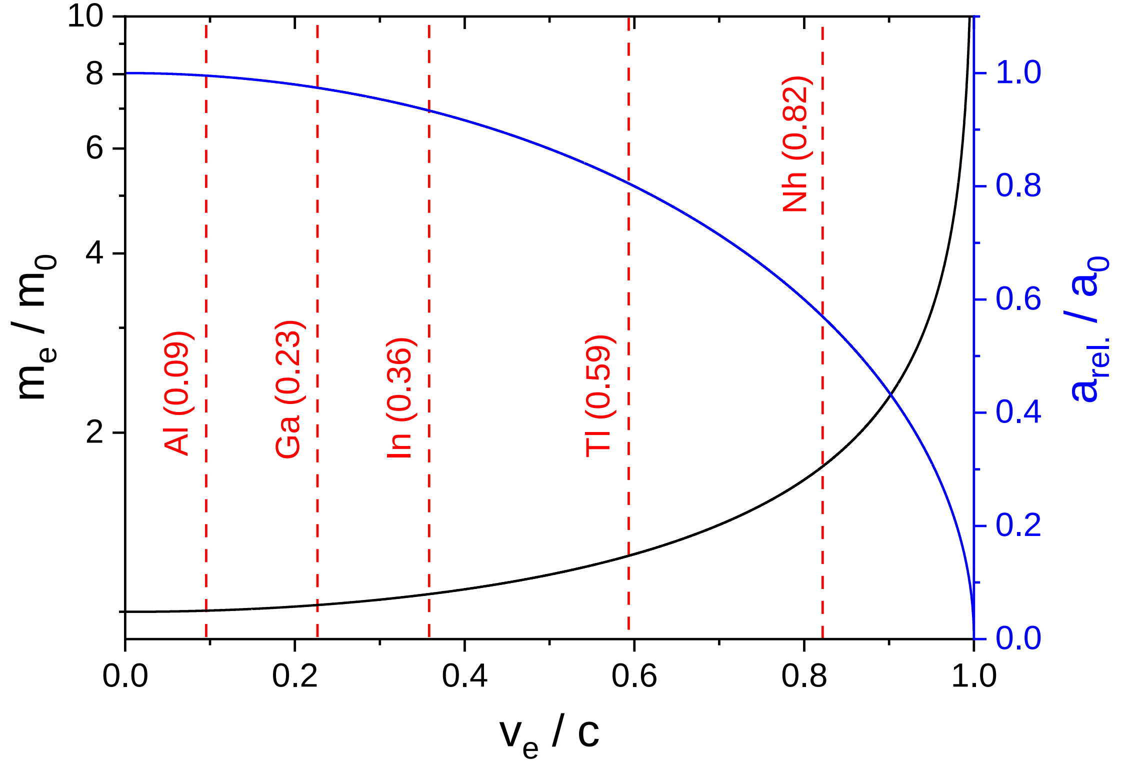


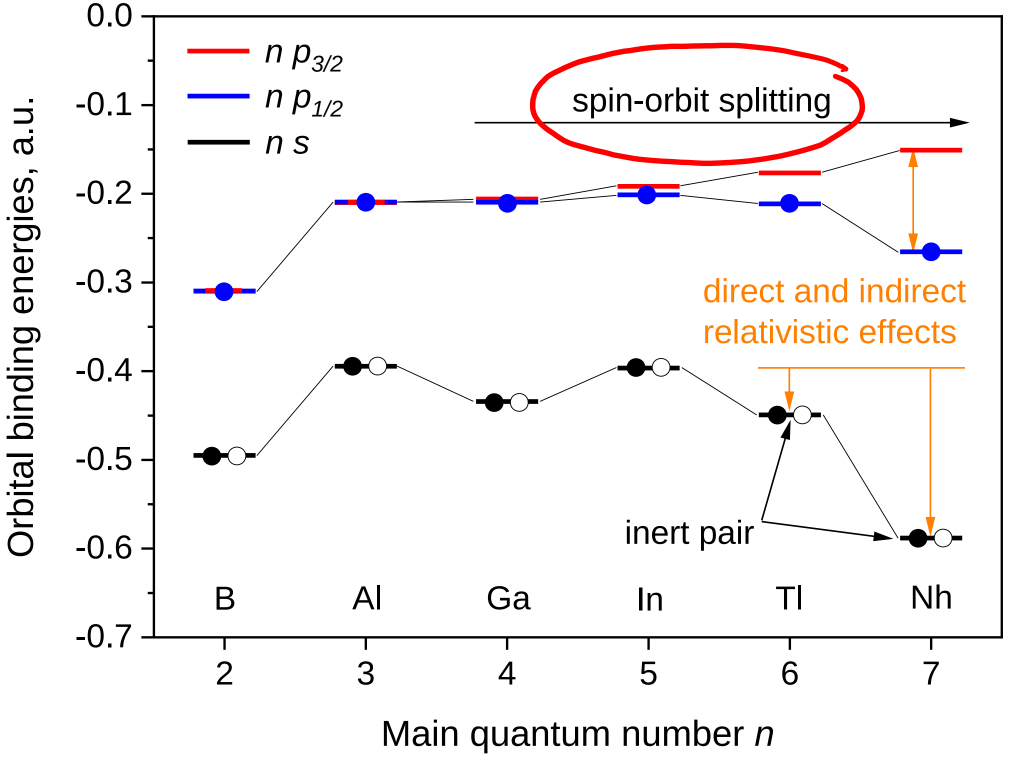
Graph (right side): P. Schwerdtfeger, Heteroatom Chemistry 13(6) (2002)

Relativitic effects

Group 13 of the periodic table and the influences of relativistic effects (ns-Orbitals).







Graph (right side): P. Schwerdtfeger, Heteroatom Chemistry 13(6) (2002)

Relativistic effects

PSI

Where else?

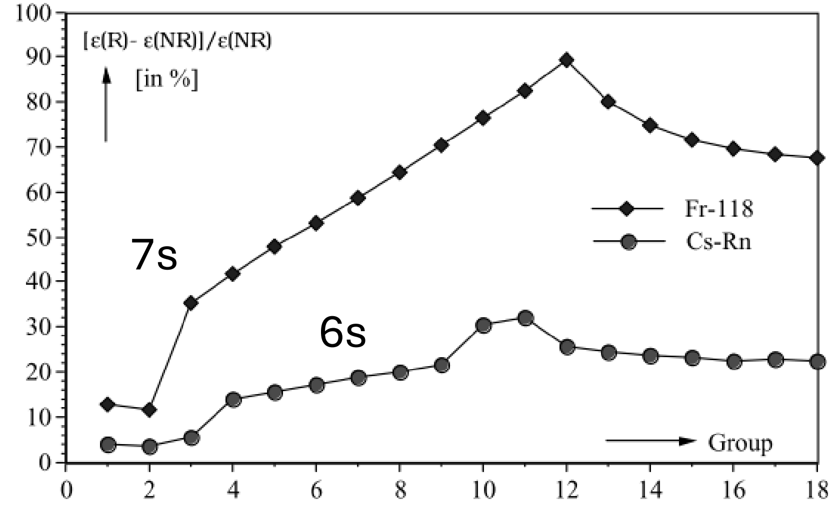
PRL **106,** 018301 (2011) PHYSICAL REVIEW LETTERS week ending 7 JANUARY 2011

Relativity and the Lead-Acid Battery

Rajeev Ahuja,[1,*] Andreas Blomqvist,[1] Peter Larsson,[1] Pekka Pyykkö,[2,†] and Patryk Zaleski-Ejgierd[2,‡]
[1]*Division of Materials Theory, Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20, Uppsala, Sweden*
[2]*Department of Chemistry, University of Helsinki, Box 55 (A. I. Virtasen aukio 1), FI-00014 Helsinki, Finland*
(Received 30 August 2010; published 5 January 2011)

The energies of the solid reactants in the lead-acid battery are calculated *ab initio* using two different basis sets at nonrelativistic, scalar-relativistic, and fully relativistic levels, and using several exchange-correlation potentials. The average calculated standard voltage is 2.13 V, compared with the experimental value of 2.11 V. All calculations agree in that 1.7–1.8 V of this standard voltage arise from relativistic effects, mainly from PbO_2 but also from $PbSO_4$.

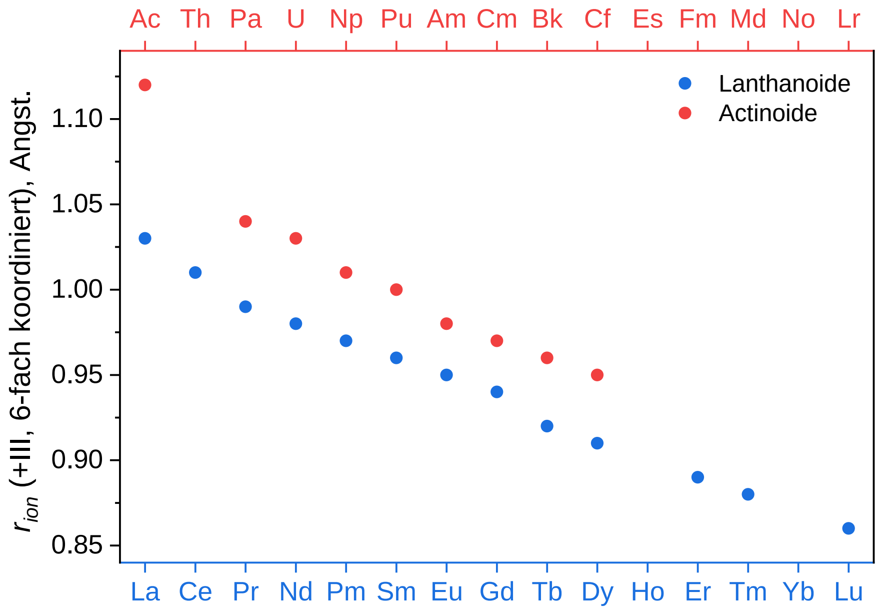
DOI: 10.1103/PhysRevLett.106.018301 PACS numbers: 82.47.Cb, 31.15.ae, 31.15.aj, 82.60.Cx



Why Is Mercury Liquid?

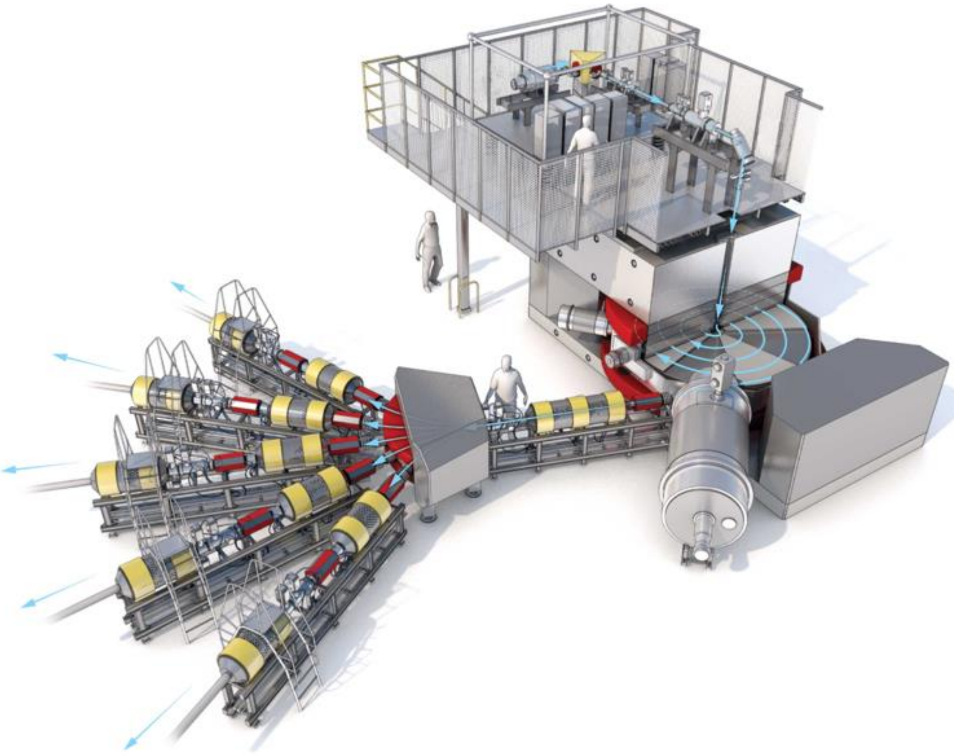
Or, Why Do Relativistic Effects Not Get into Chemistry Textbooks?

Lars J. Norrby
Royal Military College of Canada, Kingston, ON, Canada K7K 5L0



Chemical plant?

Fusion reactions.



Pictures: Adobe Stock, Science Magazine

The Alchemist’s Cookbook

Key:

atomic number Symbol name abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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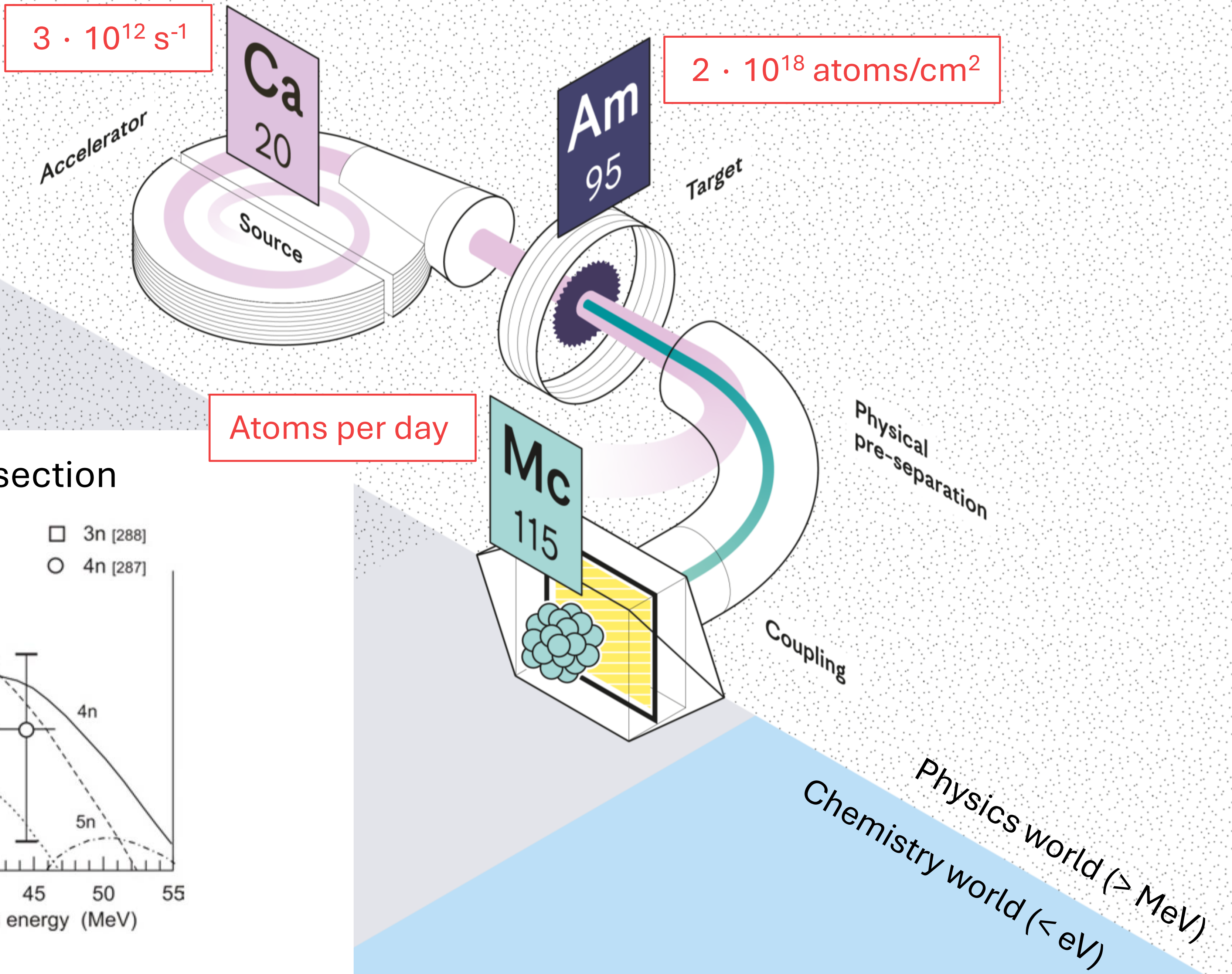
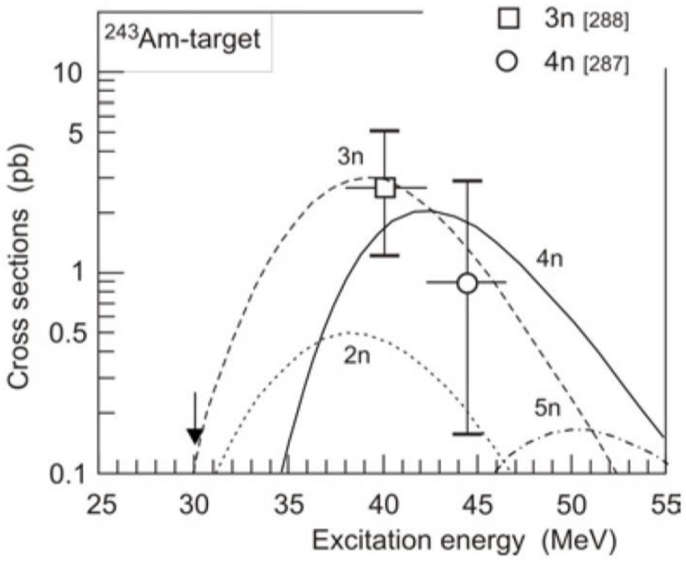
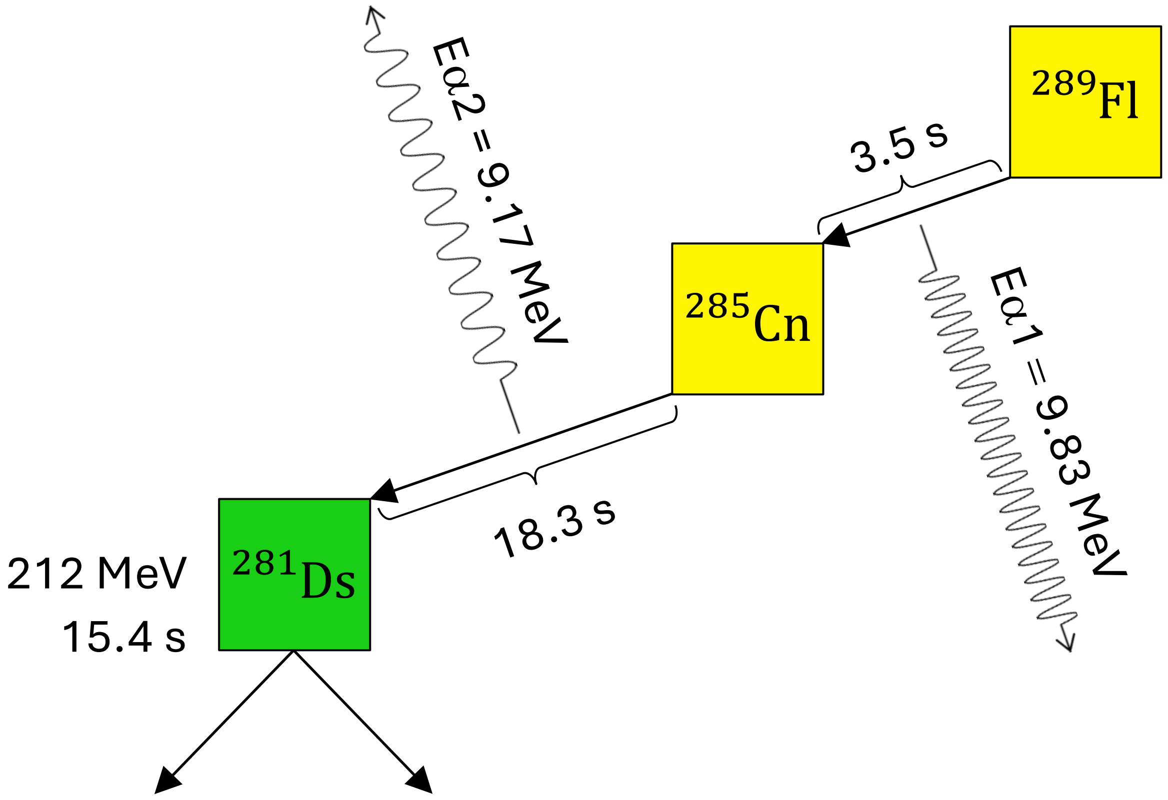
For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.

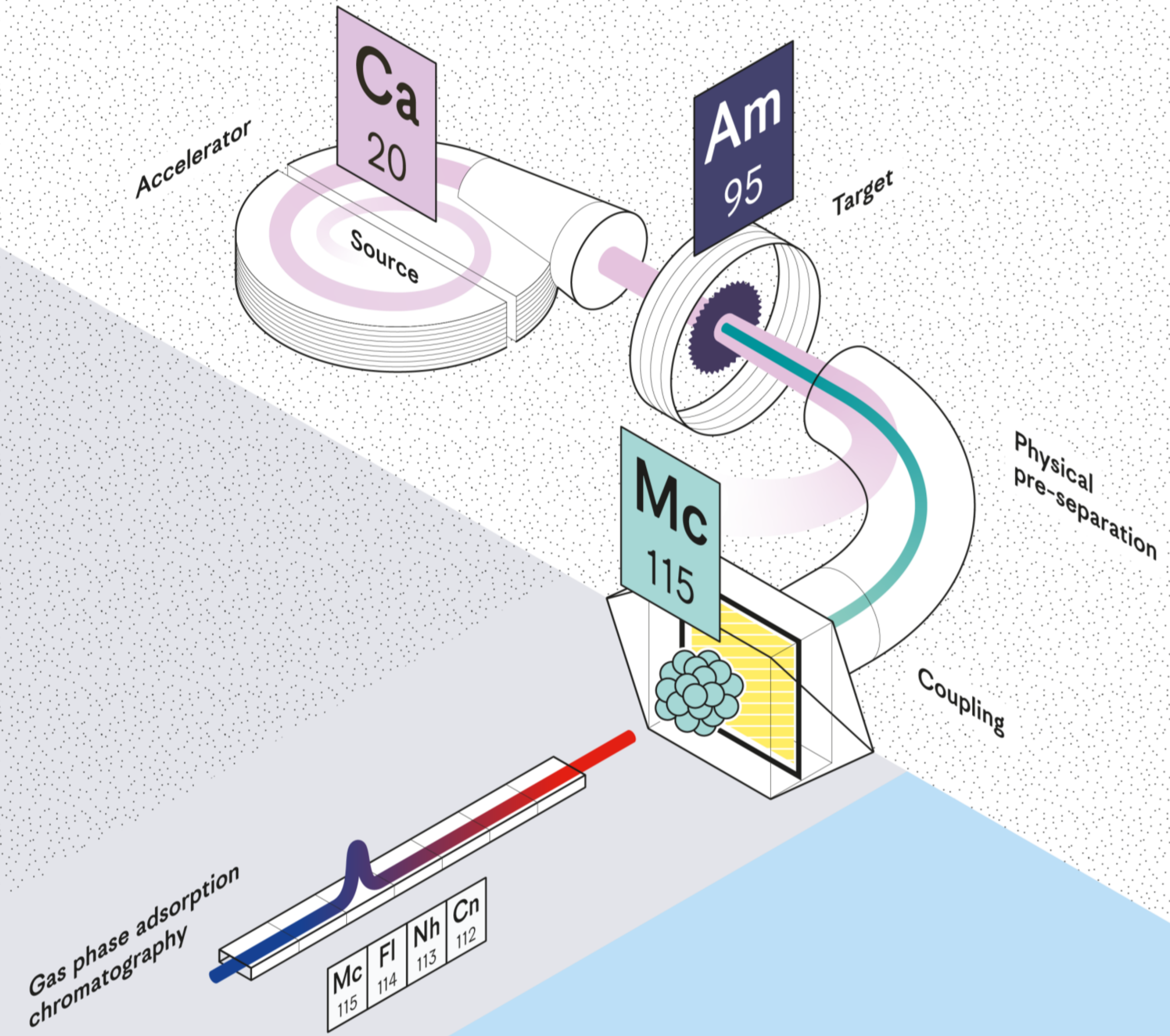


Nucear reaction cross section





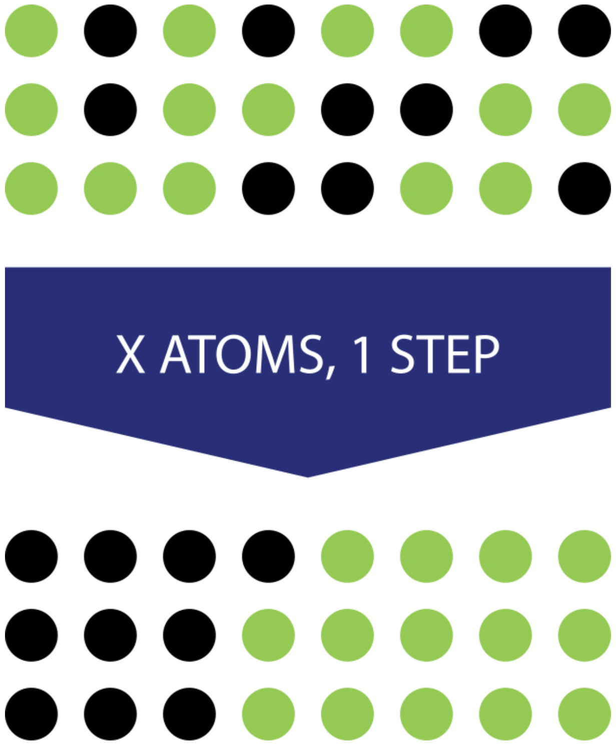
289Fl
3.5 s
Eα1 = 9.83 MeV
285Cn
Eα2 = 9.17 MeV
18.3 s
281Ds
212 MeV
15.4 s


Ca
20
Accelerator
Source
Am
95
Target
Physical pre-separation
Mc
115
Coupling
Gas phase adsorption chromatography
Mc 115
Fl 114
Nh 113
Cn 112

Fundamentals of Superheavy Element Chemistry

PSI

Classical Chemistry



K → Concentrations

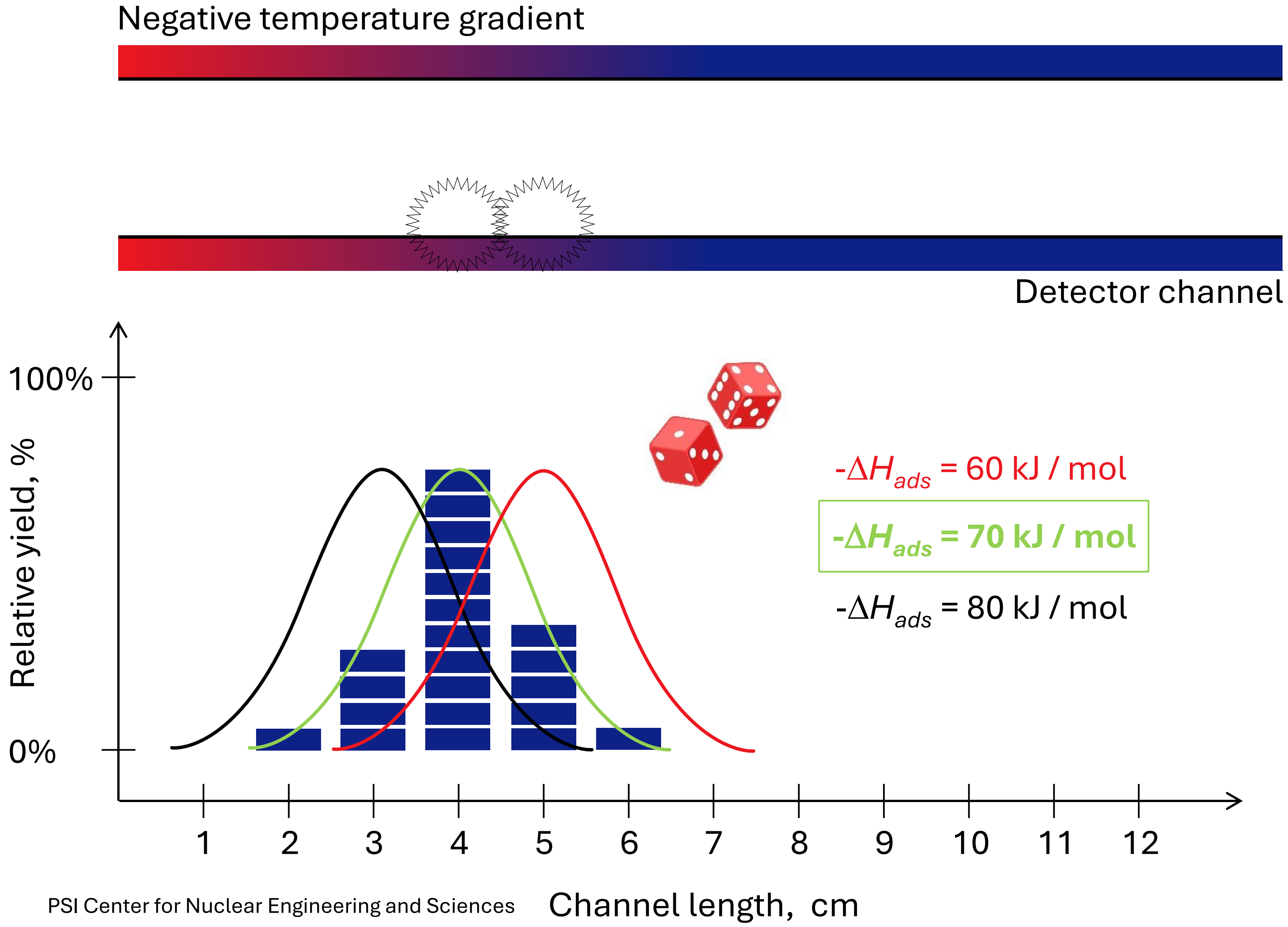
Chemistry with Superheavy Elements

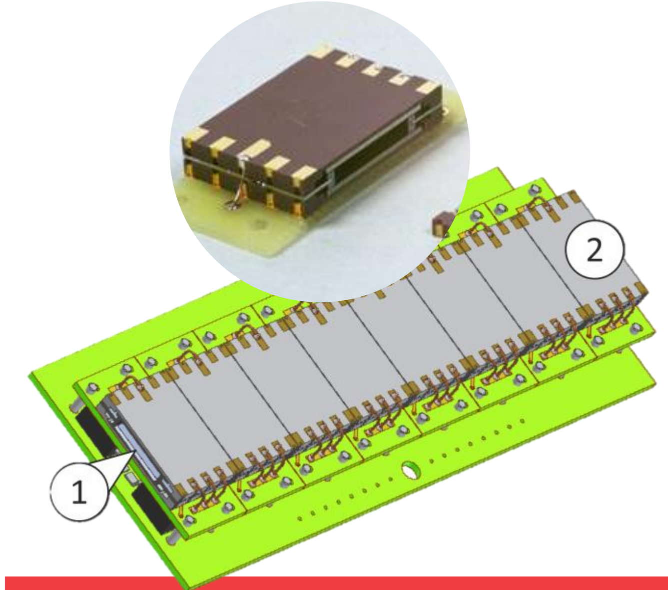
- ❑ Low production rates (≈ 1 $week^{-1}$)
- ❑ Short life-times (≈ 1 second)

K → Probabilities

The Chemistry of Superheavy Elements, 2nd edition, Springer Heidelberg

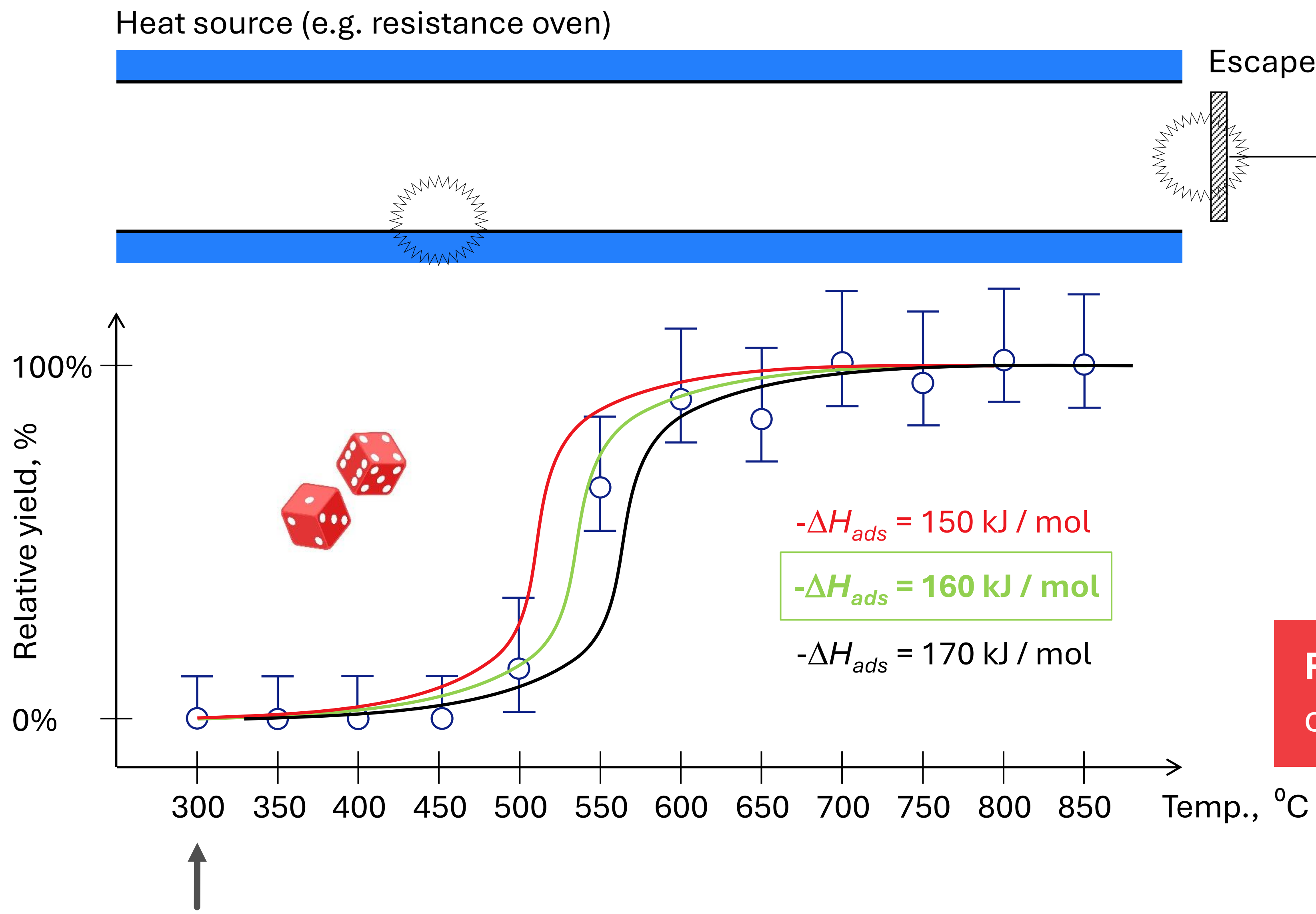
Thermochromatography





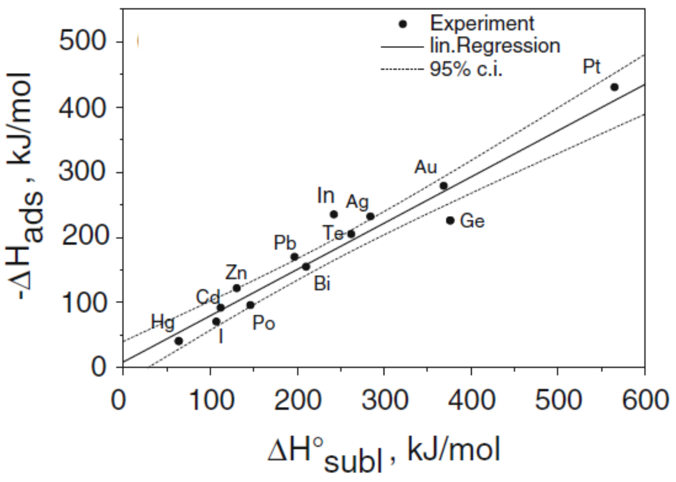
Rf – Hs as halides, oxyhalides, and oxides + **Cn, Fl, and Nh** (elemental?)

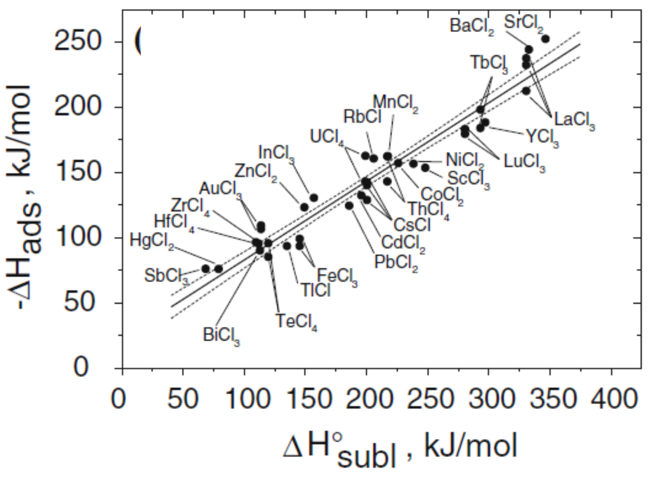
Isothermal chromatography

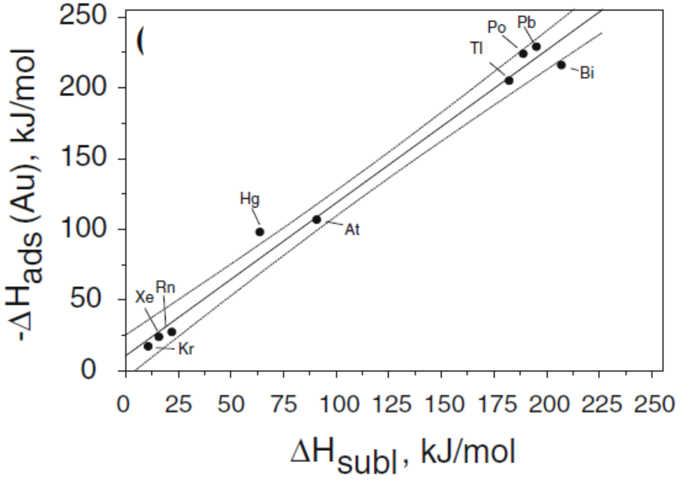


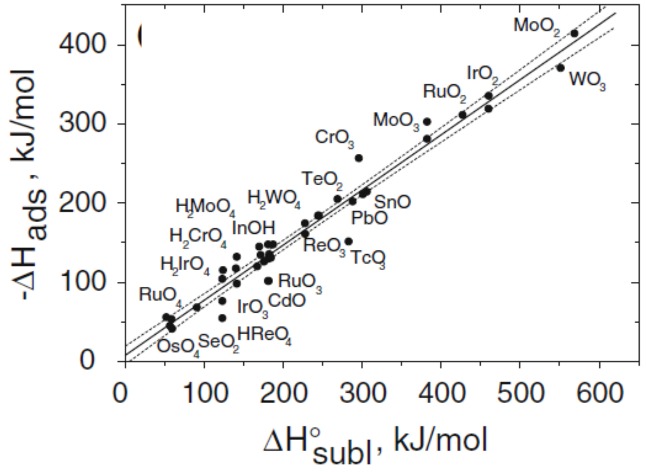
Rf – Bh as halides and oxyhalides

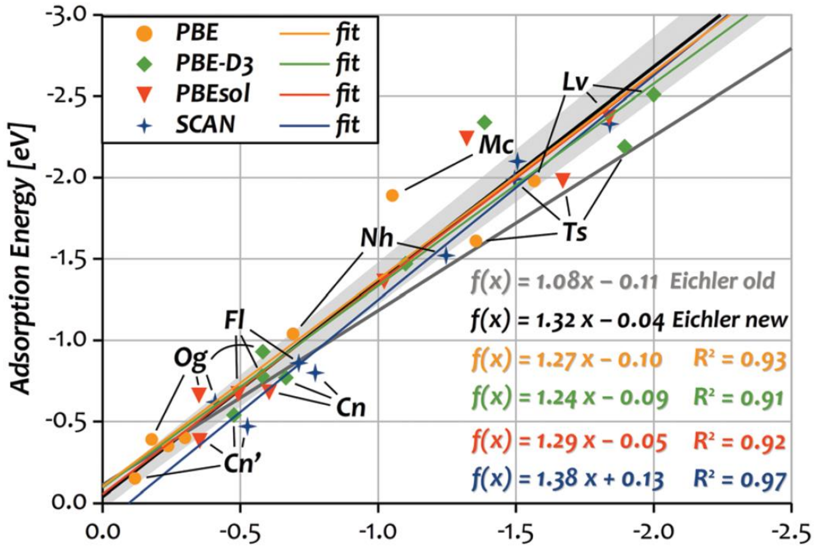
From single atoms to macroscopic amounts







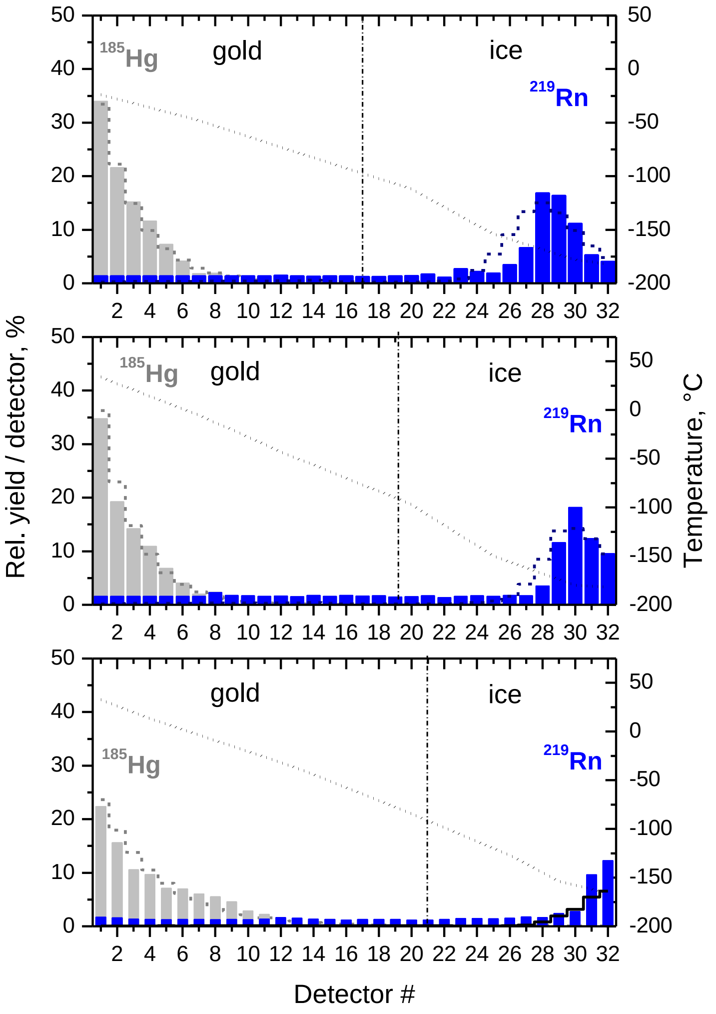


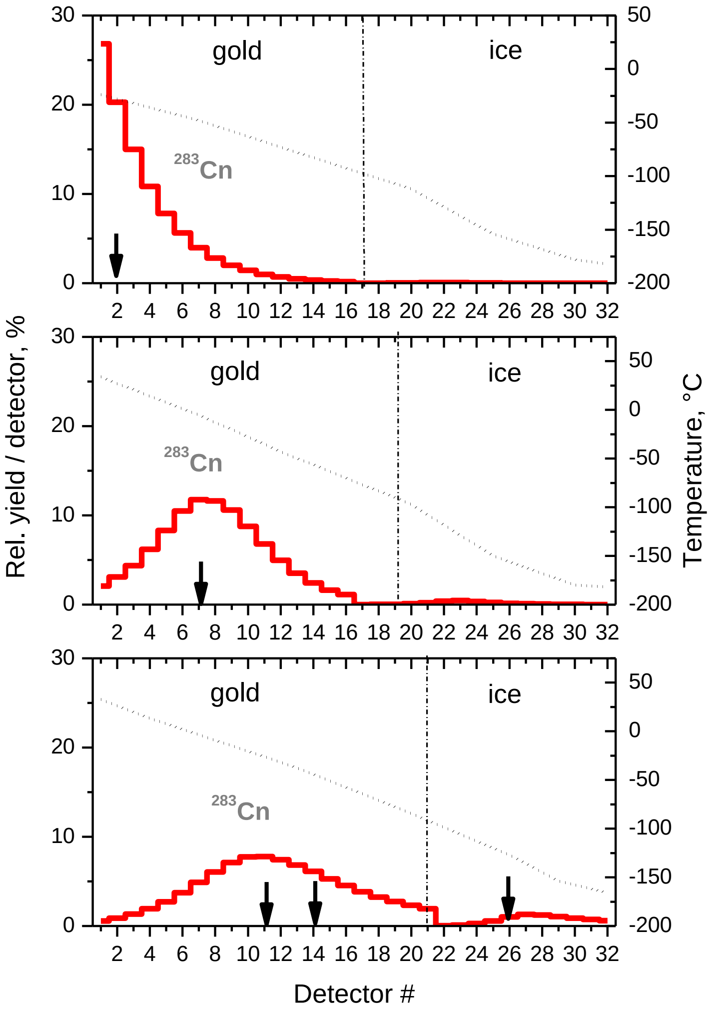


Correlations include **relativistic effects**!

The Chemistry of Superheavy Elements, 2nd edition, Springer Heidelberg | L. Trombach et al., Phys. Chem. Chem. Phys. 21 (2021), pp. 18048 – 18058

Example: Adsorption of Cn on Au





RESULTS (68% c.i.): Cn ($Z = 112$) is **very volatile** and, unlike Rn, reveals a **metallic interaction with Au** (typical group 12 element).

$$-\Delta H_{ads}^{Au}(\text{Cn}) = 52_{-3}^{+4}\ \text{kJ/mol}$$

> How does this look with **nihonium** or a chemical compond of nihonium?

R. Eichler et al., Nature 447 (2007)

The Chemistry of Gen IV Nuclear Reactors

Key:

atomic number **Symbol** name abridged standard atomic weight

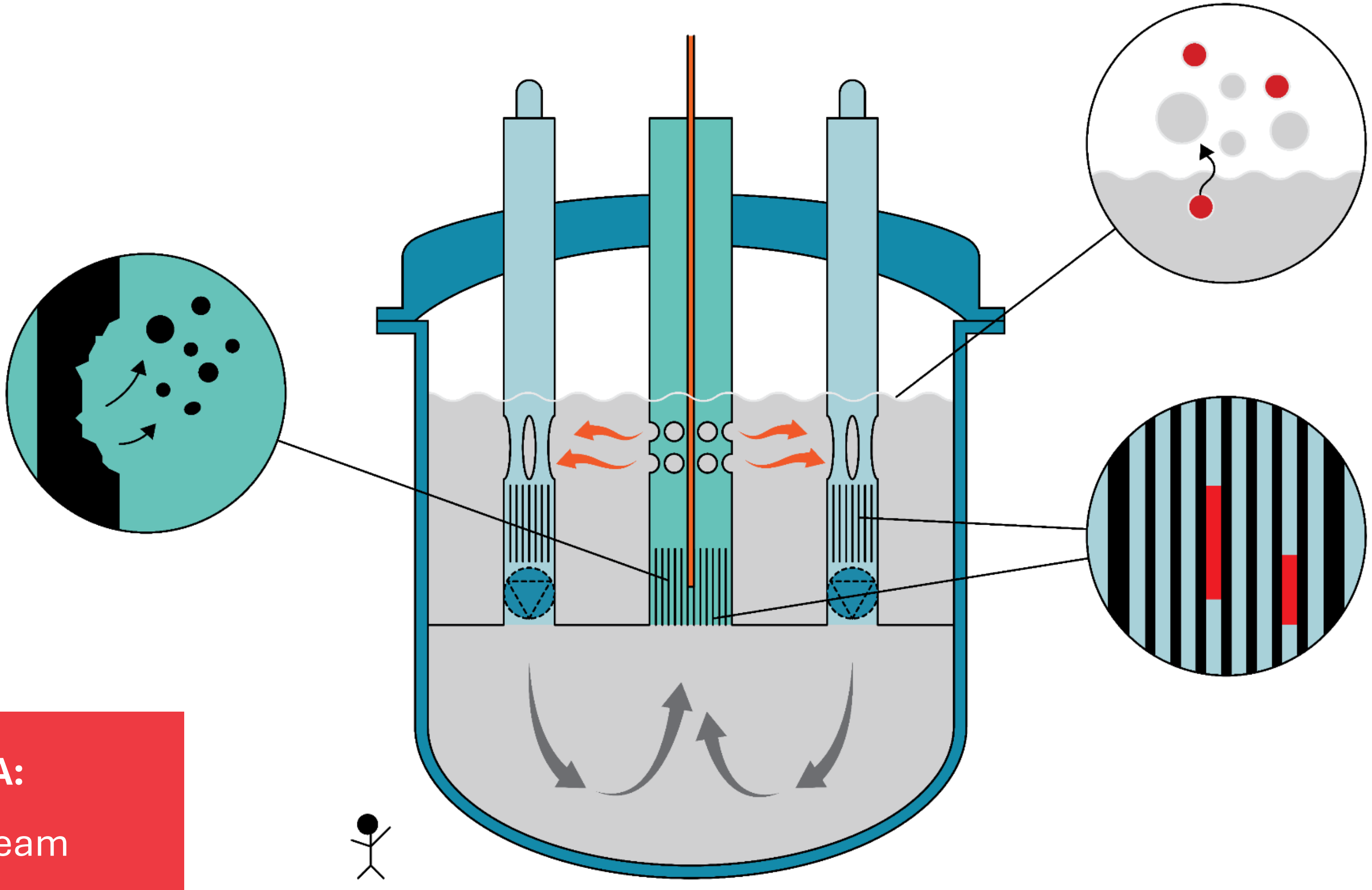
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.

PSI



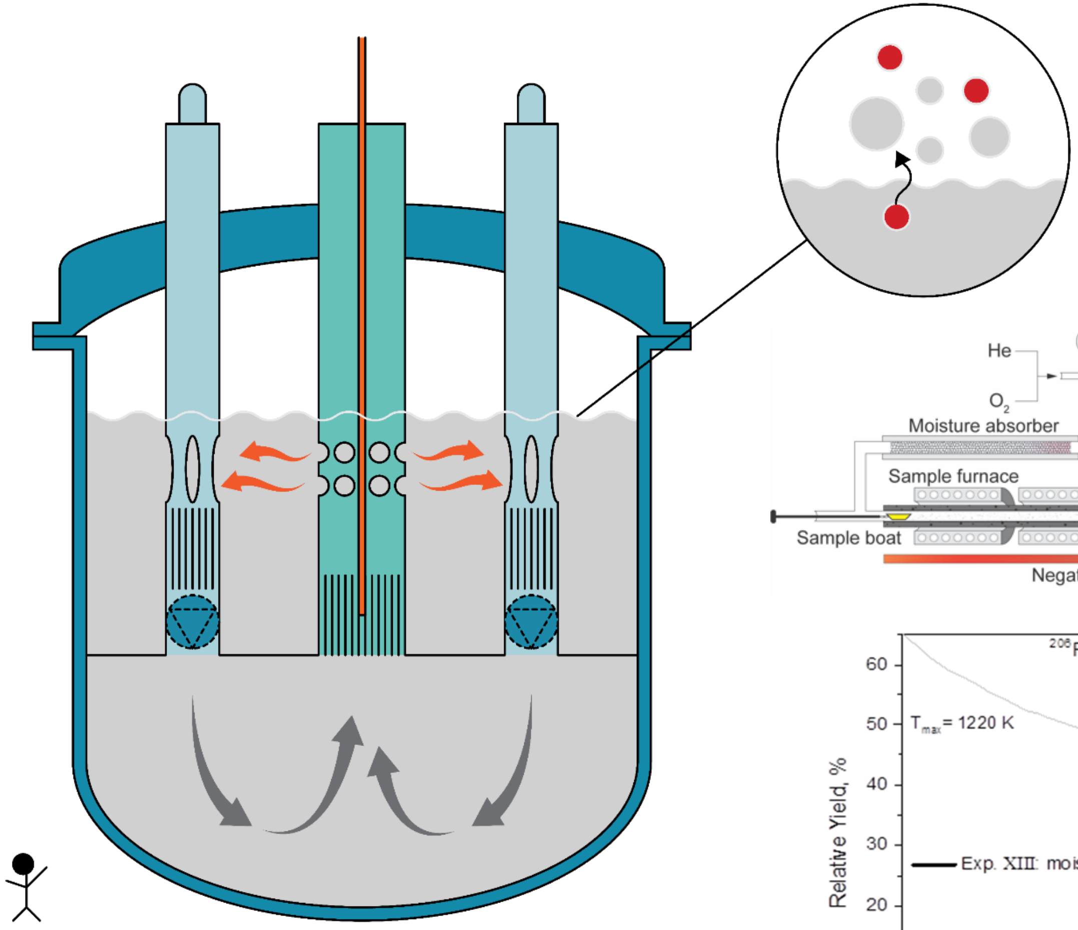
Characteristics of MYRRHA:

- 600 MeV / 4 mA proton beam
- Sub-critical 65 – 100 MW_{th}
- LBE as coolant/spallation target

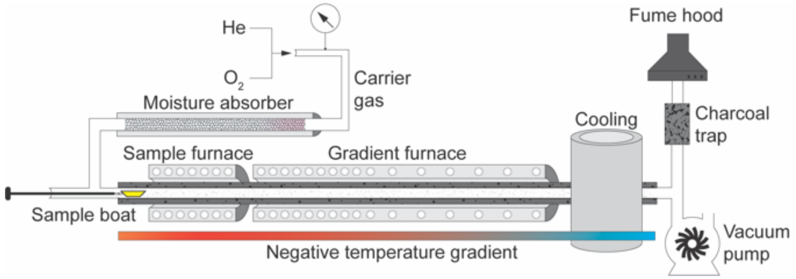
MYRRHA

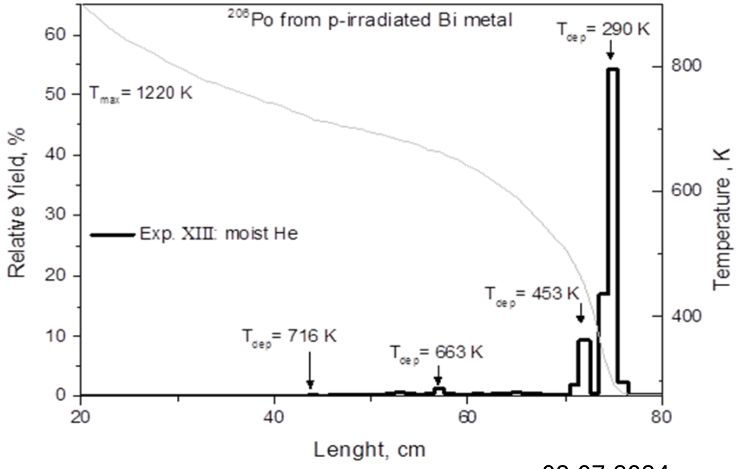
The Chemistry of Gen IV Nuclear Reactors

PSI



Same experimental gas-phase techniques as used for SHEs





Main problem: Chemistry

E.g., Po as large radiological risk

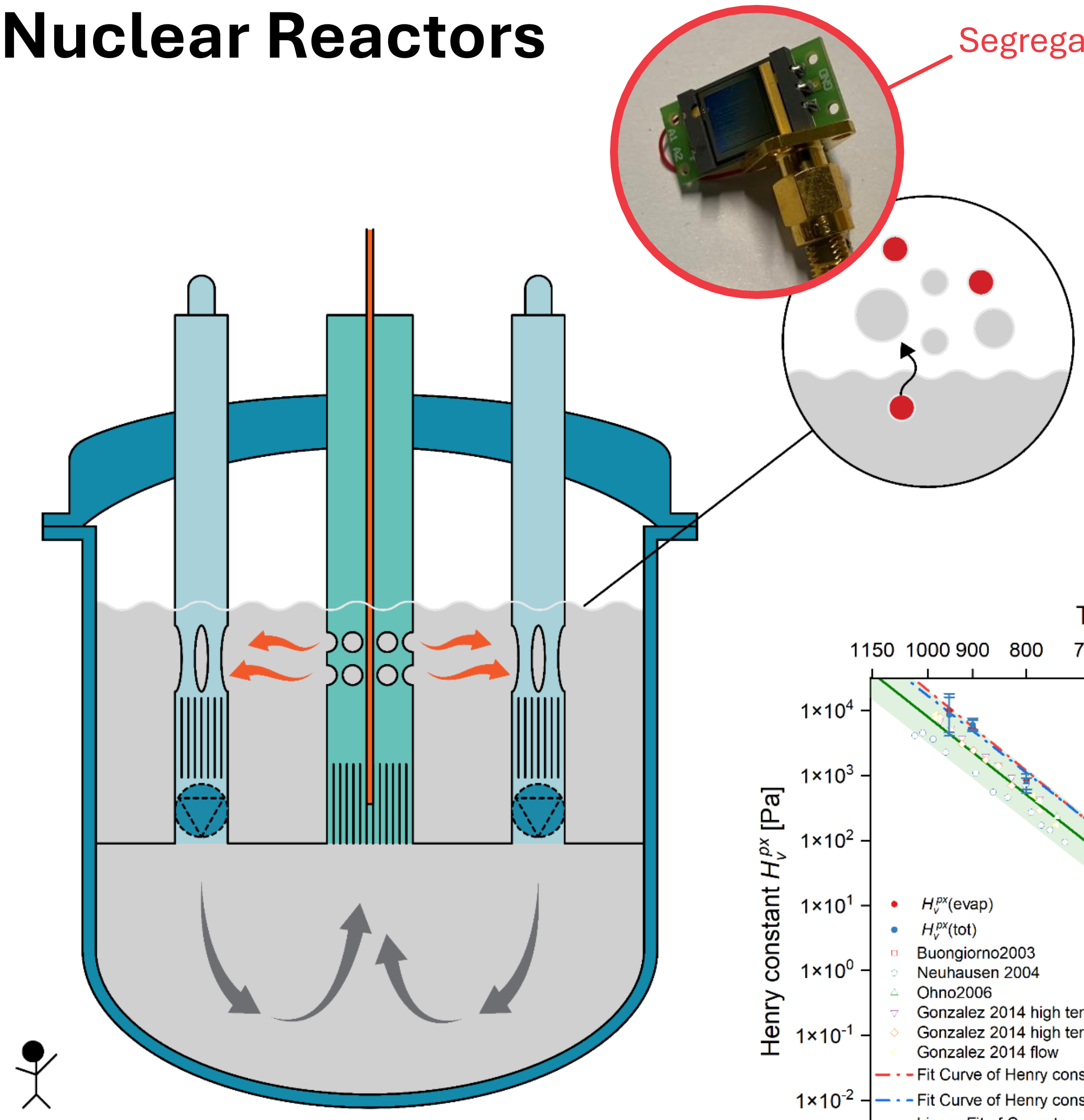
Characteristics:

- 600 MeV / 4 mA proton beam
- Sub-critical 65 – 100 MW_{th}
- LBE as coolant/spallation target

MYRRHA

The Chemistry of Gen IV Nuclear Reactors

Ivan



Segregation

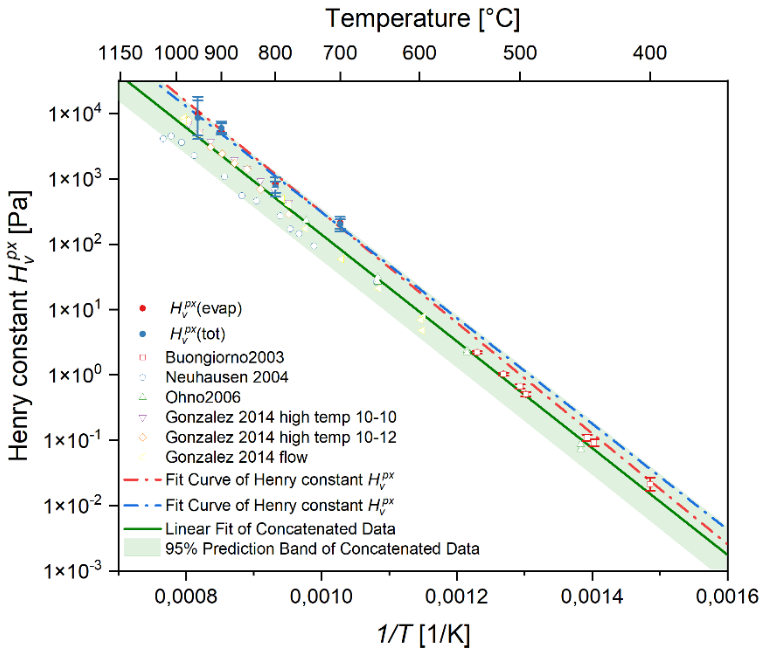
Same experimental gas-phase techniques as used for SHEs

Main problem: Chemistry

E.g., Po as large radiological risk

Characteristics:

- 600 MeV / 4 mA proton beam
- Sub-critical 65 – 100 MW_{th}
- LBE as coolant/spallation target



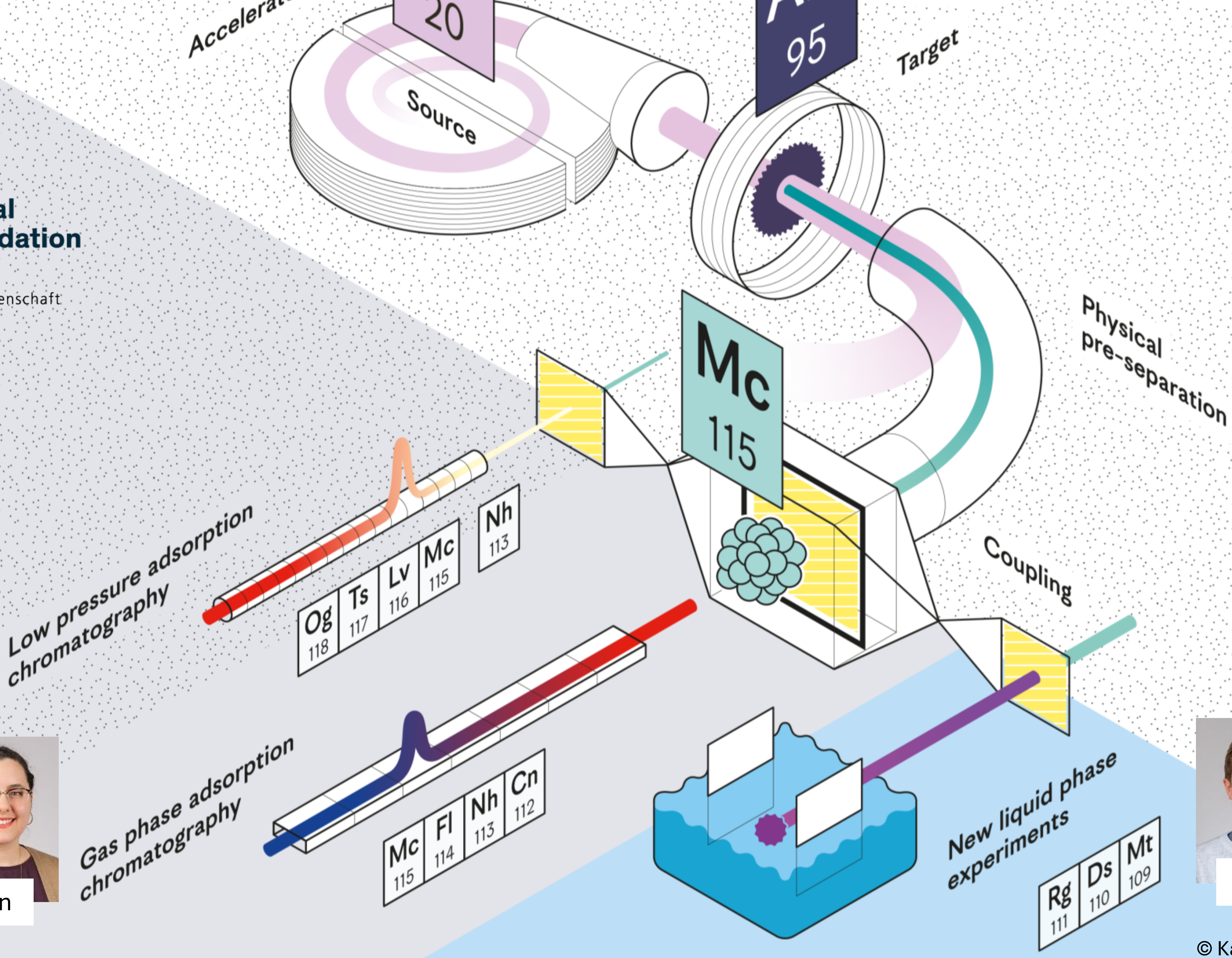
Publication in preparation; preliminary data available in our annual reports: https://www.psi.ch/en/lrc/annual-reports

The end.

Superheavy elements

Swiss National Science Foundation

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra



PSI Center for Nuclear Engineering and Sciences

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Video: https://www.psi.ch/en/lrc/heavy-elements