Superheavy Elements Are Awesome

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Exotic Beam Summer School
June 10, 2022

Outline

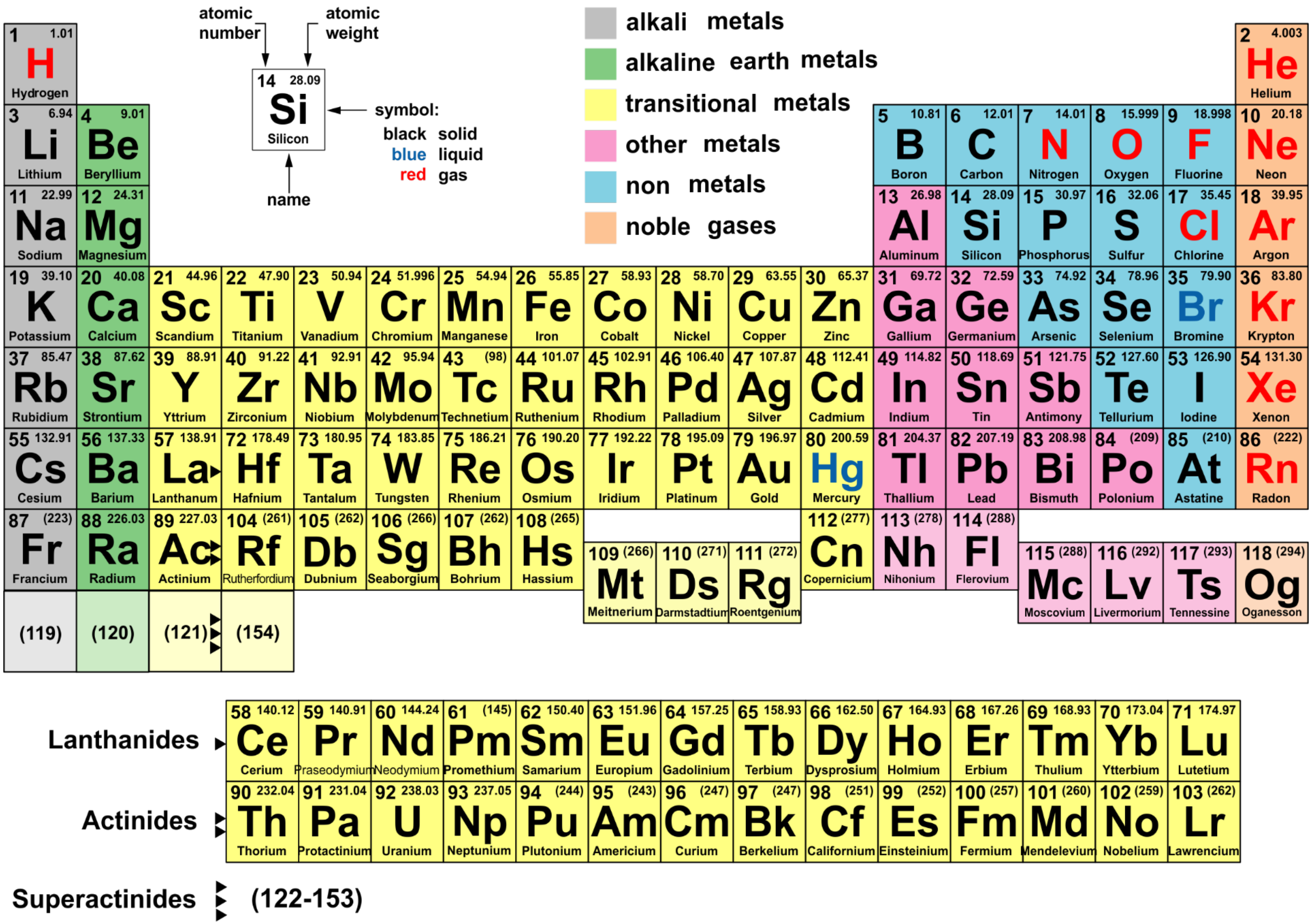
- The Elements as They Stand Today
- Nuclear Reactions Used to Make the Heaviest Elements
- The Future of New Elements
- How Do You Study Chemistry with Only a Few Atoms?
- What Has Heavy Element Science Taught Us?

The Elements as They Stand Today

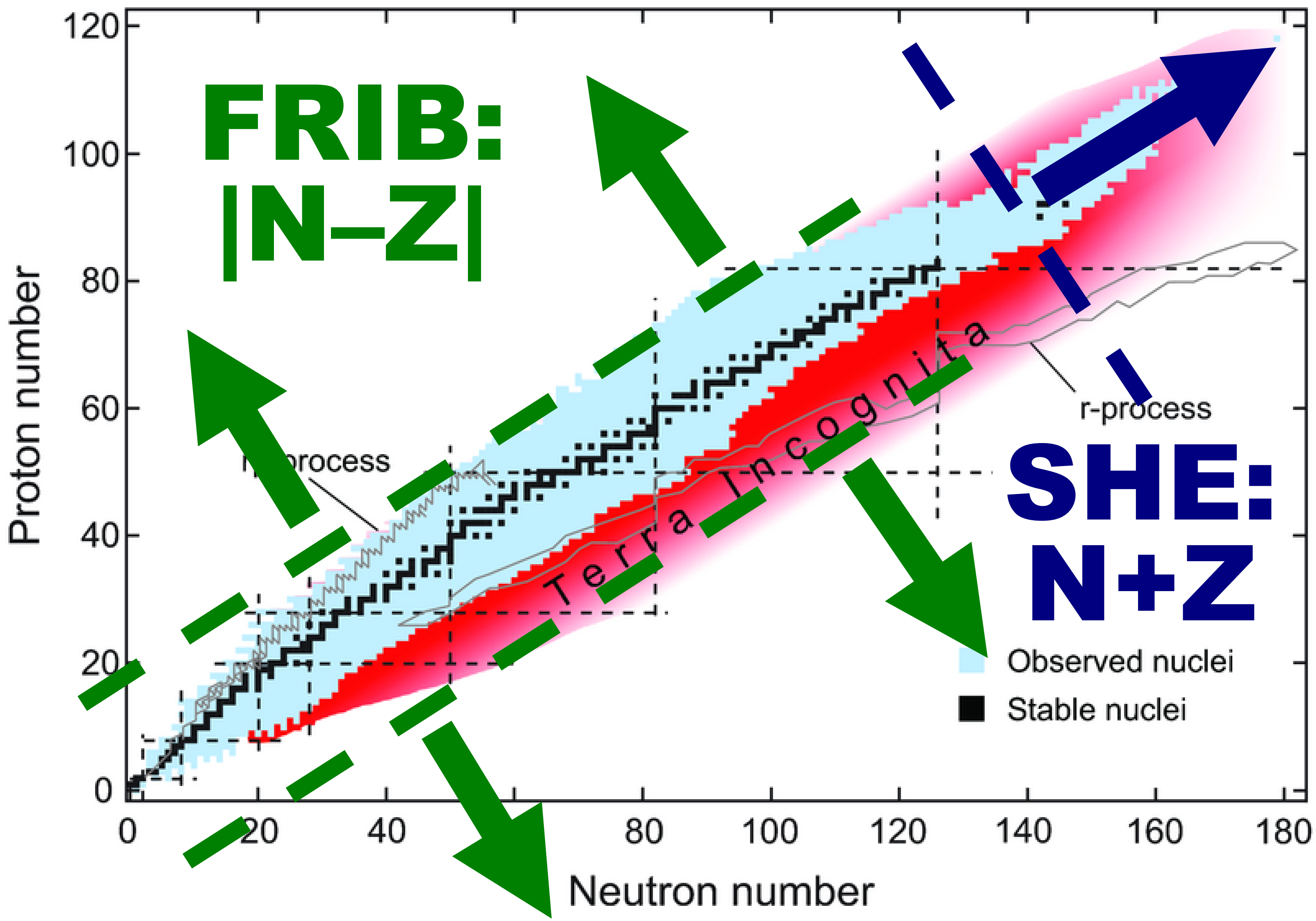
- There are 91 naturally occurring elements (but it depends on how you count them).
  - The heaviest element that occurs in large quantity is uranium (atomic number 92). You can mine it like gold.
  - Technetium (atomic number 43) does not occur naturally.
  - Promethium (atomic number 61) does not occur naturally.
  - ^{244}Pu *has* been discovered in nature. This isotope has a half-life of “only” 80 million years.

- The artificial elements bring the total to 118.

The Periodic Table Today

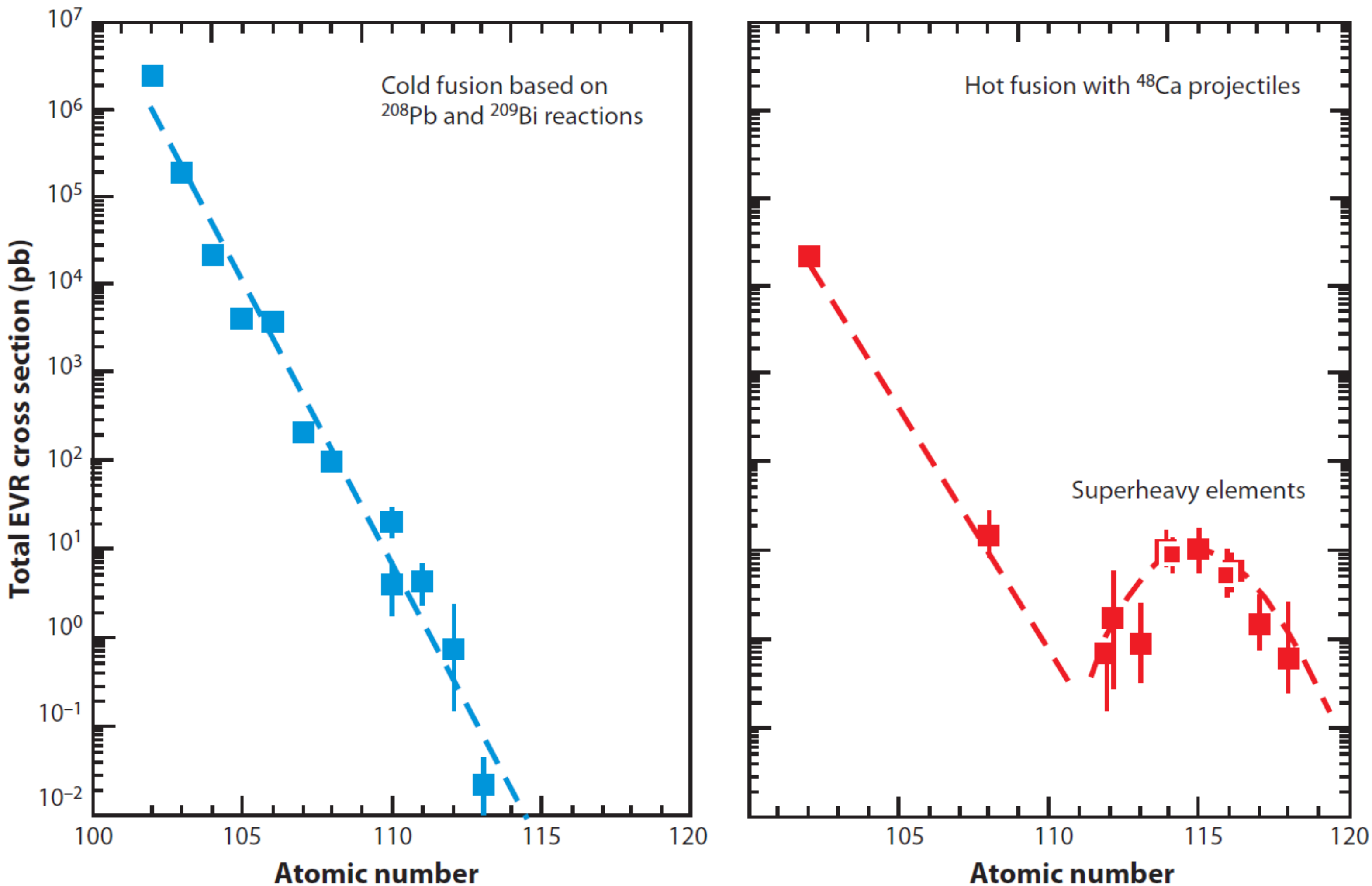


Why Study Heavy Elements?



New Element Discoveries ca. 1980-2010

One per second
One per minute
One per hour
One per day
One per week
One per month



J. H. Hamilton *et al.*, Ann. Rev. Nucl. Part. Sci. **63**, 383 (2013). (link)

Current and Future History of Elements Above Oganesson ($Z = 118$)

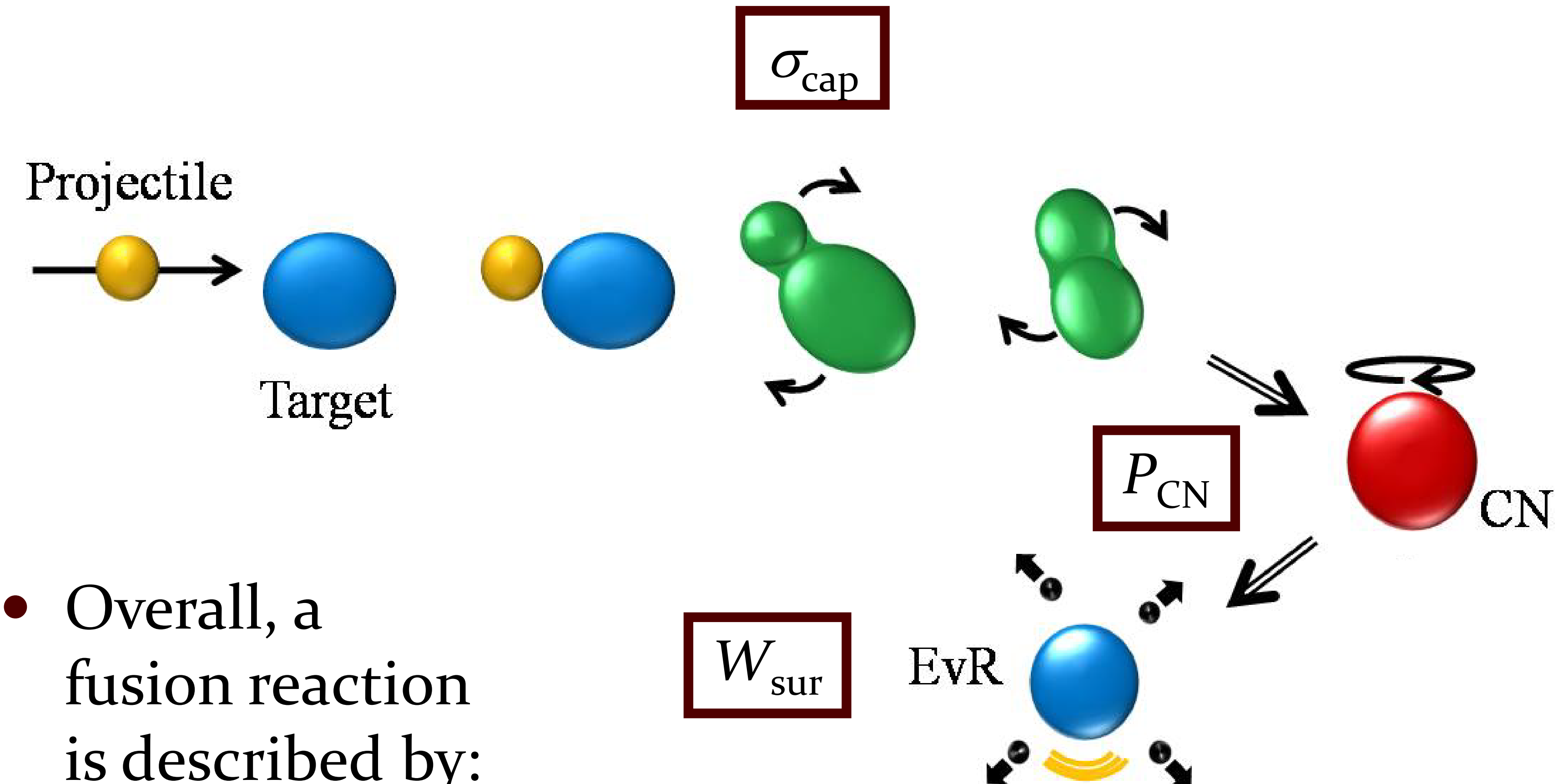
- The great question is, “What reaction is most likely to lead to the discovery of the next new element?”
- Recently, actinide elements have been irradiated with ^{48}Ca.

Lanthanides	58 140.12 **Ce** Cerium	59 140.91 **Pr** Praseodymium	60 144.24 **Nd** Neodymium	61 (145) **Pm** Promethium	62 150.40 **Sm** Samarium	63 151.96 **Eu** Europium	64 157.25 **Gd** Gadolinium	65 158.93 **Tb** Terbium	66 162.50 **Dy** Dysprosium	67 164.93 **Ho** Holmium	68 167.26 **Er** Erbium	69 168.93 **Tm** Thulium	70 173.04 **Yb** Ytterbium	71 174.97 **Lu** Lutetium
Actinides	90 232.04 **Th** Thorium	91 231.04 **Pa** Protactinium	92 238.03 **U** Uranium	93 237.05 **Np** Neptunium	94 (244) **Pu** Plutonium	95 (243) **Am** Americium	96 (247) **Cm** Curium	97 (247) **Bk** Berkelium	98 (251) **Cf** Californium	99 (252) **Es** Einsteinium	100 (257) **Fm** Fermium	101 (260) **Md** Mendelevium	102 (259) **No** Nobelium	103 (262) **Lr** Lawrencium

- A number of reactions have been studied using projectiles heavier than ^{48}Ca, but none have succeeded:

- $^{58}\mathrm{Fe} + {}^{244}\mathrm{Pu} \rightarrow {}^{298}120 + 4n$
- $^{54}\mathrm{Cr} + {}^{248}\mathrm{Cm} \rightarrow {}^{298}120 + 4n$
- $^{50}\mathrm{Ti} + {}^{249}\mathrm{Cf} \rightarrow {}^{295}120 + 4n$
- $^{64}\mathrm{Ni} + {}^{238}\mathrm{U} \rightarrow {}^{298}120 + 4n$
- $^{50}\mathrm{Ti} + {}^{249}\mathrm{Bk} \rightarrow {}^{295}119 + 4n$
- $^{51}\mathrm{V} + {}^{248}\mathrm{Cm} \rightarrow {}^{295}119 + 4n$

How does the nuclear reaction work?



- Overall, a fusion reaction is described by:

$$\boxed{\sigma = \sigma_{\mathrm{cap}}(E_{\mathrm{cm}}, l) P_{\mathrm{CN}}(E_{\mathrm{cm}}, l) W_{\mathrm{sur}}(E^{*}_{\mathrm{CN}}, l)}$$

How do you make a heavy nucleus?

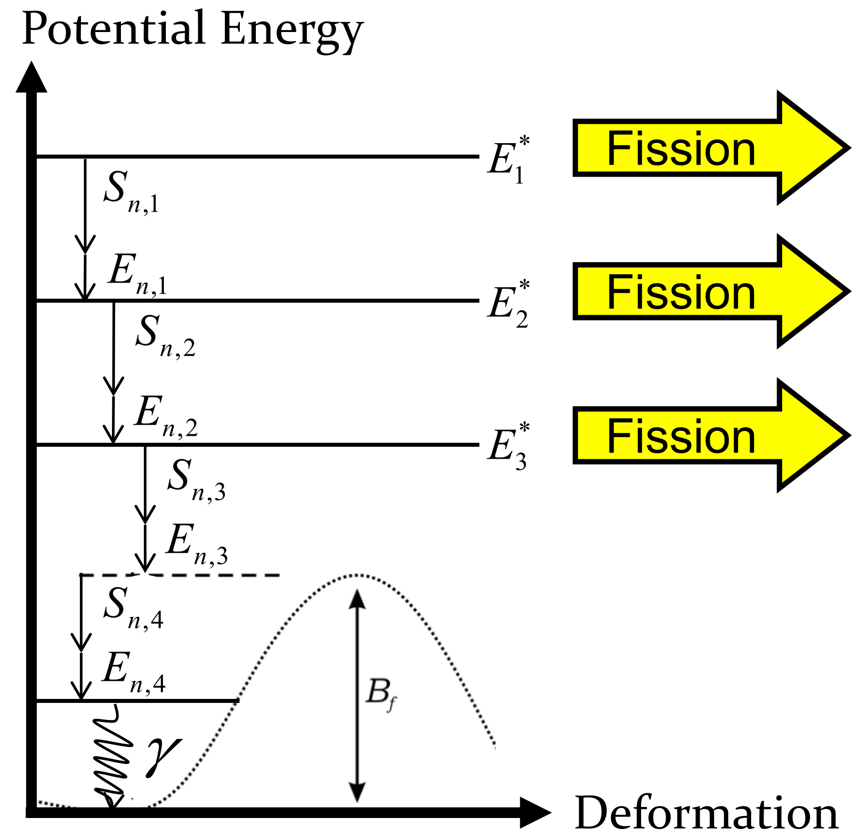
- The production of a heavy nucleus is a competition between neutron emission and fission.
- The evaporation residue cross section can be written as:

$$\sigma = \sigma_{\mathrm{cap}} P_{\mathrm{CN}} W_{\mathrm{sur}}$$

$$= \sigma_{\mathrm{cap}} P_{\mathrm{CN}} P_{\mathrm{xn}} \prod_{i=1}^{x} (\Gamma_{\mathrm{n}}/\Gamma_{\mathrm{tot}})_i$$

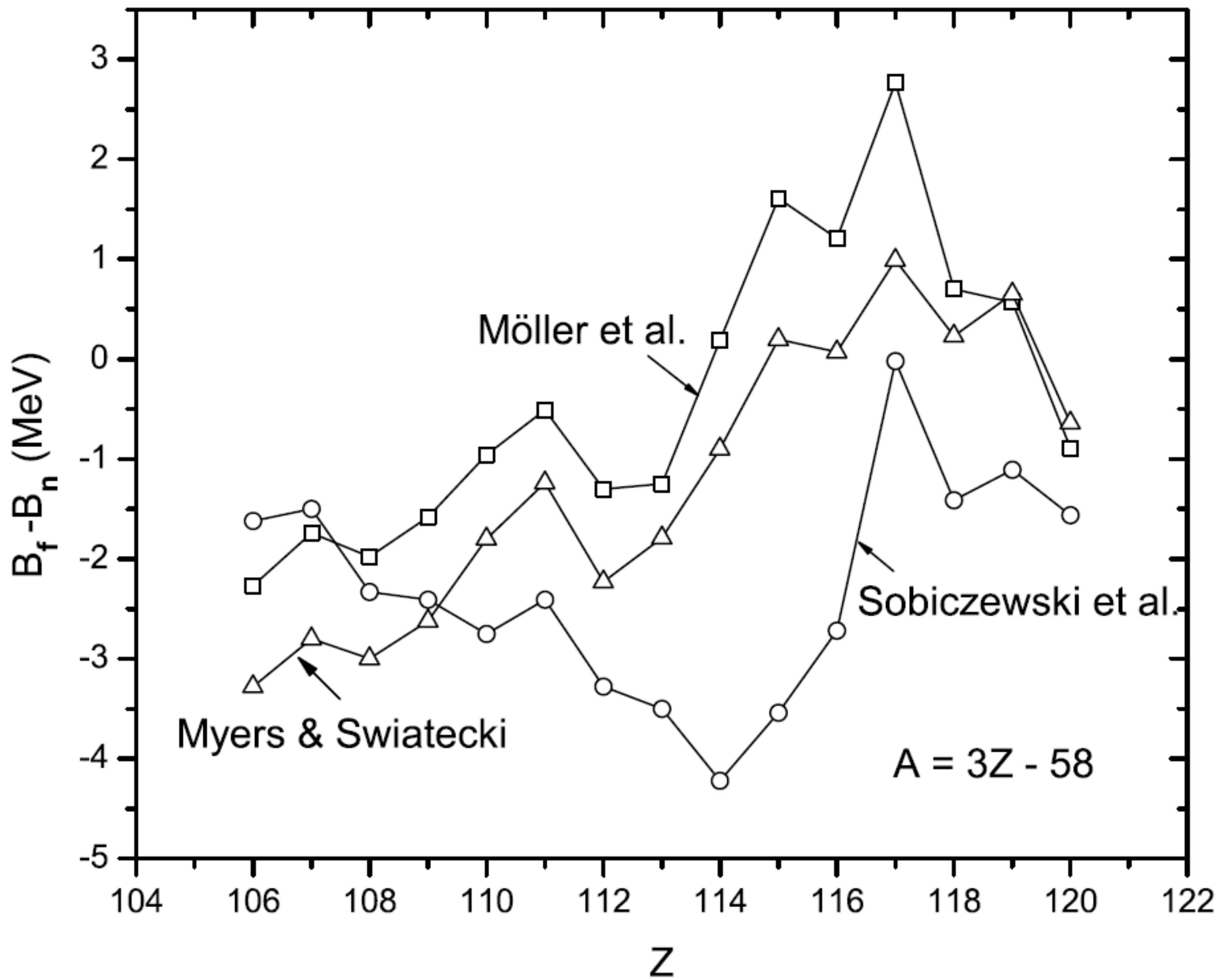
$$\approx \sigma_{\mathrm{cap}} P_{\mathrm{CN}} P_{\mathrm{xn}} \prod_{i=1}^{x} (\Gamma_{\mathrm{n}}/\Gamma_{\mathrm{f}})_i$$

$$\boxed{\Gamma_{\mathrm{n}}/\Gamma_{\mathrm{f}} \propto \exp[-(S_{\mathrm{n}} - B_{\mathrm{f}})/T]}$$



Dependence of $B_f - S_n$ on Model

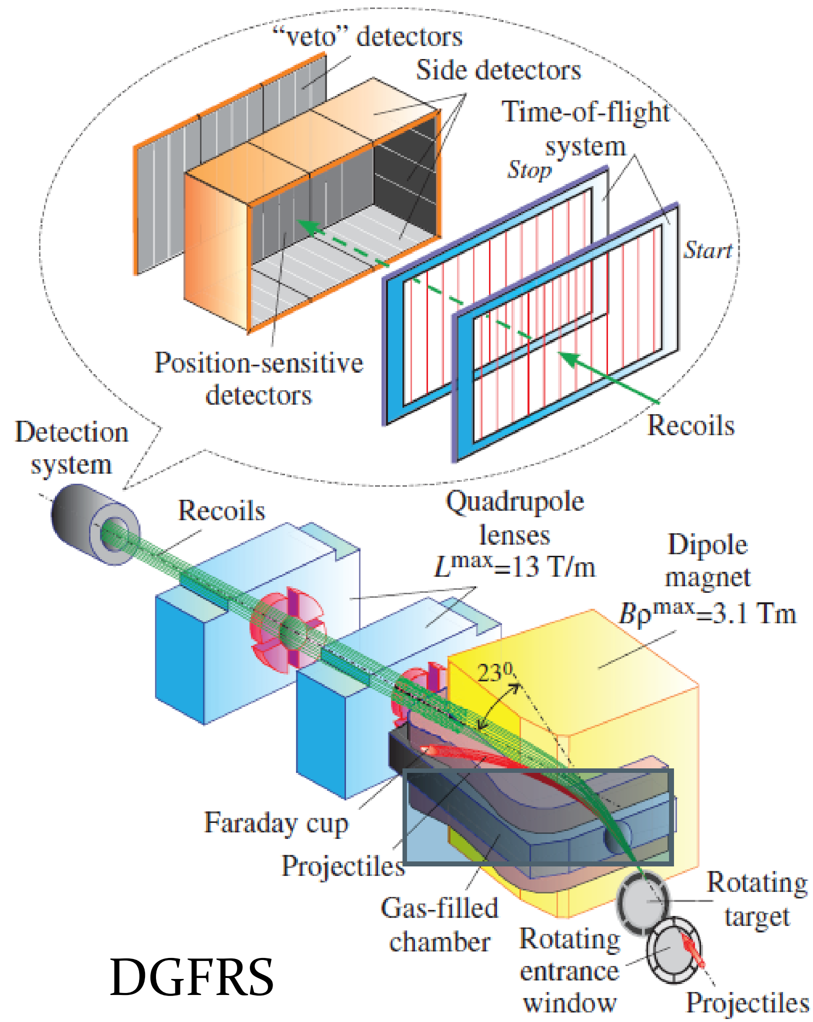
- The model in use has a dramatic impact on $B_f - S_n$.
- This has a dramatic impact on calculated cross sections.



K. Siwek-Wilczyńska *et al.*, Int. J. Mod. Phys. E **18**, 1079 (2009). (link)

How is the experiment conducted?

- We use very intense beams, rotating target wheels (to spread out the heat), and a *separator* to filter away the projectiles after the reaction. Beamtimes can last as long as one month or more.
- The separator removes the beam because exposing it to the ultra-sensitive detectors would damage them permanently.

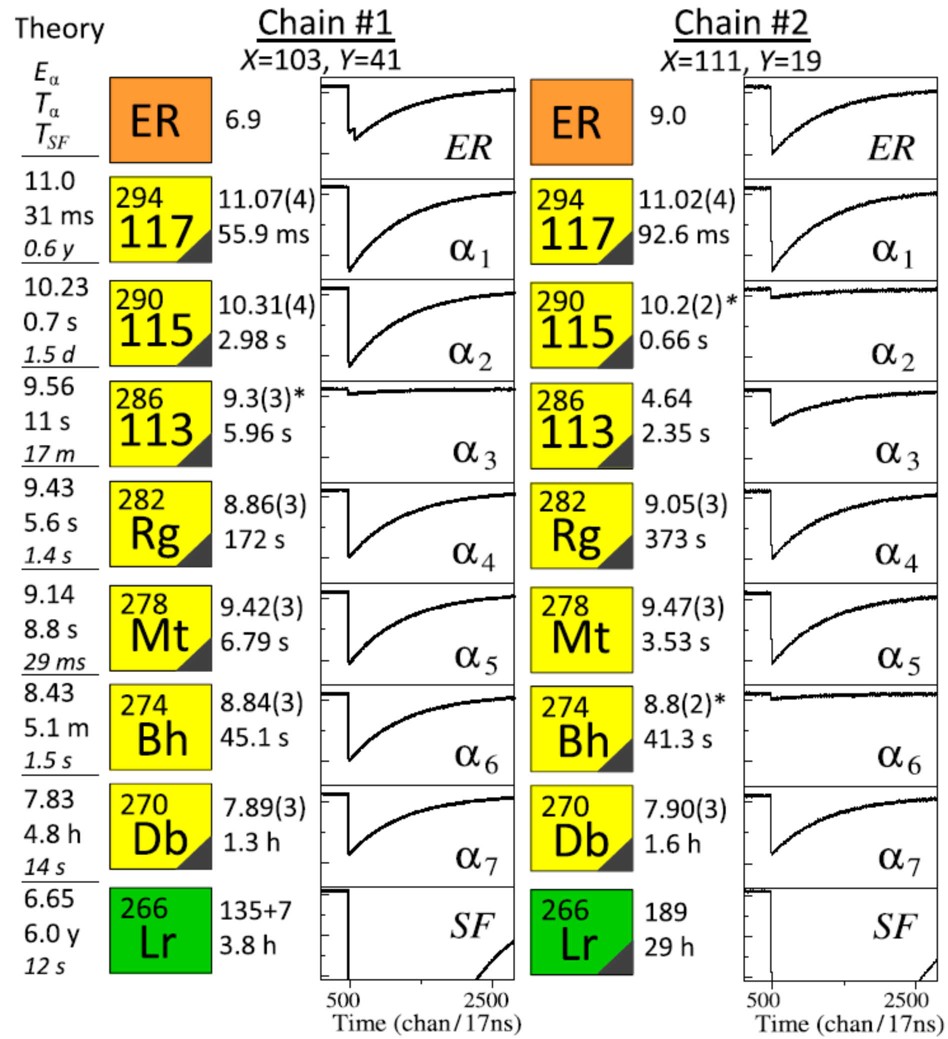


DGFRS

Yu. Ts. Oganessian and V. K. Utyonkov, Rep. Prog. Phys. **78**, 036301 (2015). (link)

How do we know when we have made one of these elements?

- We observe rare isotopes through their radioactive decay. We can observed several decays and recreate the *decay chain*, which identifies the parent nucleus definitively (sometimes).
- These decay chains confirmed the discovery of tennessine (Z = 117).



J. Khuyagbaatar *et al.*, Phys. Rev. Lett. **112**, 172501 (2014). (link)

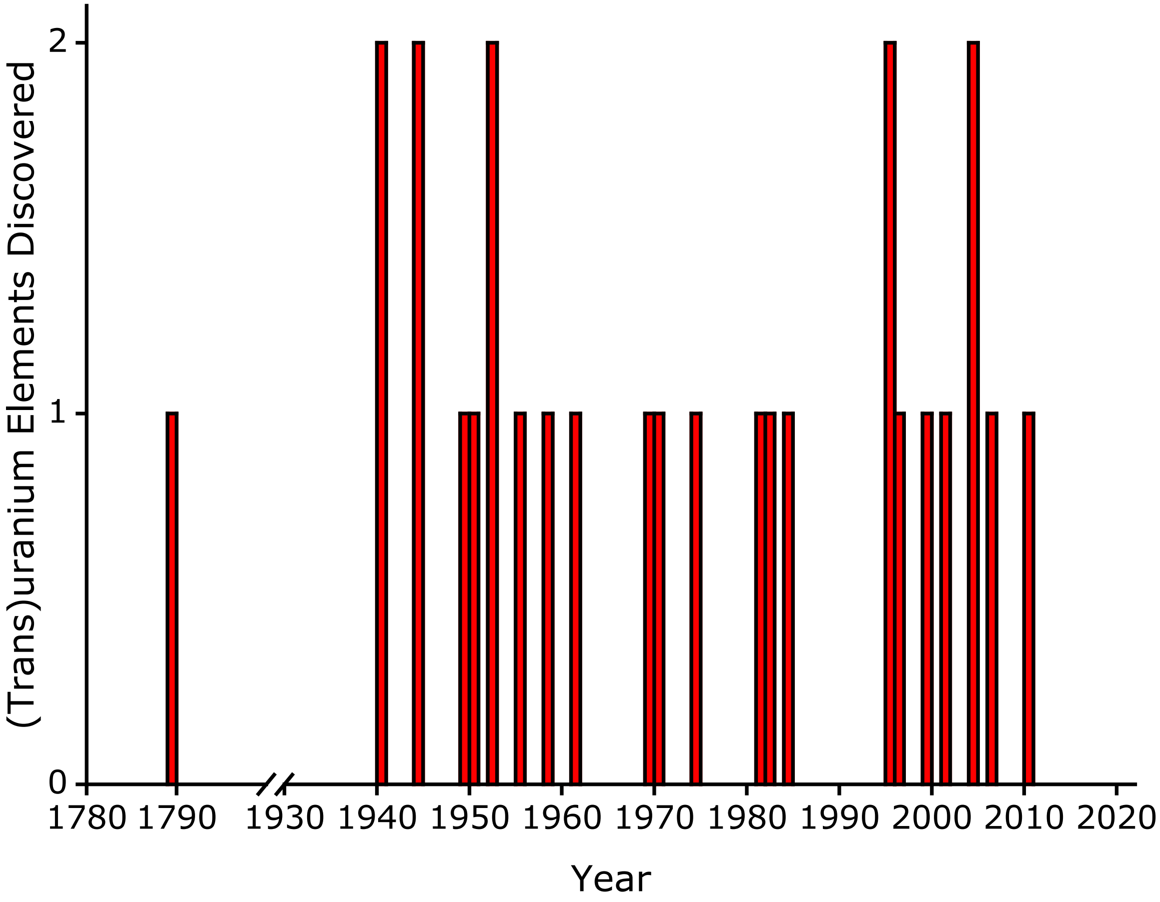
Criteria for a New Element

- Must exist for approximately 10^{-14} s. This is roughly the time needed for a nucleus to collect a cloud of electrons.
- The atomic number must be different from all known atomic numbers, beyond a reasonable doubt. It does *not* have to actually be determined, though.
- Physical or chemical methods can be used.
- Confirmatory experiments are preferred, although this may not be feasible.
- In reality, these criteria have not stopped arguments about who discovered what. They can last for years.

Primary Source: A. H. Wapstra, Pure Appl. Chem. **63**, 879 (1991). (link)
Modern Summary: P. J. Karol *et al.*, Pure Appl. Chem. **88**, 139 (2016). (link)

Prospects for the Discovery of the Next New Element

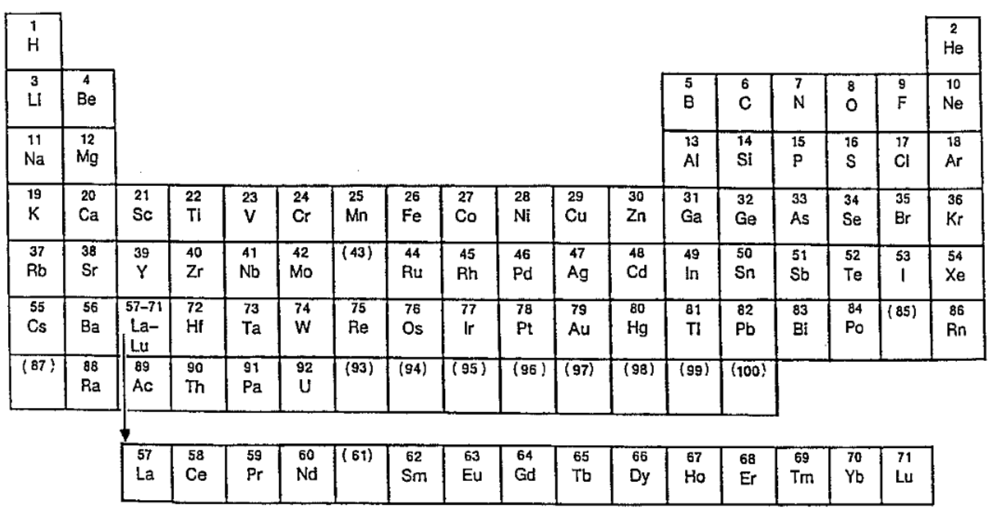
- Element discovery has progressed in groups.
- We are likely in another period of few new elements.



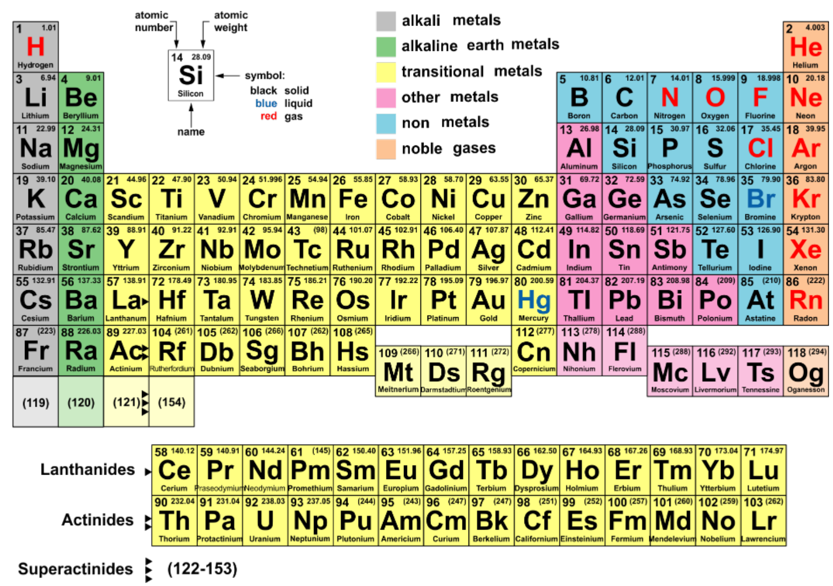
Adapted from a figure by D. C. Hoffman.

What has heavy element nuclear chemistry taught us?

- The chemistry of the heavy elements has been critical to our understanding of the periodic table.
- Glenn Seaborg developed the *actinide concept*, which places certain elements in a separate *actinide series*.



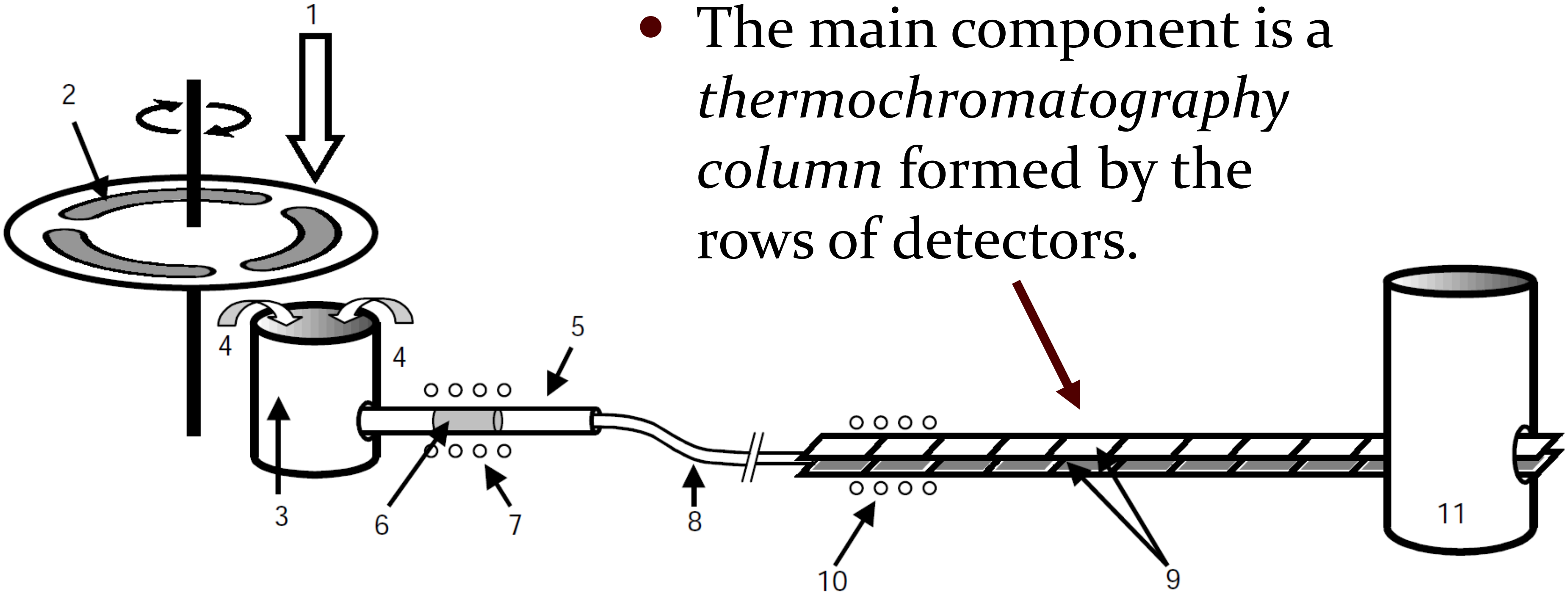
Pre-World War II Periodic Table



Modern Periodic Table

Hassium (Z = 108) Chemistry Experiment

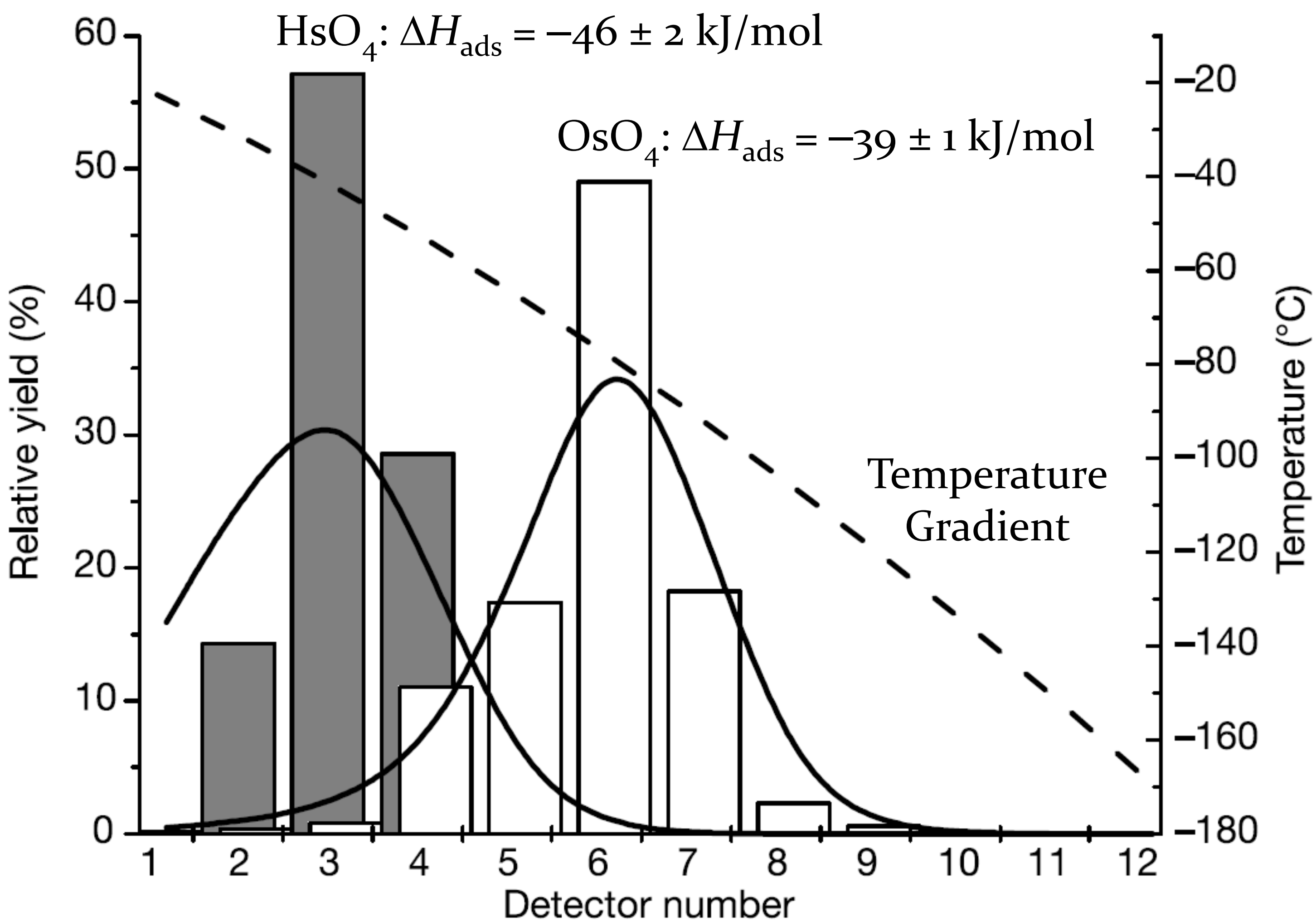
- $^{26}Mg + ^{248}Cm \rightarrow ^{269}Hs + 5n$ (a *nuclear* reaction)
- $^{269}Hs + 2O_2 \rightarrow ^{269}HsO_4$ (a *chemical* reaction)



- The main component is a *thermochromatography column* formed by the rows of detectors.

Ch. E. Düllmann *et al.*, Nature (London) **418**, 859 (2002). (link)

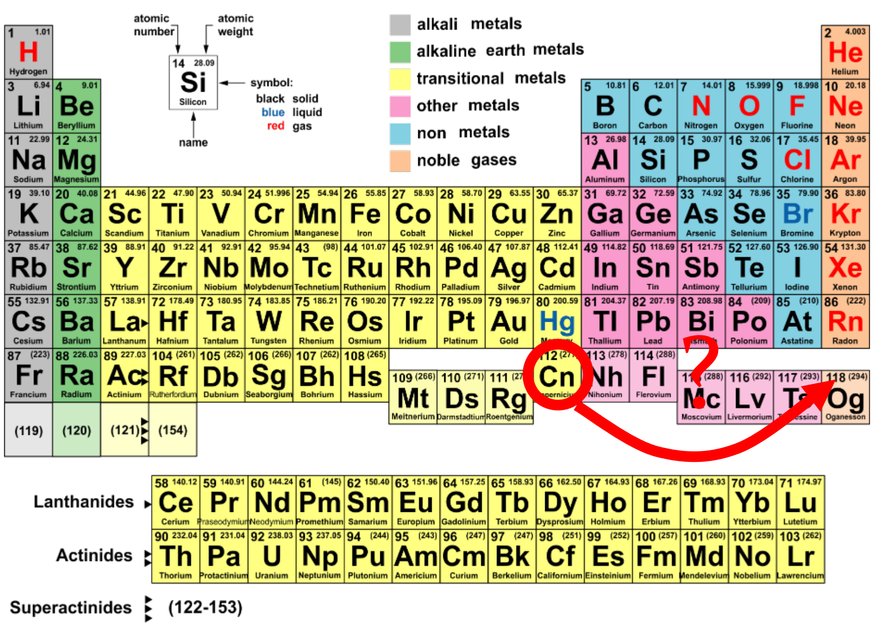
Comparison with Hassium's Lighter Homolog Osmium



Ch. E. Düllmann *et al.*, Nature (London) **418**, 859 (2002). (link)

Relativistic Effects and Copernicium (Z = 112) Chemistry

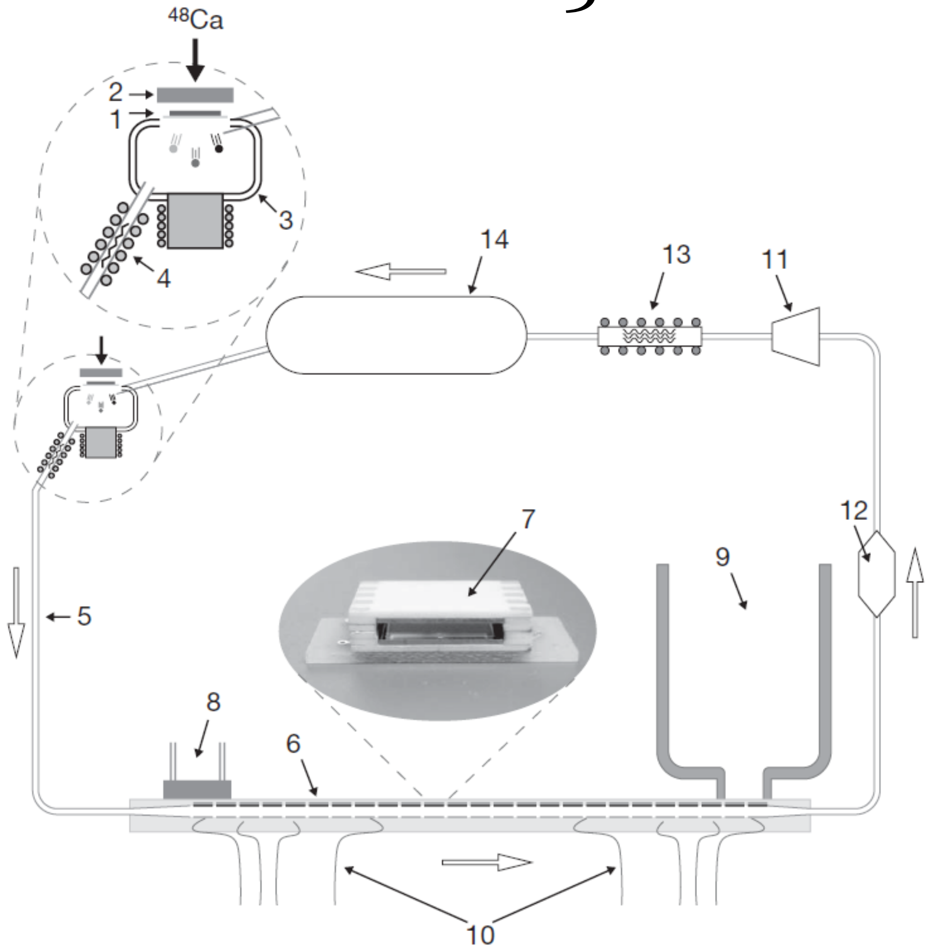
- The effect is that s and p orbitals are contracted and stabilized, while the d and f orbitals are expanded and destabilized due to *relativistic effects*.
- For Cn, this may mean that the filled $6d^{10}$ shell may behave like the filled $6s^2 6p^6$ orbitals of a noble gas.
- Does Cn behave chemically like the noble gas radon or like its periodic table homolog mercury?



K. S. Pitzer, J. Chem. Phys. **63**, 1032 (1975). (link)

Copernicium (Z = 112) Chemistry Setup

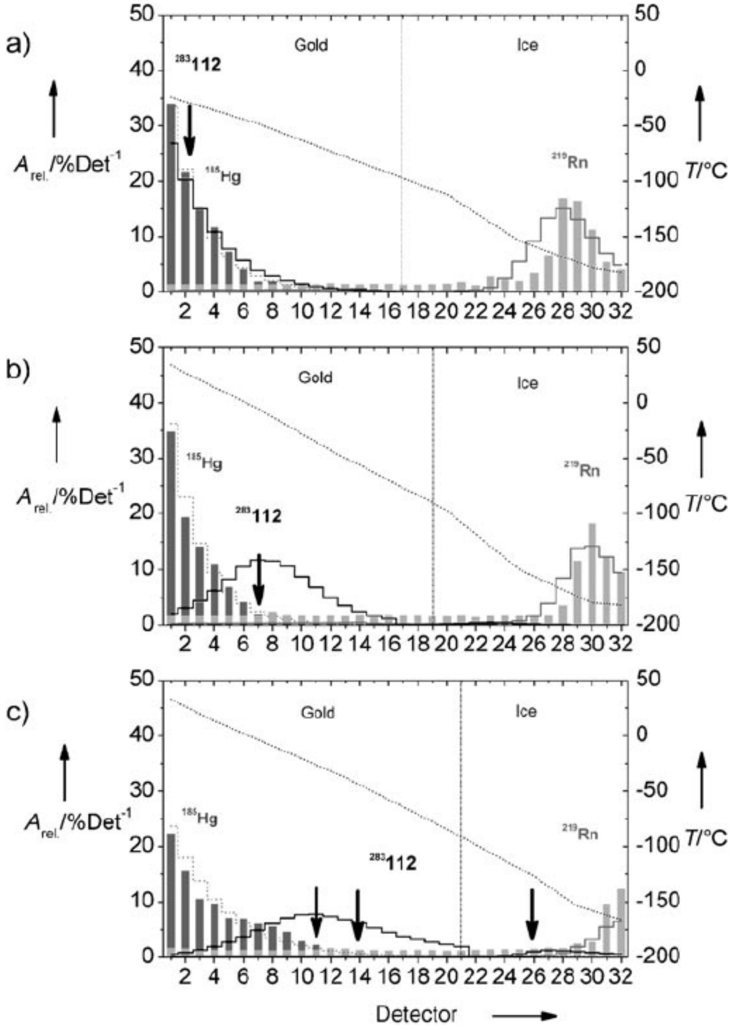
- The *nuclear* reaction is $^{48}Ca + {}^{238}U \rightarrow {}^{283}Cn + 3n$.
- The reaction products are stopped in a mixture of He and Ar.
- They go through a purification step into a closed-loop system with minimal oxygen and water.
- The main component is a *thermochromatography column*.



R. Eichler *et al.*, Nature (London) **447**, 72 (2007). (link)

Copernicium (Z = 112) Chemistry Results

- The experiment was designed to produce Cn, Hg, and Rn at the same time.
- Hg is not volatile and deposits even at high temperatures.
- Rn is volatile and only deposits at low temperatures.
- Cn was more like Hg.



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

Nihonium ($Z = 113$) Chemistry Experiment

- Dmitriev *et al*. reported a broad distribution of nihonium on room-temperature Au surfaces with $-\Delta H_{ads} > 60$ kJ/mol.

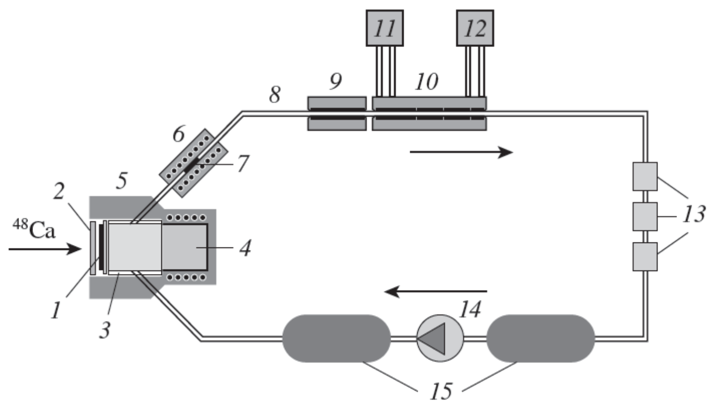


Figure 1 Schematic diagram of the experimental setup for studying the chemical properties of element 113: (*1*) ^{243}Am (1.5 mg cm^{-2}) + ^{nat}Nd (15 μg cm^{-2}) target on the backing of Ti (2 μm); (*2*) vacuum window (4 μm Ti foil); (*3*) cylindrical quartz insertion; (*4*) beam-stop with water cooling; (*5*) target chamber; (*6*) oven; (*7*) quartz filter; (*8*) transport capillary; (*9*) isothermal detector of 16 pairs of Au(Si) detectors at ambient temperature; (*10*) cryodetector of 32 pairs of Au(Si) detectors; warm end at +20 °C and cold end at –50 °C; (*11*) water thermostat; (*12*) cryothermostat; (*13*) gas purification system; (*14*) pump; and (*15*) buffer volumes.

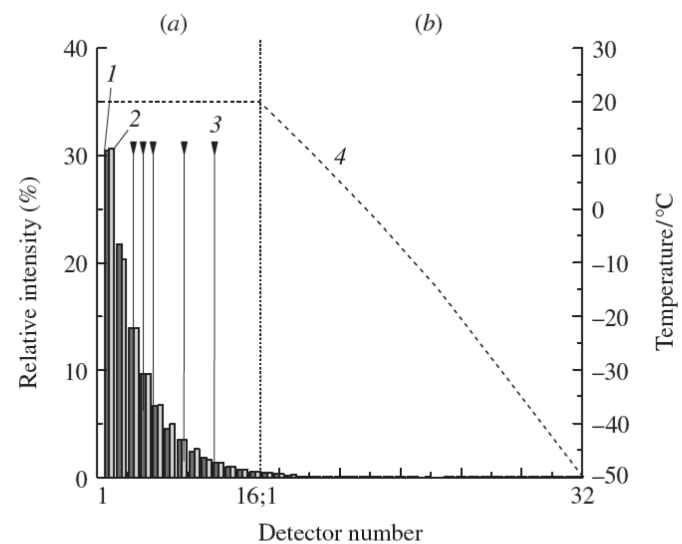
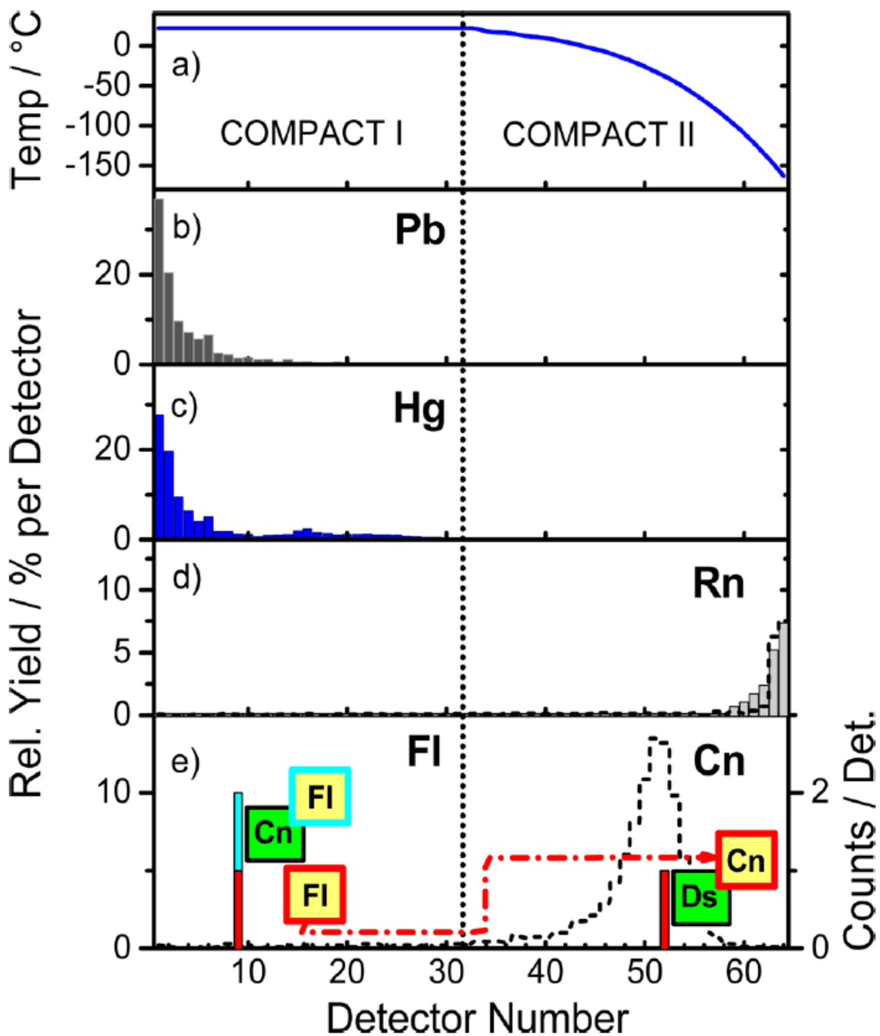


Figure 3 Distribution of (*1*) ^{185}Hg and (*2*) ^{211}At in the detector modules together with (*3*) the position of the observed decay chains attributed to ^{284}113; dashed line (*4*) represents the temperature gradient from +20 to –50 °C at (*a*) isothermal and (*b*) cryomodules of the detector.

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

Flerovium (Z = 114) Chemistry Results

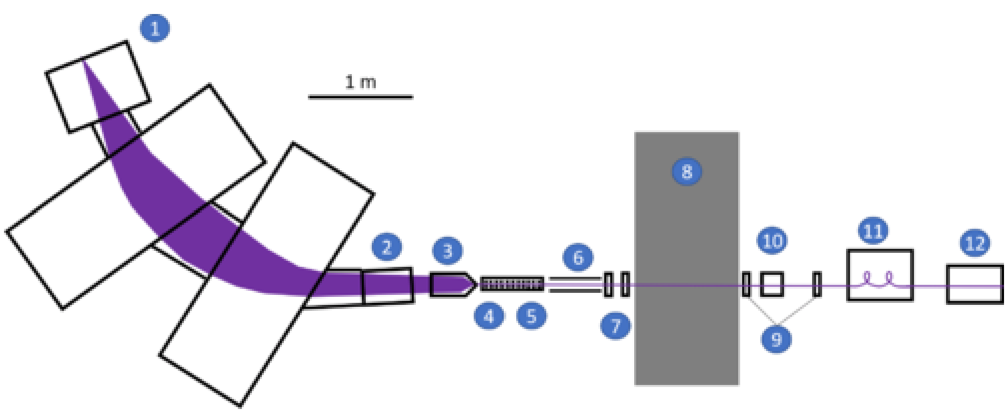
- The experiment produced Fl, Pb, Hg, and Rn at the same time.
- Pb and Hg are *not* volatile and deposit even at high temperatures.
- Rn is volatile and only deposits at low temperatures.
- "Fl is a *volatile metal*, the least reactive one in group 14." (emphasis in original).

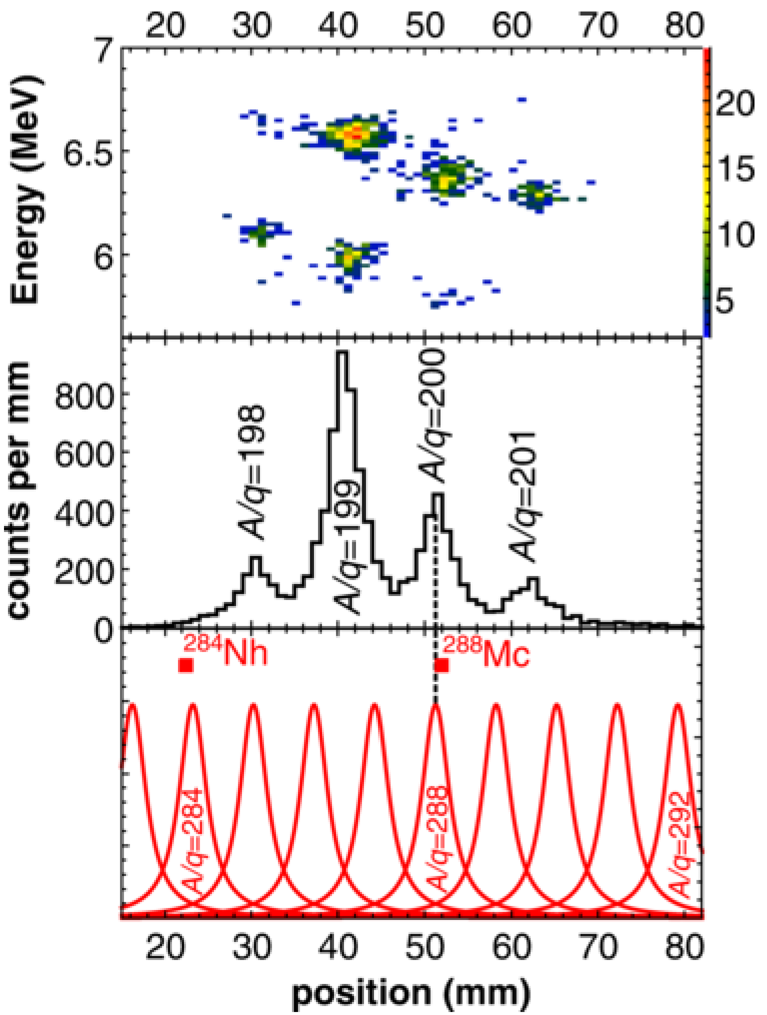


A. Yakushev *et al.*, Inorg. Chem. **53**, 1624 (2014). doi:10.1021/ic4026766

Mass Spectrometry of Moscovium (Z = 115)

- A recent experiment directly measured the mass numbers of the products of ^{48}Ca + ^{243}Am for the first time.
- The results suggested that one atom of ^{288}Mc and one atom of ^{284}Nh were detected.

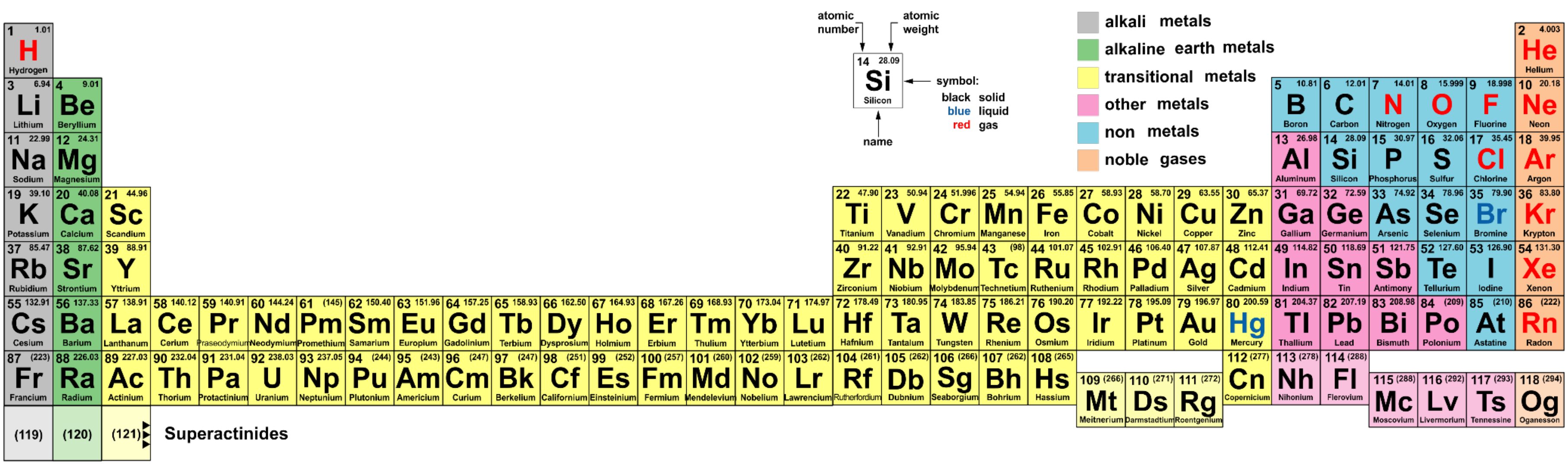




J. M. Gates *et al.*, Phys. Rev. Lett. **121**, 222501 (2018). doi:10.1103/PhysRevLett.121.222501

The Full Form of the Periodic Table

- The correct form of the periodic table has 32 columns.
- The “normal” form just makes it more convenient for printing.

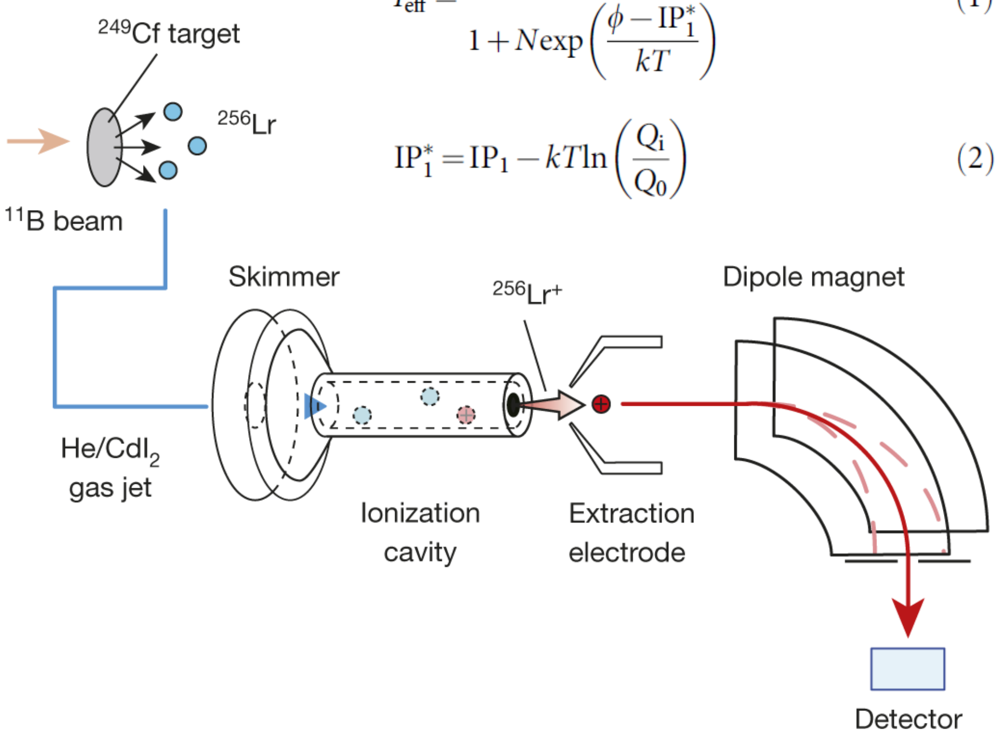


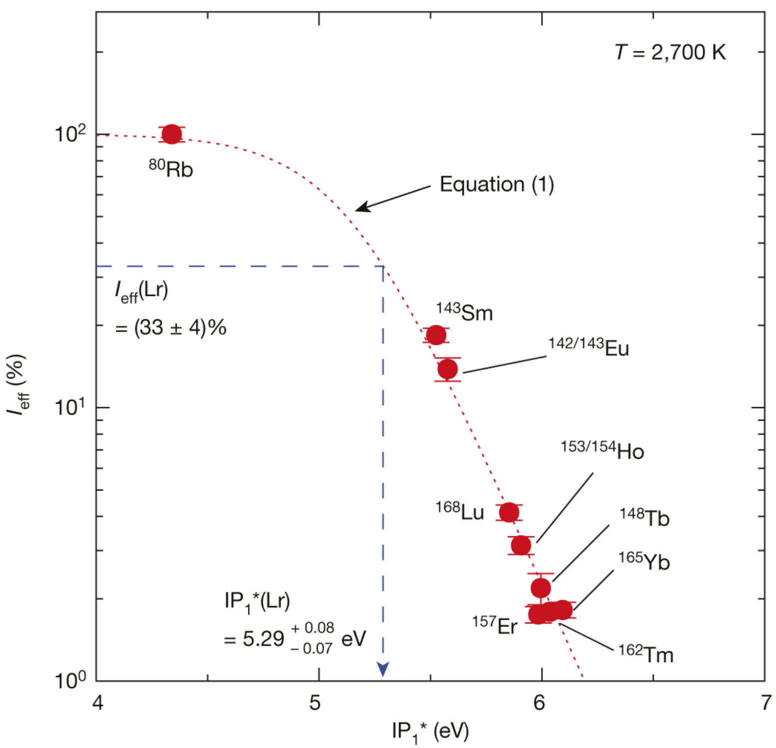
First Ionization Potential of Lr

- By measuring the yield through an "ionization cavity" and fitting to a calibration curve, the IP was determined.

$$I_{\mathrm{eff}} = \frac{N\exp\left(\frac{\phi - \mathrm{IP}_1^*}{kT}\right)}{1 + N\exp\left(\frac{\phi - \mathrm{IP}_1^*}{kT}\right)} \quad (1)$$

$$\mathrm{IP}_1^* = \mathrm{IP}_1 - kT\ln\left(\frac{Q_i}{Q_0}\right) \quad (2)$$



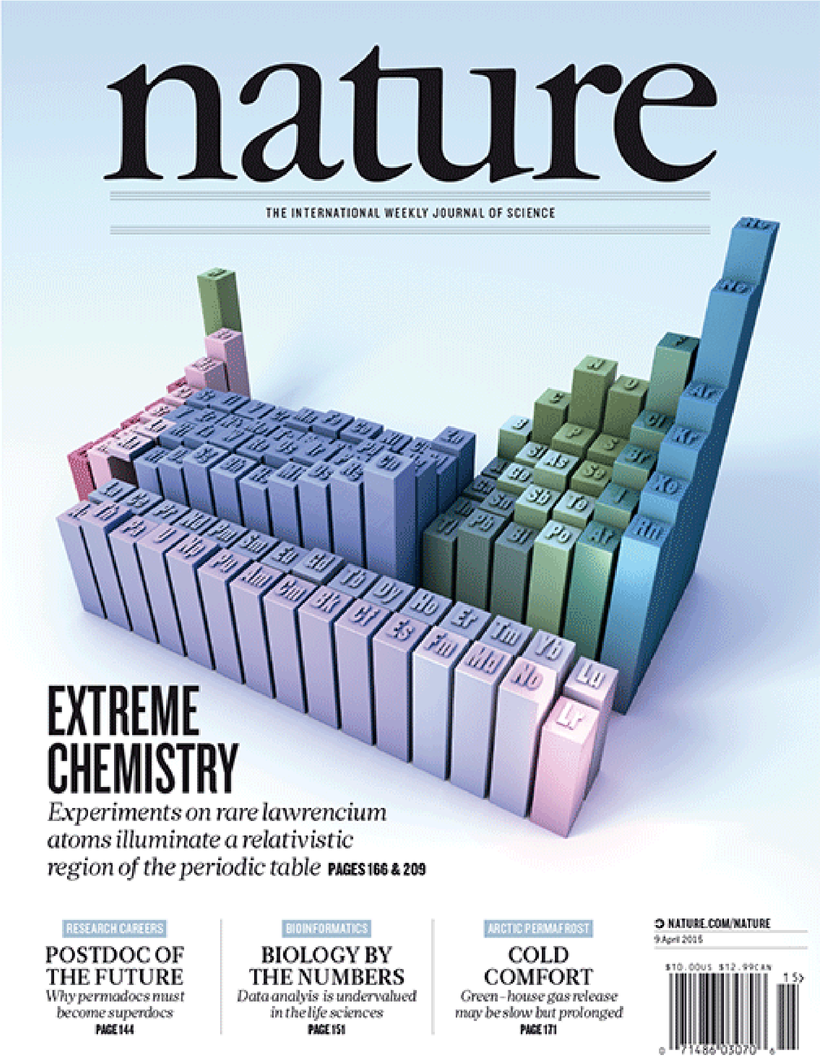


T. K. Sato *et al.*, Nature (London) **520**, 209 (2015). doi:10.1038/nature14342

Ionization Potentials of the Elements

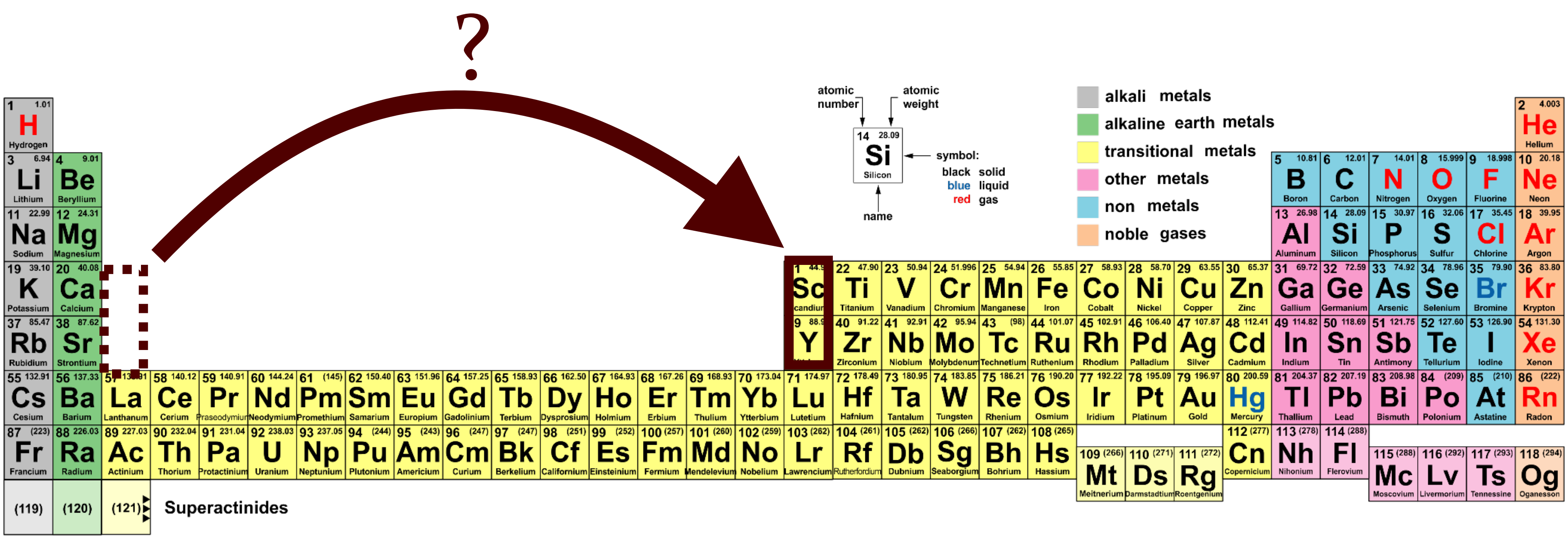
- Lawrencium has the fifth lowest ionization potential (479 kJ/mol) of all elements that have been measured.

- The fact that lawrencium has such a low IP could have implications for how we understand the structure of the periodic table.



What is the correct form of the periodic table?

- Is lawrencium actually the point where the elements return to the main body of the periodic table?
- Should lawrencium be part of the main body rather than the actinides?



Summary

- On the upside, many scientists believe that the compound nucleus mechanism is still viable for discovering new elements.
- On the downside, there are both theoretical and experimental challenges to discovering new elements.
- Chemical studies of the heaviest elements are helping us to understand the structure of the periodic table.
- There are still many open questions to answer!