

# The Heaviest Elements

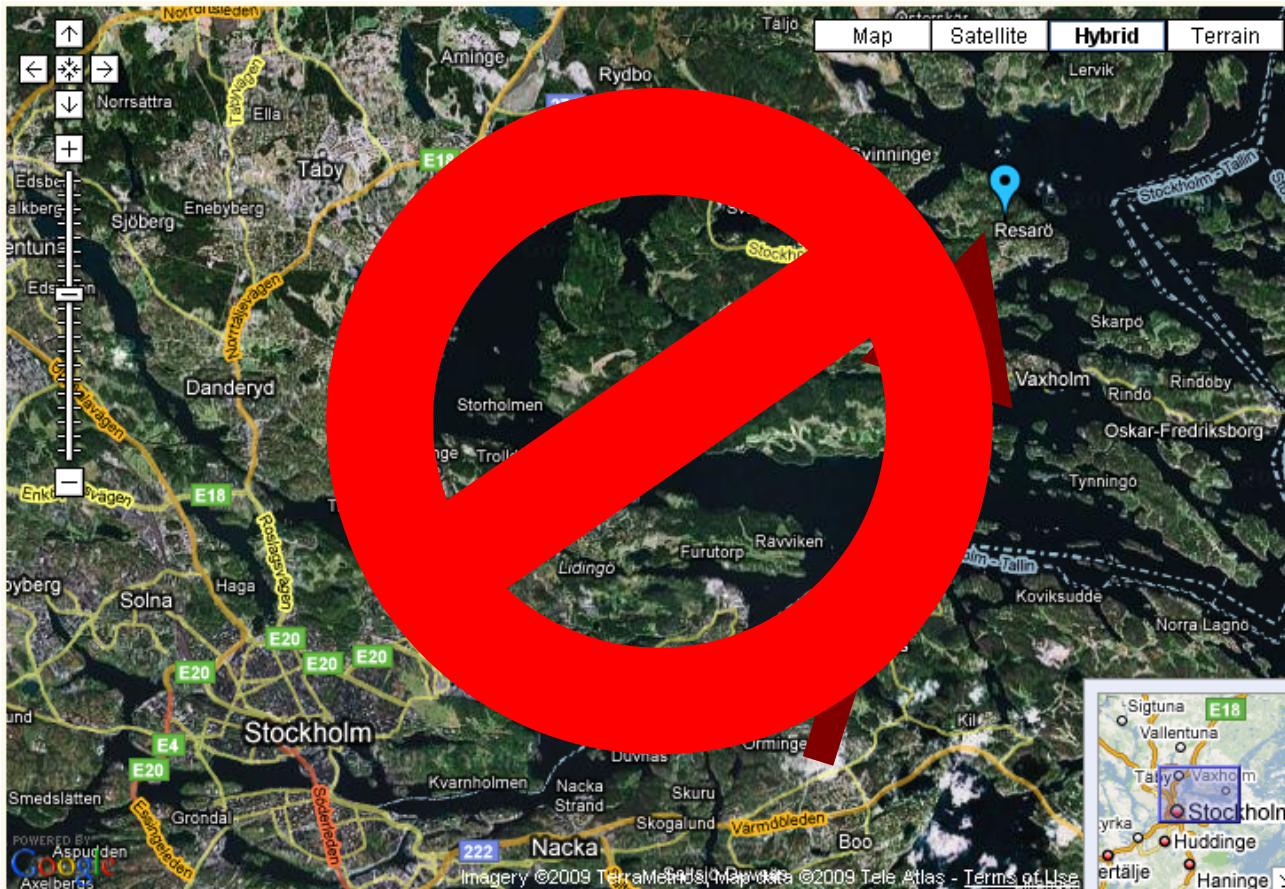
Prof. Cody Folden

June 20, 2012

Let's set the stage.

# They keep finding new elements. Where are they?

- Ytterby, Sweden is the namesake of four elements: ytterbium, yttrium, erbium, and terbium.



# Outline

- The Elements as They Stand Today
- Nuclear Reactions Used to Make the Heaviest Elements
- The So-Called “Island of Stability”
- How are the experiments performed?
- How do you study chemistry with only a few atoms?
- The Future of New Elements

# 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.
  - $^{244}\text{Pu}$  *has* been discovered in nature! This isotope has a half-life of “only” 80 million years.
- The artificial elements bring the total to 118.

# $^{244}\text{Pu}$ in Nature (1971)

## Detection of Plutonium-244 in Nature

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Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

J. L. MEWHERTER & F. M. ROURKE

General Electric Company, Knolls Atomic Power Laboratory, Schenectady, New York

- Sample:  $1.0 \times 10^{-18}$  g  $^{244}\text{Pu}$  per gram of sample.
- Crust:  $5 \times 10^{-25}$  g  $^{244}\text{Pu}$  per gram of Earth.
- There is an extremely weak “rain” of  $^{244}\text{Pu}$  that falls on the Earth, creating an *equilibrium* that balances its radioactive decay.





# The Periodic Table 2012

atomic number

atomic weight

14

28.09

Si

Silicon

symbol:

black

blue

red

solid

liquid

gas

name

alkali metals

alkaline earth metals

transitional metals

other metals

non metals

noble gases

1 1.01 H Hydrogen																	2 4.003 He Helium	
3 6.94 Li Lithium	4 9.01 Be Beryllium																	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium																	18 39.95 Ar Argon
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton	
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon	
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon	
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac Actinium	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium					112 (277) Cn Copernicium		114 (288) Fl Flerovium				
								109 (266) Mt Meitnerium	110 (271) Ds Darmstadtium	111 (272) Rg Roentgenium		(284)		(288)	116 (292) Lv Livermorium	(293)	(294)	
(119)	(120)	(121)	(154)															

Lanthanides

58 140.12	59 140.91	60 144.24	61 (145)	62 150.40	63 151.96	64 157.25	65 158.93	66 162.50	67 164.93	68 167.26	69 168.93	70 173.04	71 174.97
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium

Actinides

90 232.04	91 231.04	92 238.03	93 237.05	94 (244)	95 (243)	96 (247)	97 (247)	98 (251)	99 (252)	100 (257)	101 (260)	102 (259)	103 (262)
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium

Superactinides (122-153)

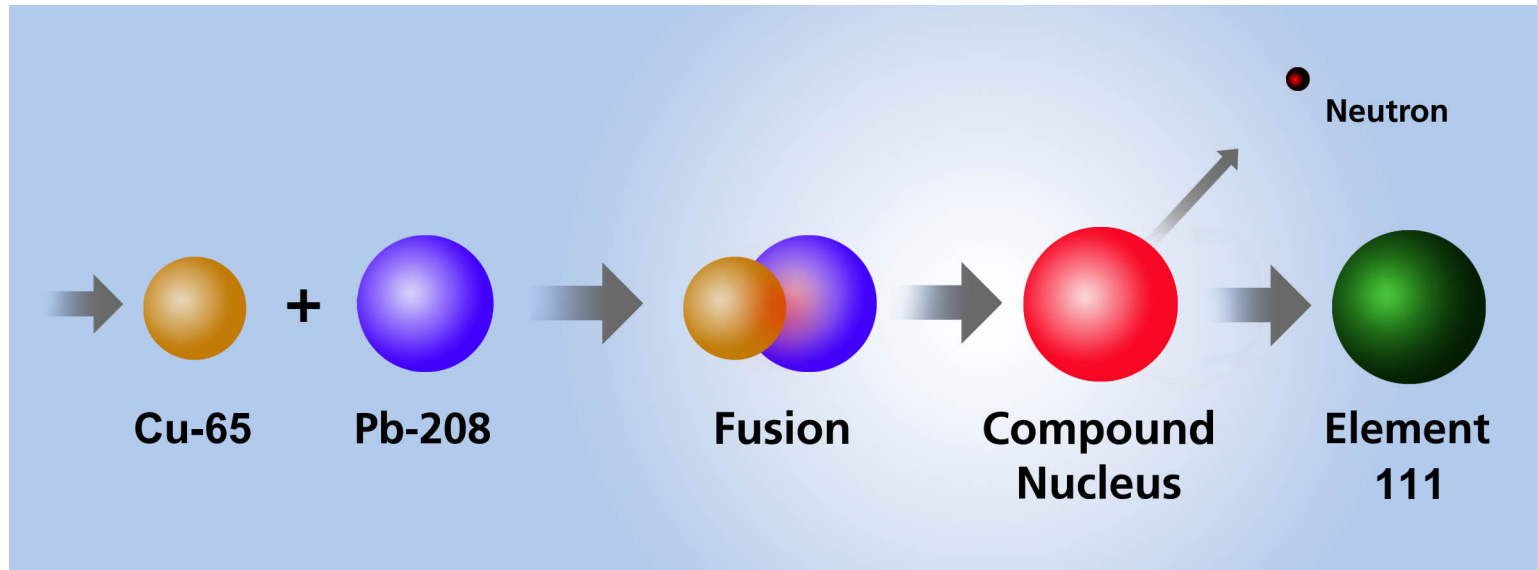
The heaviest elements are all produced *artificially*!

# Why study heavy elements?

- Studies at the extremes of nuclear stability.
- Chemistry at the limits of the periodic table:
  - What is the influence of relativistic effects?
  - Does the periodicity of the elements hold?
  - The chemistry of the elements is the most fundamental goal in chemistry.
- Interplay of chemistry and physics.



# How does the nuclear reaction work?



Beam:  
 $\sim 10^{12}$  per  
second

Fusion:  
(Net Effect:  
 $10^{-8}$ )

Survival:  
 $(\sim 10^{-5})^x$   
 $x = \text{neutrons}$

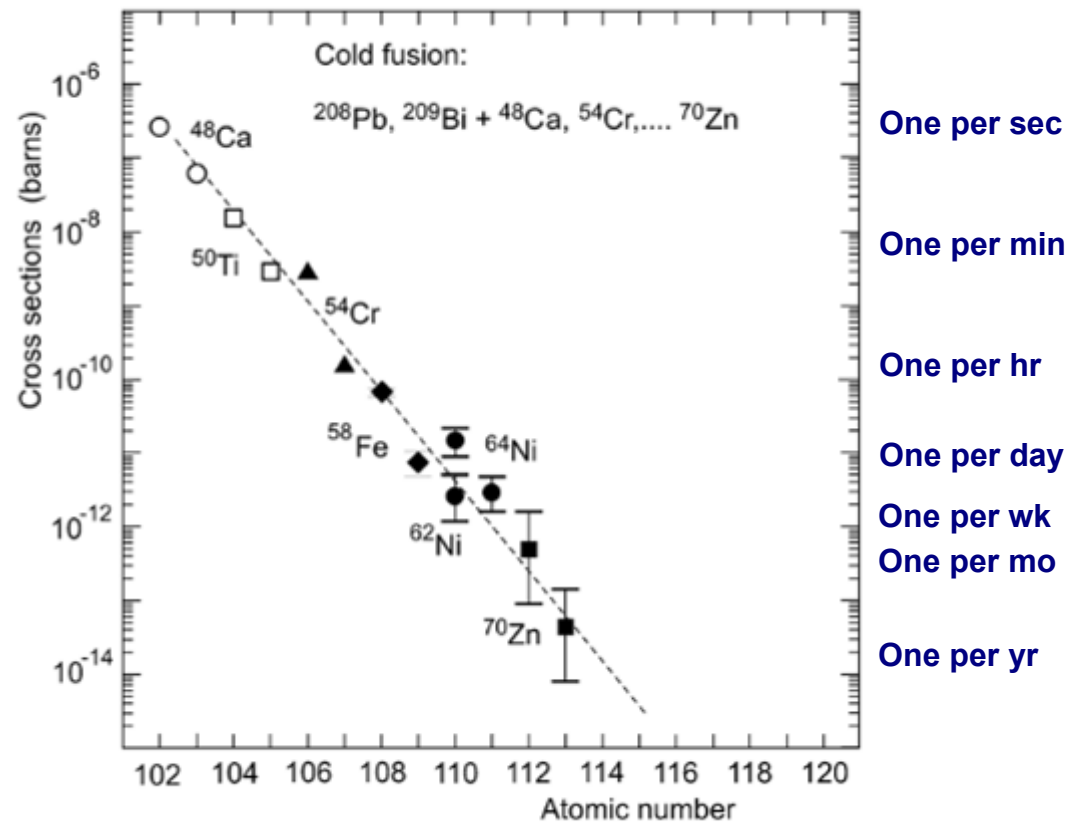
Residual  
Nucleus:  
0.1 per second

- In reality, it's not that easy. There is an additional nuclear physics issue that reduces the rate by another  $10^{-5}$ .

# Element Discoveries: Cold Fusion

- Cold Fusion relies on “shell stabilized” targets.
- Production rates decrease sharply as atomic number increases.
- These reactions were preferred ca. 1980-1997.

Reaction Probability ↑

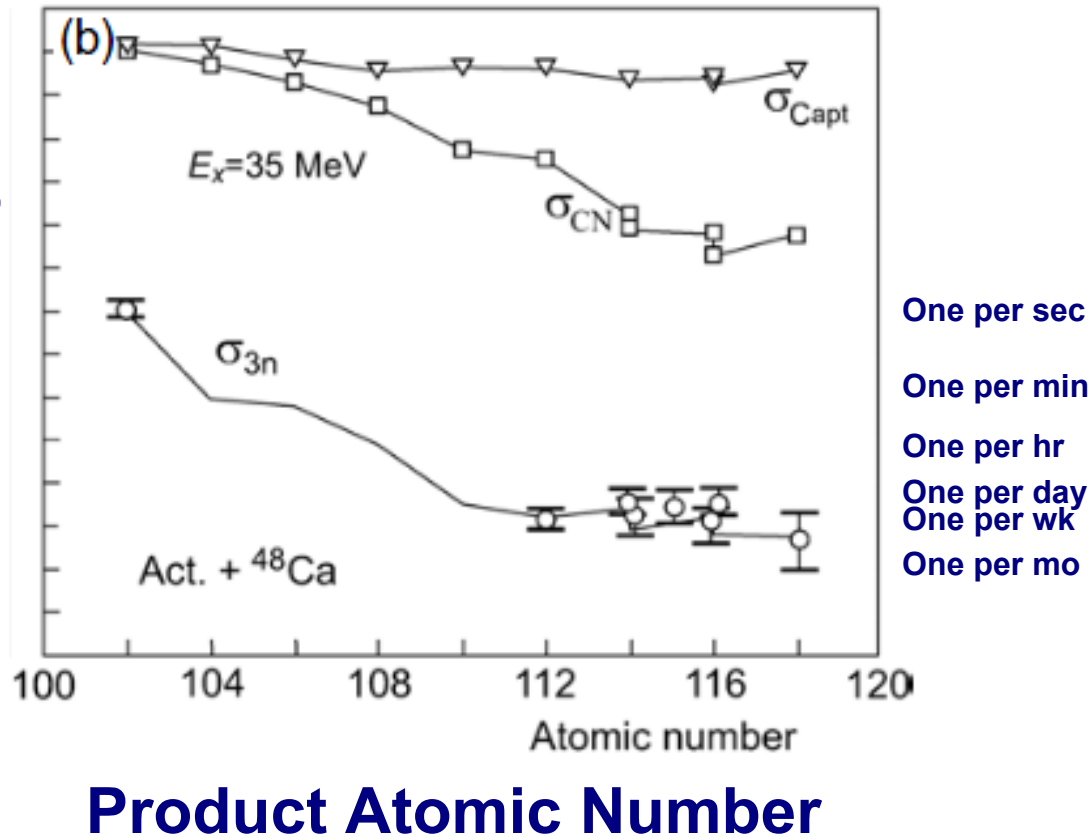


**Product Atomic Number**

# Element Discoveries: Warm Fusion

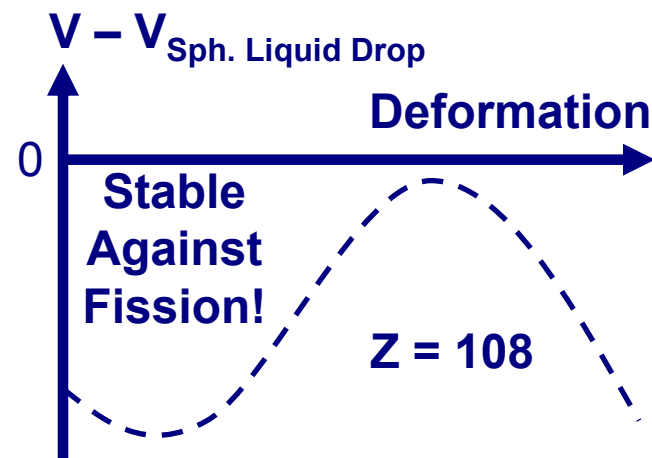
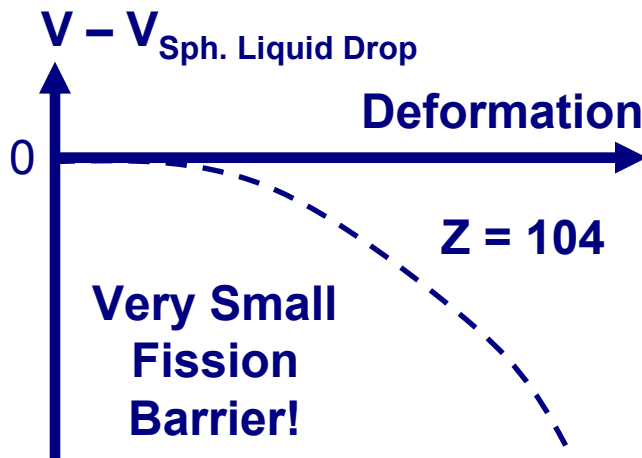
- Cold Fusion relies on “doubly magic”  $^{48}\text{Ca}$  beams.
- Production rates almost flat as atomic number increases.
- These reactions are preferred ca. 1998-present.

Reaction Probability ↑



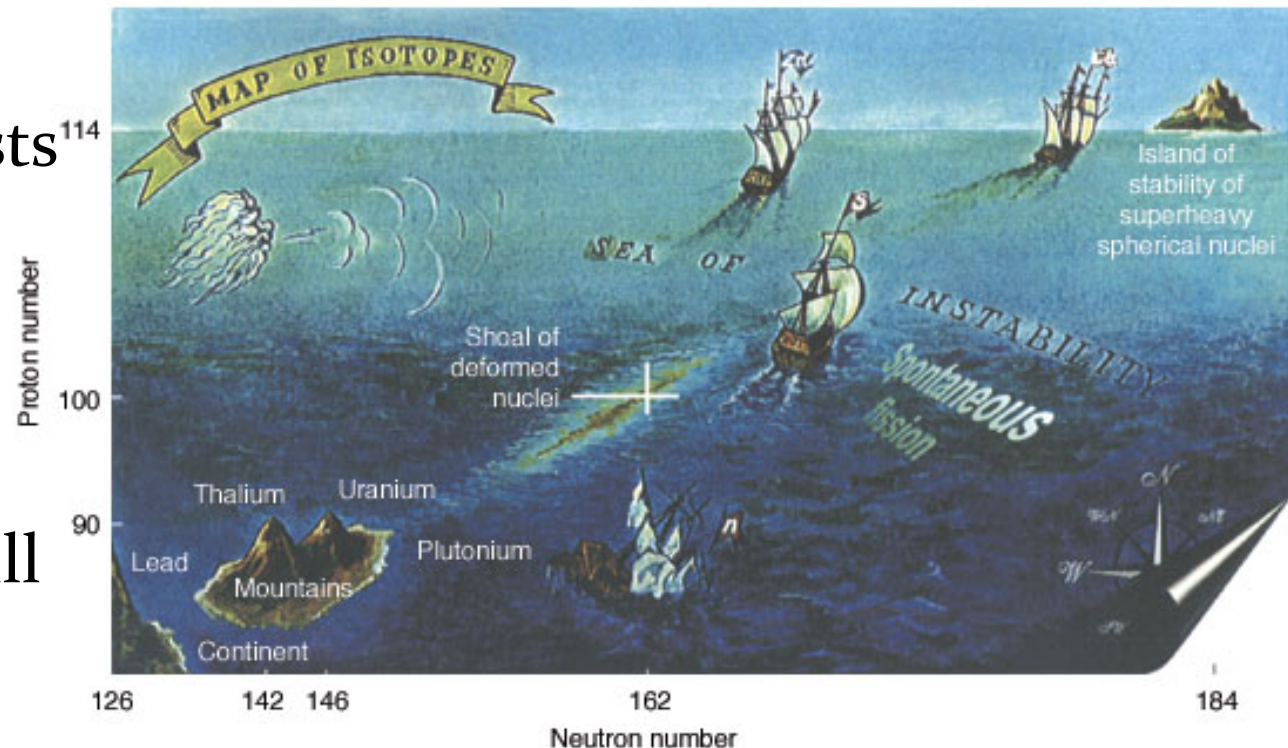
# Shell Corrections

- Next major spherical shell above  $Z = 82$ ,  $N = 126$  is variously predicted to occur at:
  - $Z = 114$  and  $N = 184$  (Sobiczewski).
  - $Z = 120$  and  $N = 172$  (Greiner).
  - $Z = 126$  and  $N = 184$  (Meldner, Ćwiok).
- There is a known deformed subshell at  $Z = 108$  and  $N = 162$ . This is why we can form element 108, for example.



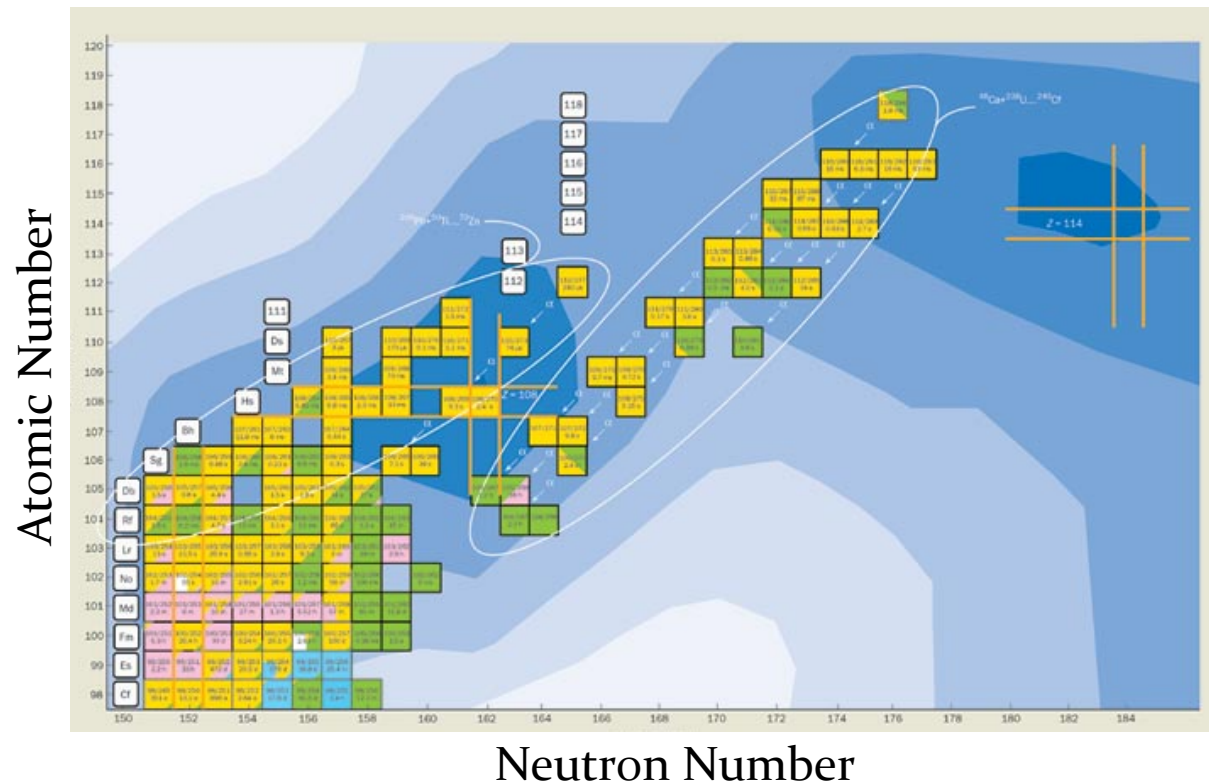
# The “Island of Stability”

- The “Island of Stability” is a way of stating a theory that there may be a region of nuclei that might have very long half-lives (years or more). Most heavy elements have half-lives of less than a few seconds.
- Theoretical nuclear physicists have been speculating on the location of the Island since 1967 and it is still not certain!



# Can we actually reach the “Island of Stability”?

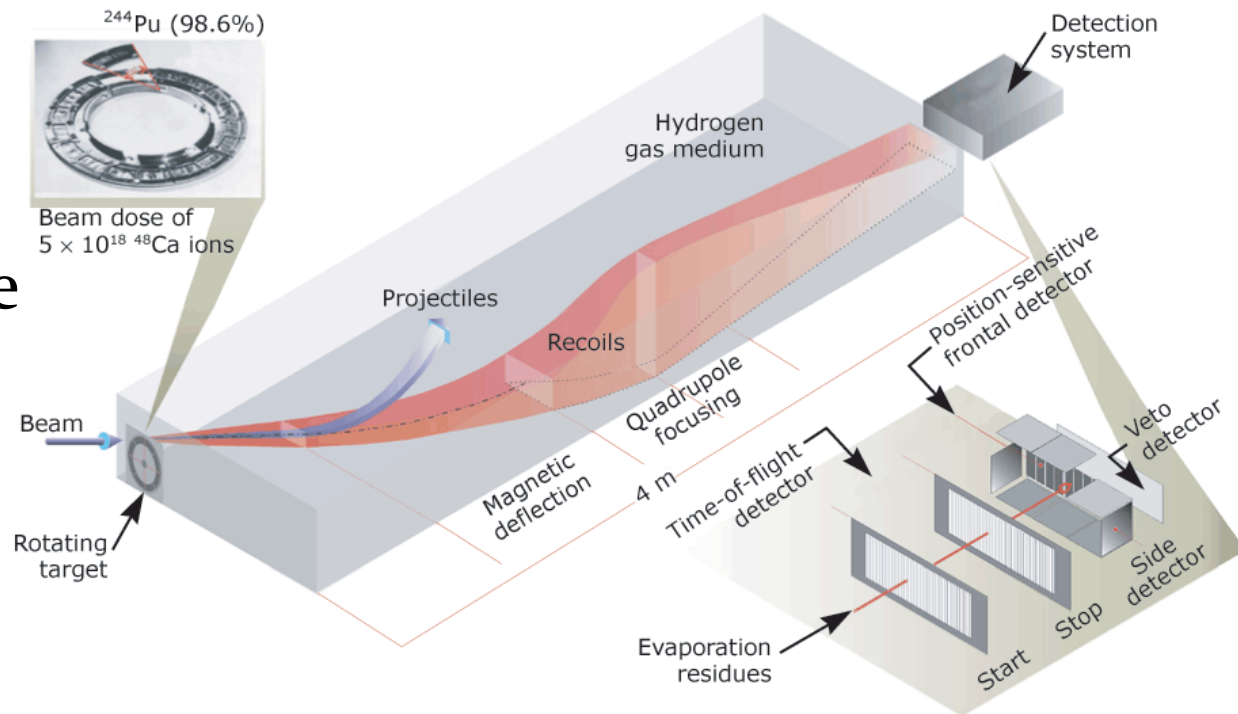
- The crosshairs on the right show where the Island *might* be located. The known isotopes are shown as squares. Unfortunately, it is not likely that we can reach this location with current technology.
- The problem is that we need higher ratios of protons to neutrons that are not available with current beams and targets.





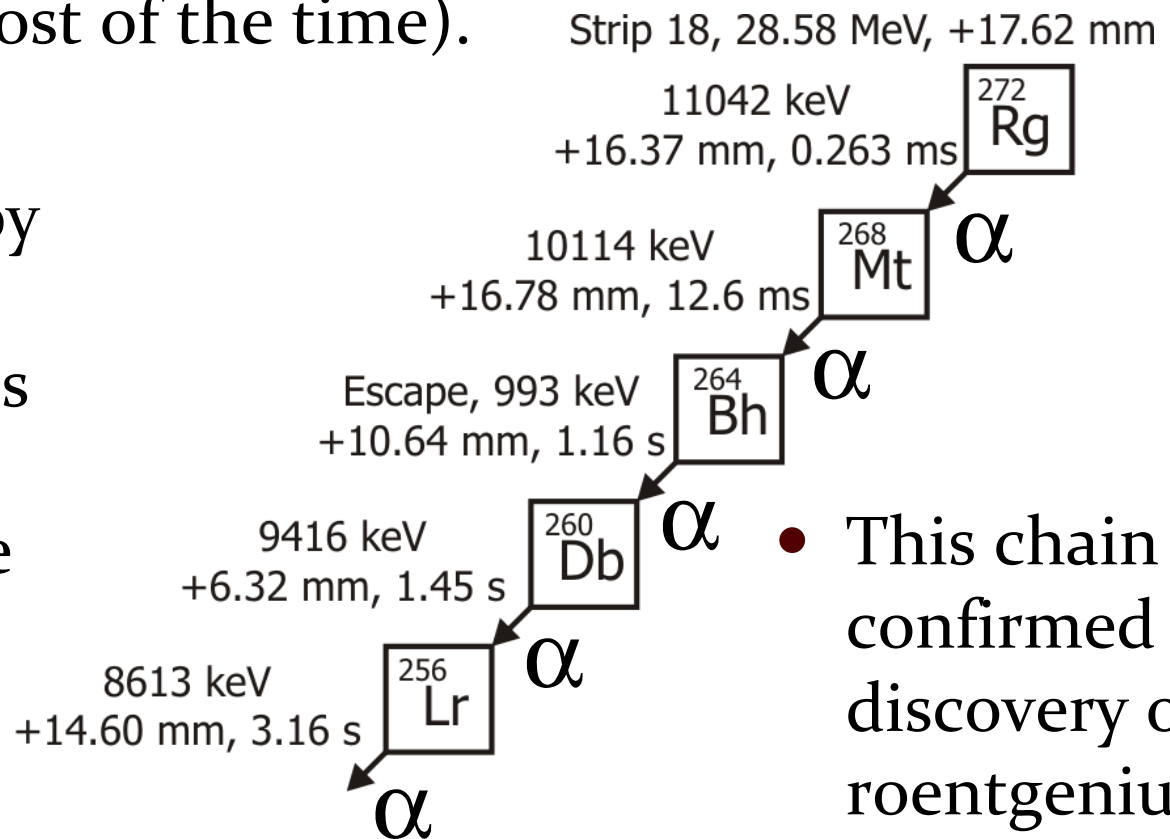
# How do the experiments work?

- 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.



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

- We observe rare isotopes through their radioactive decay. We can observe several decays and recreate the *decay chain*, which identifies the parent nucleus definitively. (Most of the time).
- Many heavy isotopes decay by alpha particle emission. This is easy to detect and tells you the exact relation between the chain members.



# 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.
- The same goes for the mass number.
- Physical or chemical methods can be used.
- Confirmatory experiments are preferred.
- Giving it a name immediately is discouraged.
- In reality, these criteria have not stopped arguments about who discovered what. They can last for years.

# The Future of New Elements

- There were two attempts to discover element 120 in 2011 at GSI (Germany):
  - $^{54}\text{Cr} + ^{248}\text{Cm} \rightarrow ^{298}_{120} + 4n$
  - $^{50}\text{Ti} + ^{249}\text{Cf} \rightarrow ^{295}_{120} + 4n$
- The success of these experiments likely depends on two factors:
  - The probability that the two nuclei will fuse.
  - The size of the fission barrier.
- All theoretical predictions indicate very low production rates in either case.

# Experimental $P_{\text{CN}}$ Values

- $P_{\text{CN}}$  decreases substantially with increasing  $A_{\text{proj}}$ .

**Preliminary  
Results**

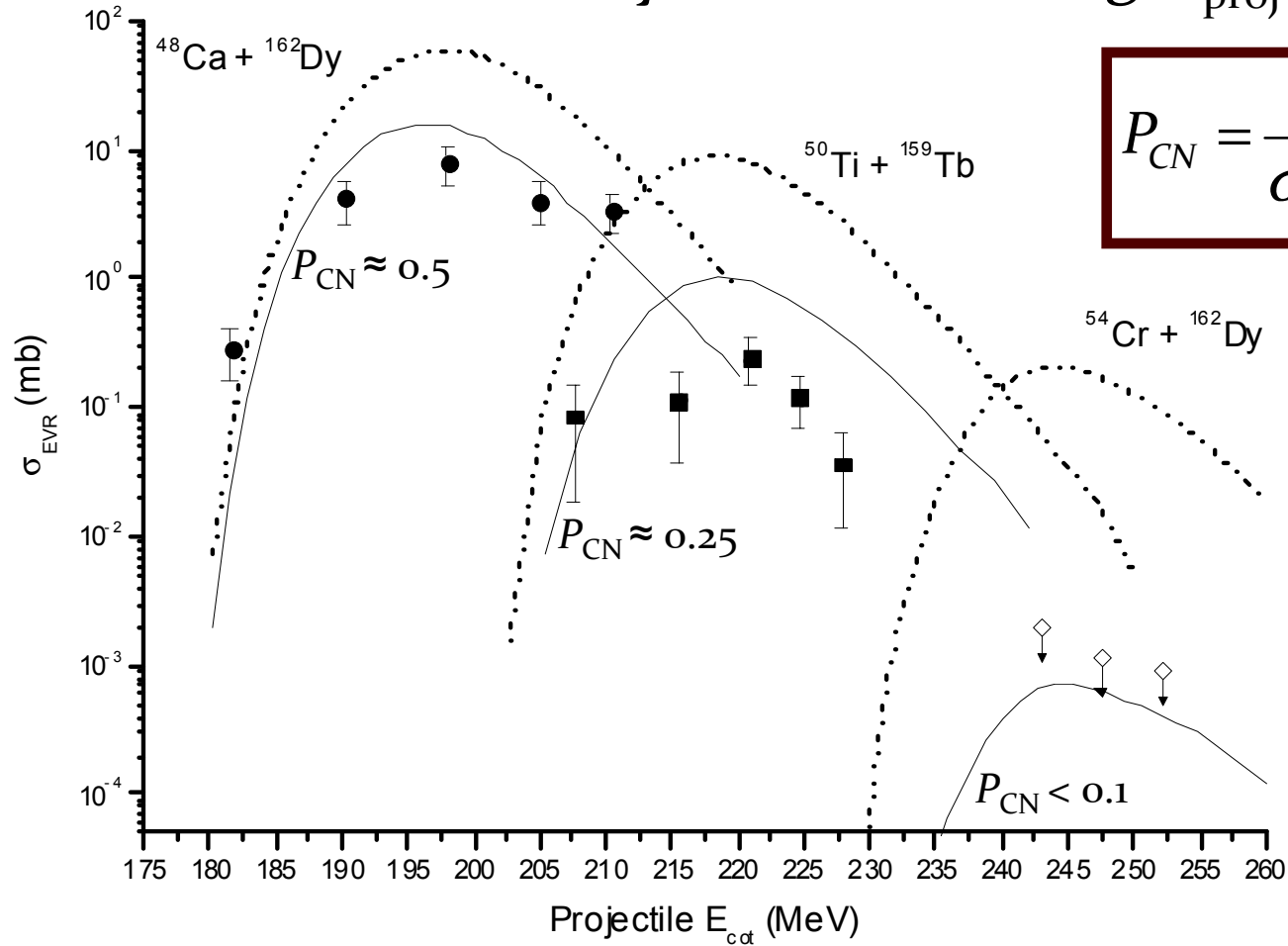


Figure courtesy of D. A. Mayorov.

# Implications for Reactions with Projectiles Heavier Than $^{48}\text{Ca}$

- The change from  $^{48}\text{Ca}$  to  $^{50}\text{Ti}$  or  $^{54}\text{Cr}$  affects the cross section:
- Good Things:
  - $\sigma_{\text{cap}}$  is flat at best.
  - Slight increase in separator efficiency.
- Bad Things:
  - Substantial decrease in  $P_{\text{CN}}$ .
  - Substantial decrease in  $W_{\text{sur}}$ .
  - (Possibly) slight decrease in beam intensity.
- We may discover elements 119 and 120, but after that it is going to be very difficult.





# What can heavy element chemistry tell us?

- More recently, we have begun to wonder whether the periodic table still works for very high atomic numbers. (It's not guaranteed).
- The problem is *relativistic effects*, the result of the fact that all the positive charge in the nucleus can accelerate the electrons to speeds near the speed of light.
- The relativistic effects change the electron orbitals and the chemical properties of the heaviest elements.
- We can study this by comparing the chemical properties of the artificial elements with their lighter *homologs*.
- We need to produce the transactinide, then measure some property, and do the same for the homologs.

# 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.
- 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?

atomic number      atomic weight

symbol: black solid blue liquid red gas

name

alkali metals  
alkaline earth metals  
transitional metals  
other metals  
non metals  
noble gases

1 1.01 H Hydrogen  
3 6.94 Li Lithium  
4 9.01 Be Beryllium  
11 22.99 Na Sodium  
12 24.31 Mg Magnesium  
19 39.10 K Potassium  
20 40.08 Ca Calcium  
21 44.96 Sc Scandium  
22 47.87 Ti Titanium  
23 50.94 V Vanadium  
24 51.996 Cr Chromium  
25 54.94 Mn Manganese  
26 55.85 Fe Iron  
27 58.93 Co Cobalt  
28 58.70 Ni Nickel  
29 63.55 Cu Copper  
30 65.37 Zn Zinc  
31 69.72 Ga Gallium  
32 72.59 Ge Germanium  
33 74.92 As Arsenic  
34 78.96 Se Selenium  
35 79.90 Br Bromine  
36 83.80 Kr Krypton  
37 85.47 Rb Rubidium  
38 87.62 Sr Strontium  
39 88.91 Y Yttrium  
40 91.22 Zr Zirconium  
41 92.91 Nb Niobium  
42 95.94 Mo Molybdenum  
43 98 Tc Technetium  
44 101.07 Ru Ruthenium  
45 102.91 Rh Rhodium  
46 106.40 Pd Palladium  
47 107.87 Ag Silver  
48 112.41 Cd Cadmium  
49 114.82 In Indium  
50 115.69 Sn Tin  
51 121.75 Sb Antimony  
52 127.60 Te Tellurium  
53 126.90 I Iodine  
54 131.30 Xe Xenon  
55 132.91 Cs Cesium  
56 137.33 Ba Barium  
57 138.91 La Lanthanum  
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  
71 174.07 Lu Lutetium  
72 183.84 Hf Hafnium  
73 186.21 Ta Tantalum  
74 188.91 W Tungsten  
75 186.21 Re Rhenium  
76 186.90 Os Osmium  
77 190.23 Ir Iridium  
78 195.08 Pt Platinum  
79 196.97 Au Gold  
80 200.59 Hg Mercury  
81 204.37 Tl Thallium  
82 208.98 Pb Lead  
83 209 Bi Bismuth  
84 209 Po Polonium  
85 210 At Astatine  
86 222 Rn Radon  
87 223 Fr Francium  
88 226 Ra Radium  
89 227 Ac Actinium  
90 232 Th Thorium  
91 231 Pa Protactinium  
92 238 U Uranium  
93 237 Np Neptunium  
94 244 Pu Plutonium  
95 247 Am Americium  
96 247 Cm Curium  
97 247 Bk Berkelium  
98 251 Cf Californium  
99 252 Es Einsteinium  
100 252 Fm Fermium  
101 257 Md Mendelevium  
102 259 No Nobelium  
103 262 Lr Lawrencium  
104 262 Rf Rutherfordium  
105 262 Db Dubnium  
106 263 Sg Seaborgium  
107 263 Bh Bohrium  
108 265 Hs Hassium  
109 266 Mt Meitnerium  
110 271 Ds Darmstadtium  
111 272 Rg Roentgenium  
112 285 Cn Copernicium  
113 284 Nh Nihonium  
114 285 Fl Flerovium  
115 286 Lv Livermorium  
116 286 Ts Tennessine  
117 289 Og Oganesson  
118 289 Og Oganesson

Lanthanides: Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

Actinides: Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr

Superactinides: (122-153)

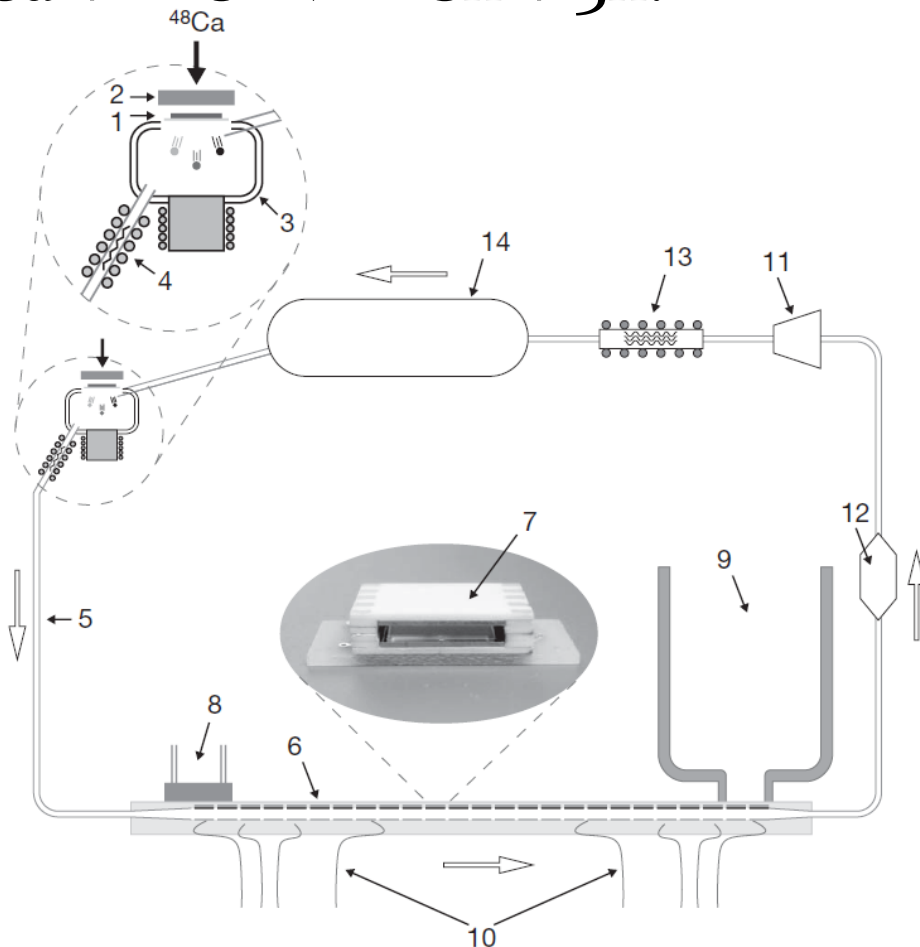
Modern Periodic Table

# How does a transactinide chemistry experiment work?

- We want to compare some transactinide chemical property to that of its lighter homologs.
- We have billions and billions of atoms of a homolog available (remember that  $1 \text{ mol} = 6.022 \times 10^{23} \text{ atoms}$ ), but only a few of the transactinide for comparison.
- We have to be clever!
- Step 1: Use a nuclear reaction to make the transactinide.
- Step 2: Possibly use a chemical reaction to make a compound of this transactinide. Dimers are not allowed.
- Step 3: Measure the radioactive decay of the heavy atom.
- Use the data to extrapolate to macroscopic quantities.

# Copernicium Chemistry Setup

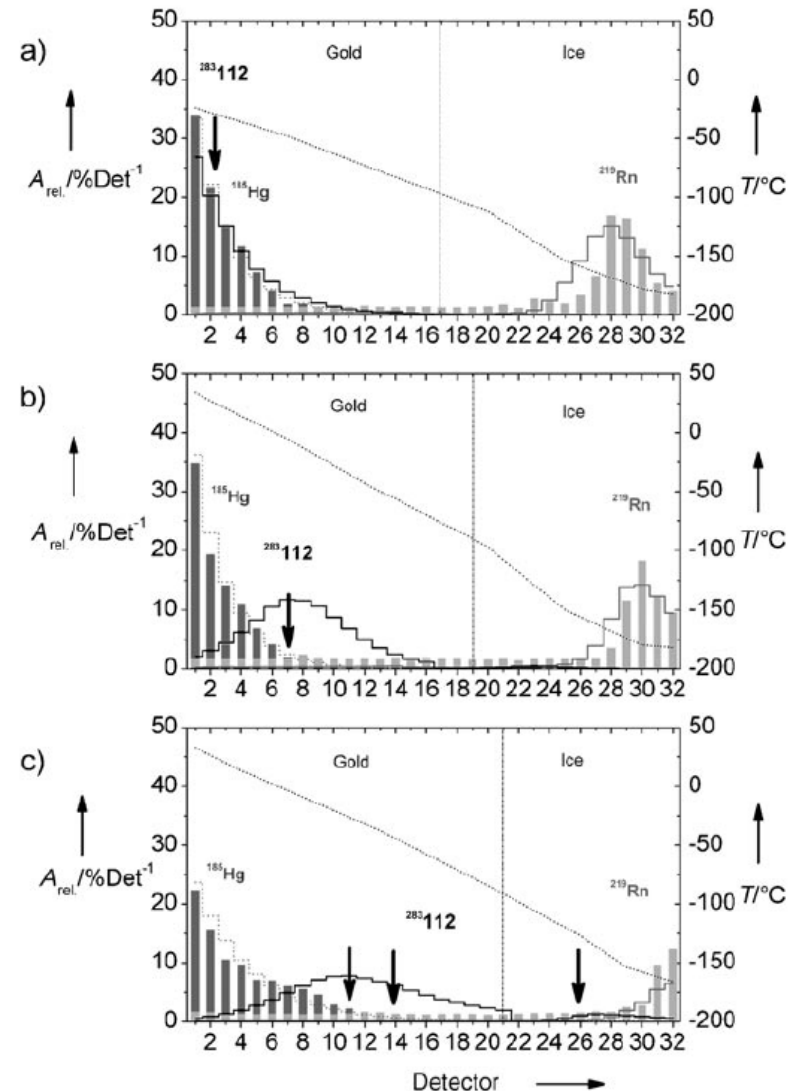
- The *nuclear* reaction is  $^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{283}\text{Cn} + 3\text{n}$ .
- The reaction products are stopped in a mixture of He and Ar.
- They go through a purification step into a closed-loop system with minimal oxygen and water.
- The main component is *thermochromatography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



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

# Copernicium 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 is somewhere in between.





# Simulation and Results

- Once you have the experimental data, you do a *Monte Carlo simulation* of the experiment that takes into account the geometry of the channel, the temperature profile, and the observed decay chains.
- The simulation tells you the *adsorption enthalpy* of the metal on the detector surface (Au) that is most likely to give you the observed distribution.
- Hg:  $\Delta H_{\text{ads}} = -98 \pm 3 \text{ kJ/mol}$                       Rn:  $-27 \pm 3 \text{ kJ/mol}$
- Cn:  $\Delta H_{\text{ads}} = -52 \pm 4 \text{ kJ/mol}$
- Notice that this experiment give you the energy *per mole*, even though there were only *four* molecules.
- The element is placed on the periodic table!

# What are all these heavy elements good for?

- The search for the heaviest elements answers questions like:
  - Q: What is the heaviest element that can be formed?
    - A: Not known.
  - Q: What mechanism is involved in their production?
    - A: The fusion of two lighter nuclei (plus some details).
  - Q: Does the periodicity of the elements continue for very high atomic numbers?
    - A: So far so good (but this could change in the future).
  - Q: What are their chemical properties?
    - A: Mostly, they are like their homologs, but we need more data.
- In summary, the study of the heaviest elements continues to influence our understanding of nuclei and the periodic table!