The Heaviest Elements

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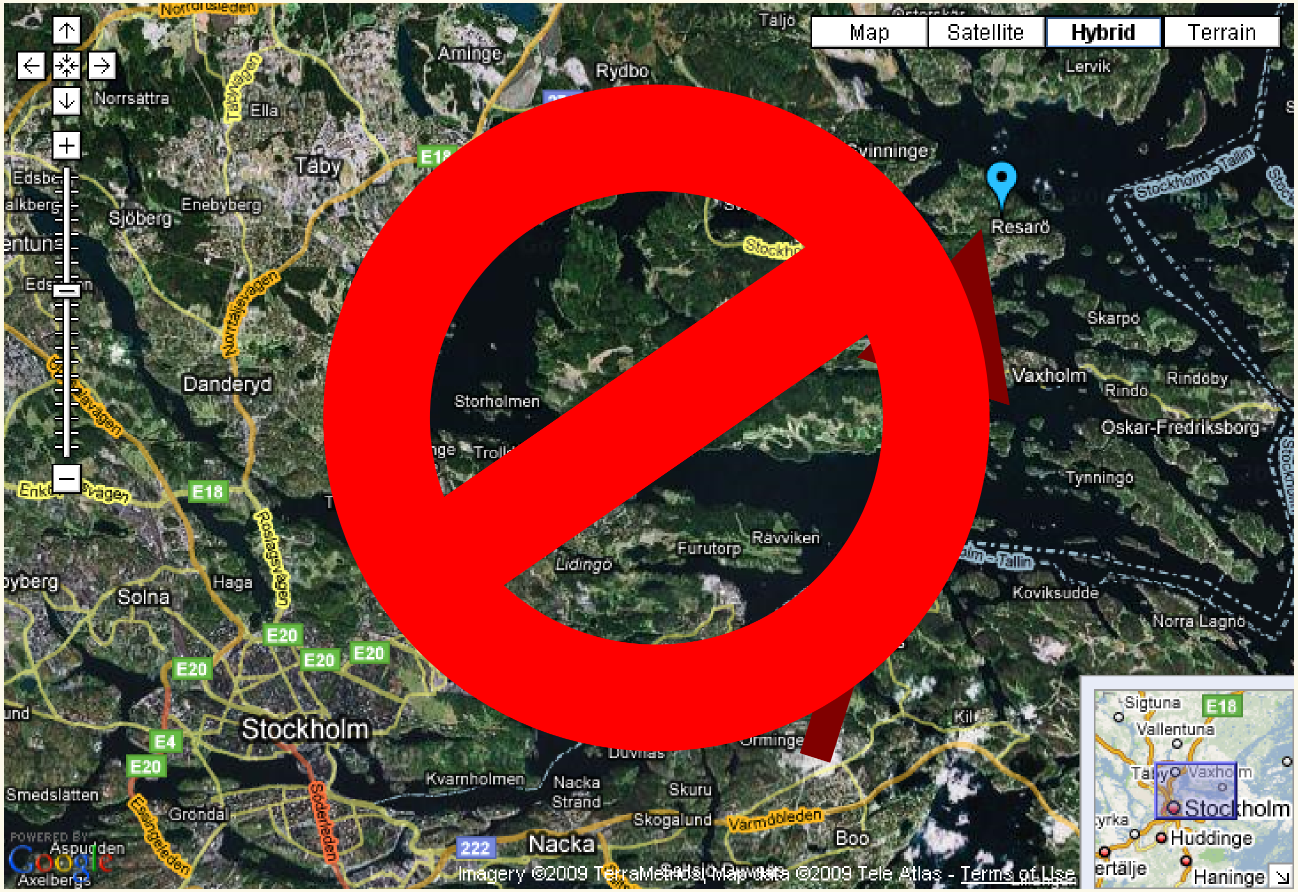
June 20, 2012

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}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}Pu in Nature (1971)

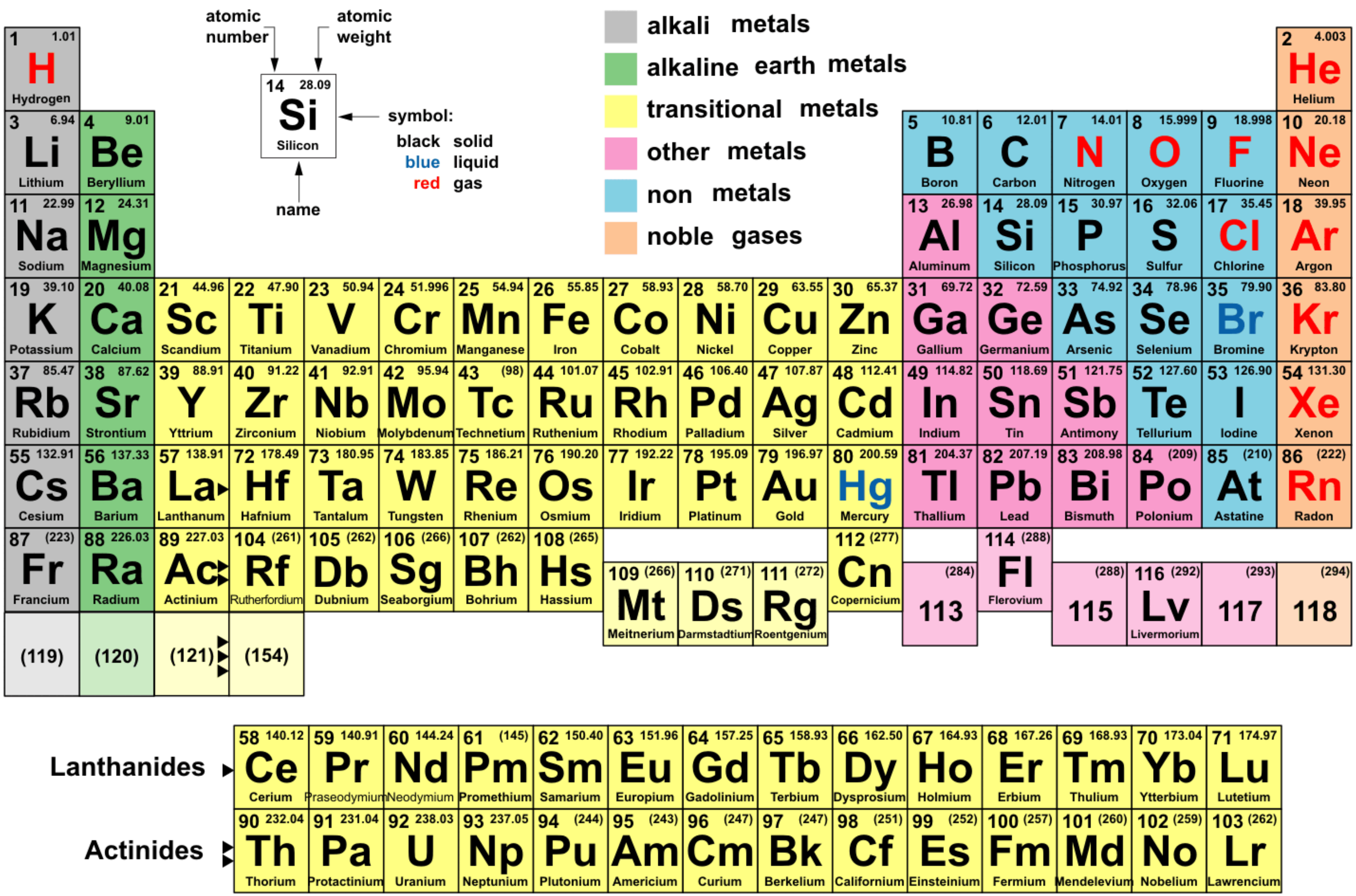
Detection of Plutonium-244 in Nature

D. C. HOFFMAN & F. O. LAWRENCE
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: 1.0×10^{-18} g ^{244}Pu per gram of sample.
- Crust: 5×10^{-25} g ^{244}Pu per gram of Earth.
- There is an extremely weak "rain" of ^{244}Pu that falls on the Earth, creating an *equilibrium* that balances its radioactive decay.

The Periodic Table 2012



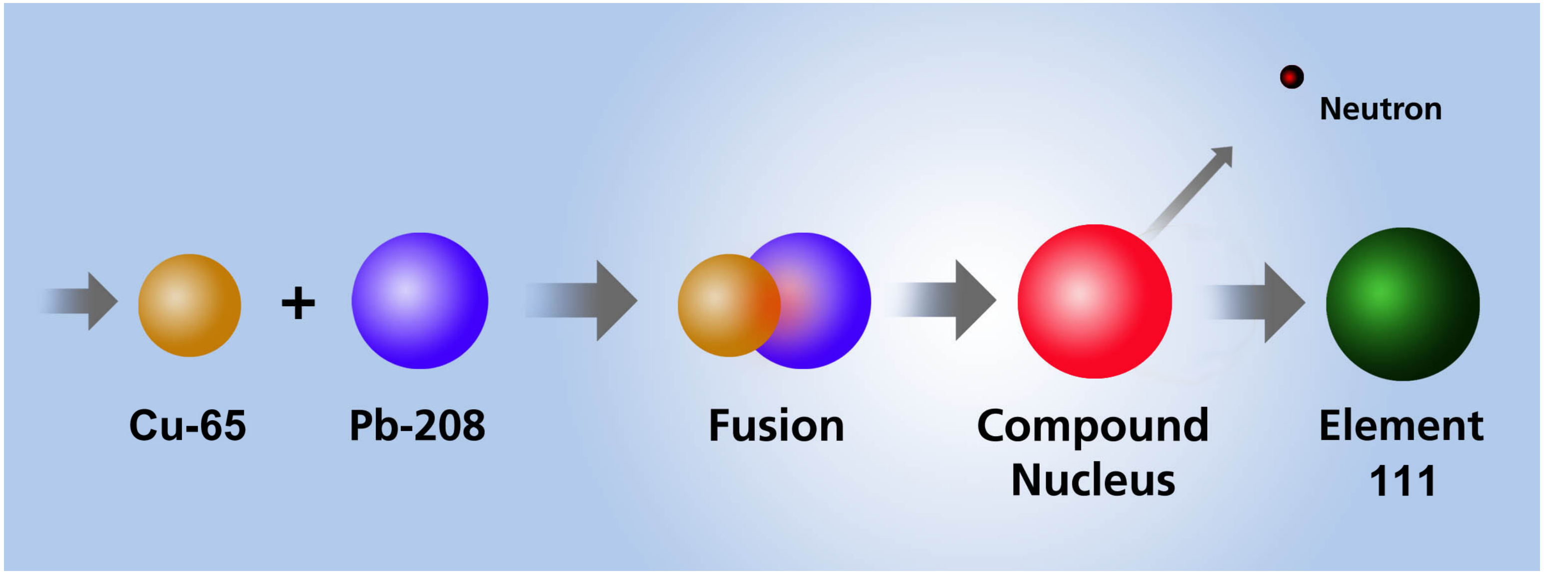
Superactinides (122-153)

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?

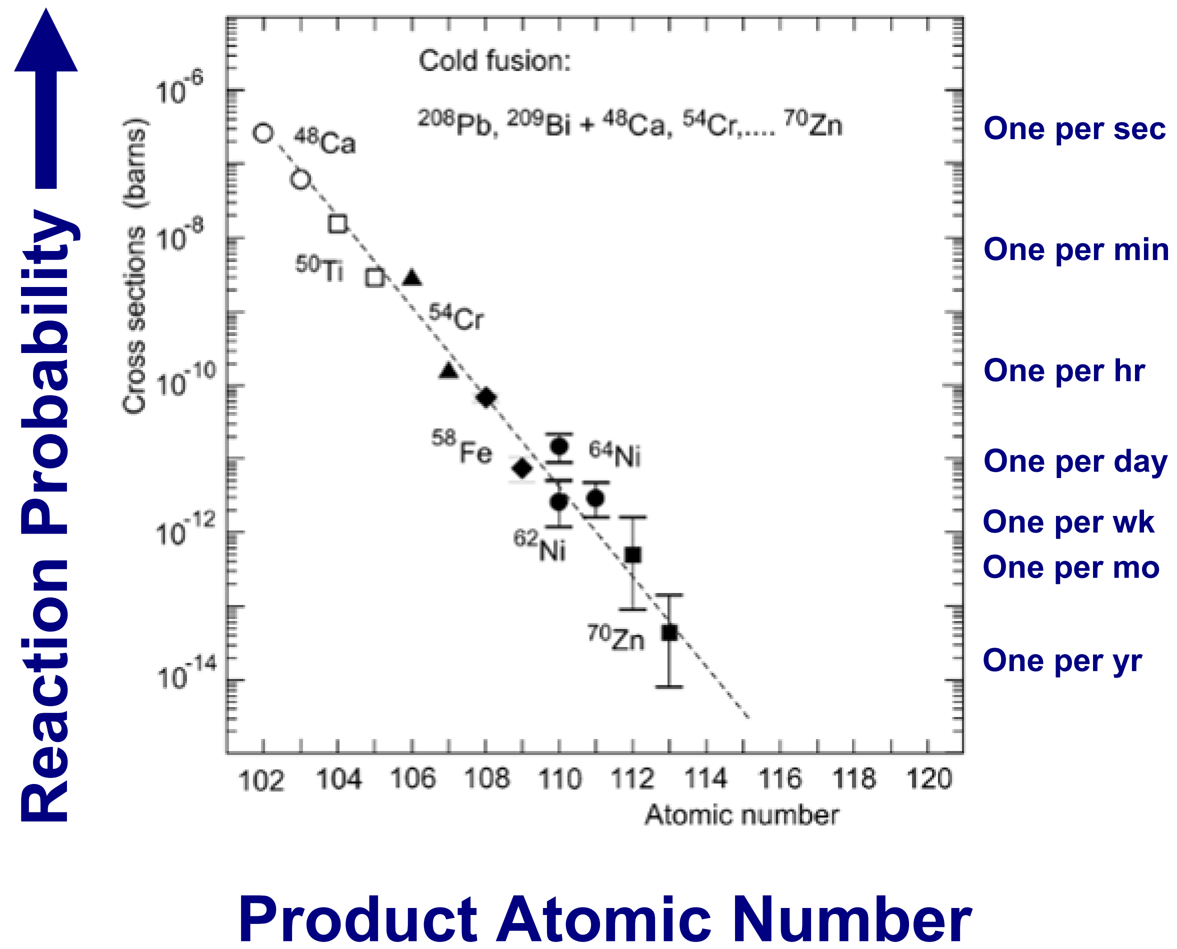


Beam:	Fusion:	Survival:	Residual Nucleus:
~10^{12} per second	(Net Effect: 10^{-8})	$(\sim 10^{-5})^x$ x = neutrons	0.1 per second

- 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

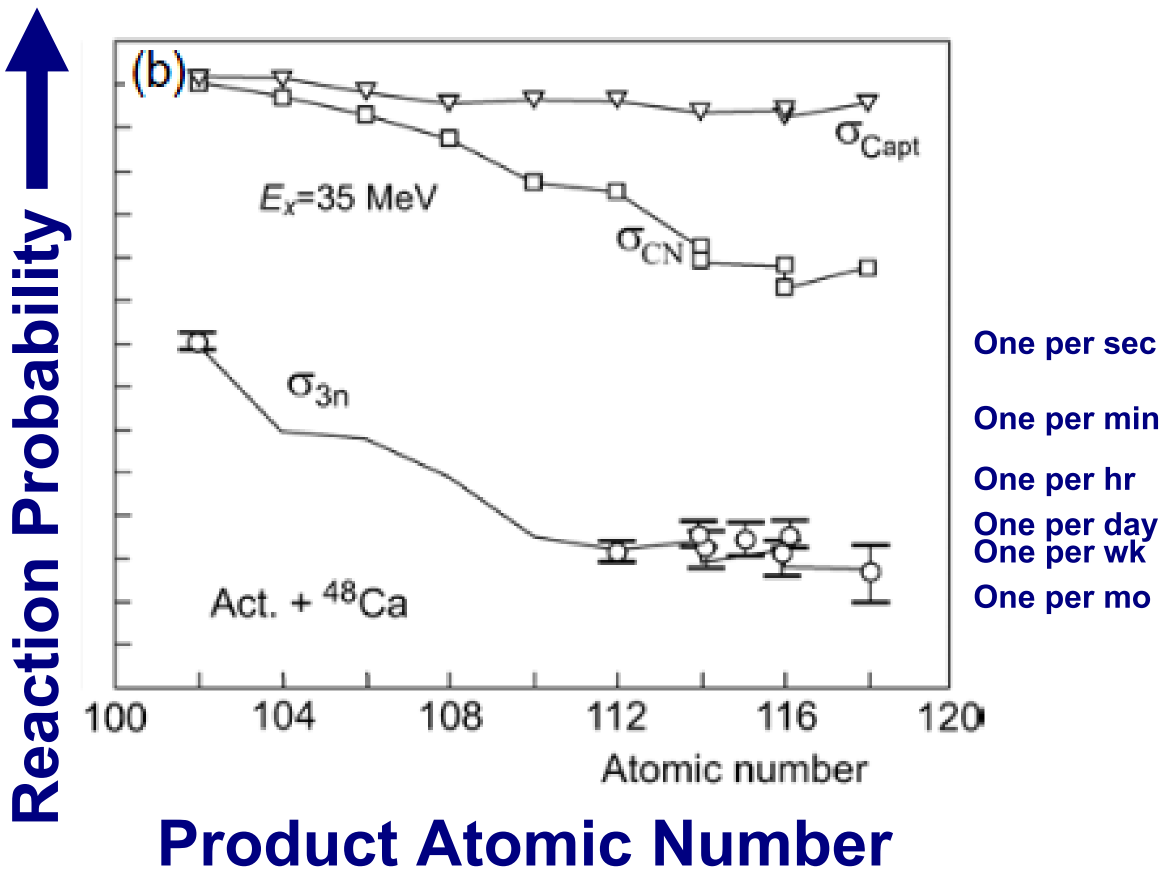
- Cold Fusion relies on “shell stabilized” targets.
- Production rates decrease sharply as atomic number increases.
- These reactions were preferred ca. 1980-1997.



Yu. Oganessian, J. Phys. G **34**, R165 (2007).

Element Discoveries: Warm Fusion

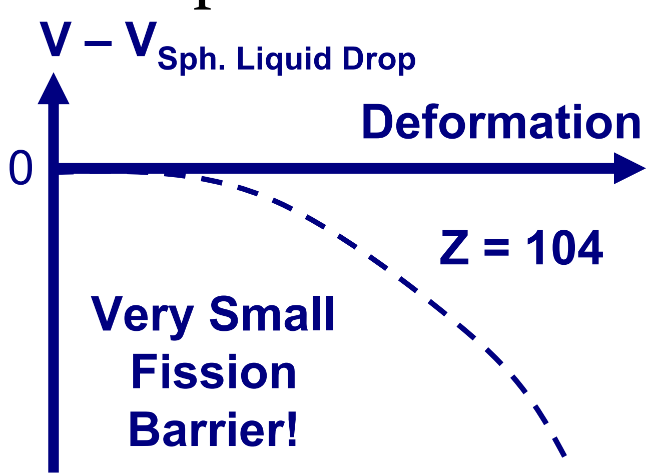
- Cold Fusion relies on "doubly magic" ^{48}Ca beams.
- Production rates almost flat as atomic number increases.
- These reactions are preferred ca. 1998-present.

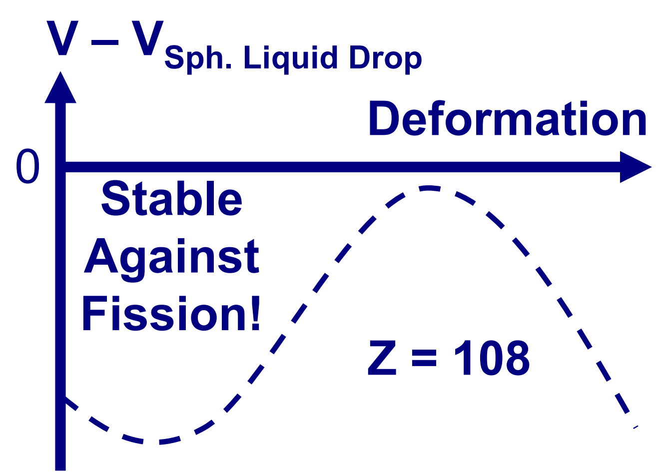


Yu. Oganessian, J. Phys. G **34**, R165 (2007).

Shell Corrections

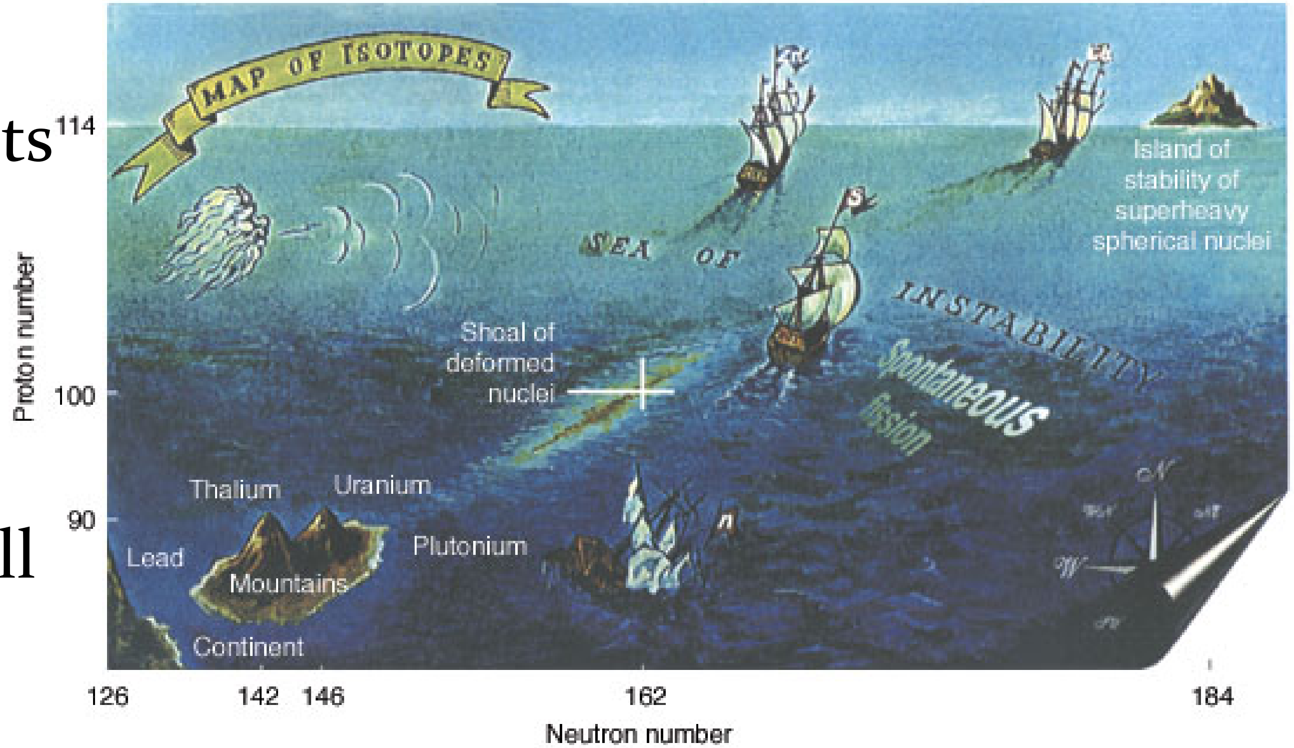
- Next major spherical shell above $Z = 82$, $N = 126$ is variously predicted to occur at:
  - $Z = 114$ and $N = 184$ (Sobiczewski).
  - $Z = 120$ and $N = 172$ (Greiner).
  - $Z = 126$ and $N = 184$ (Meldner, Ćwiok).
- There is a known deformed subshell at $Z = 108$ and $N = 162$. This is why we can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





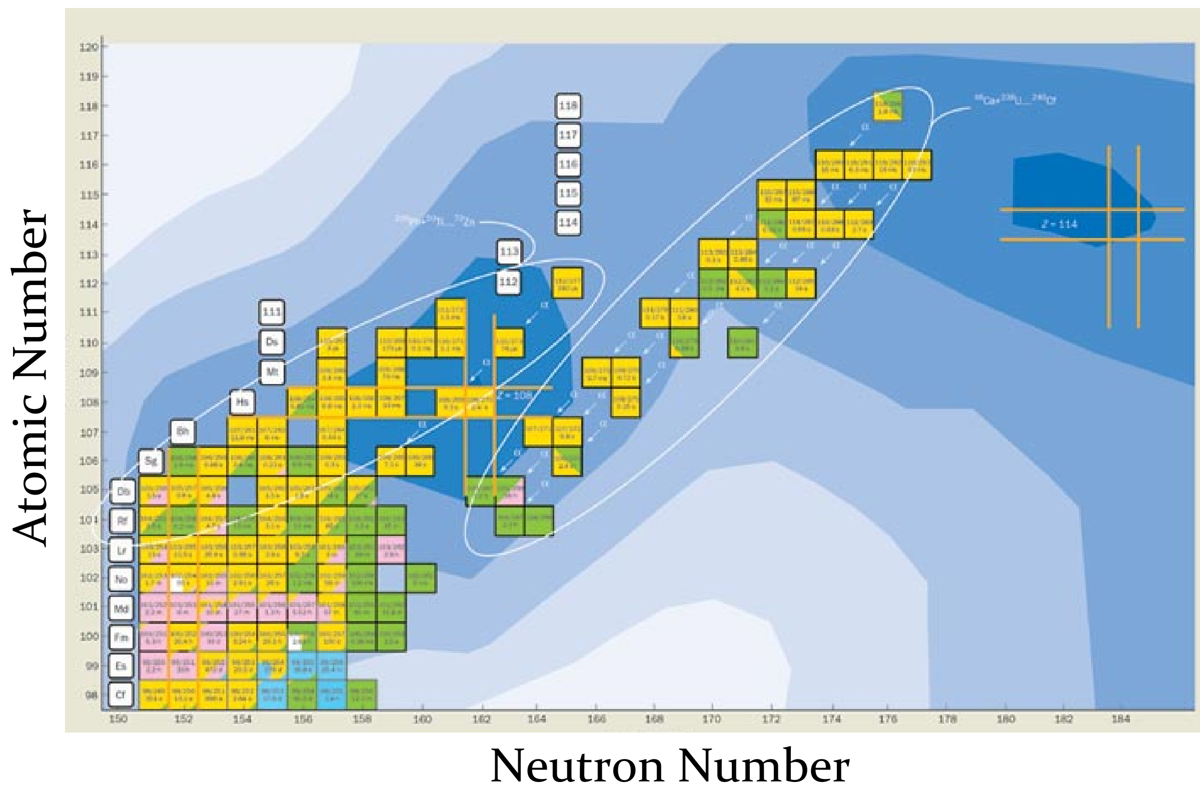
The "Island of Stability"

- 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!



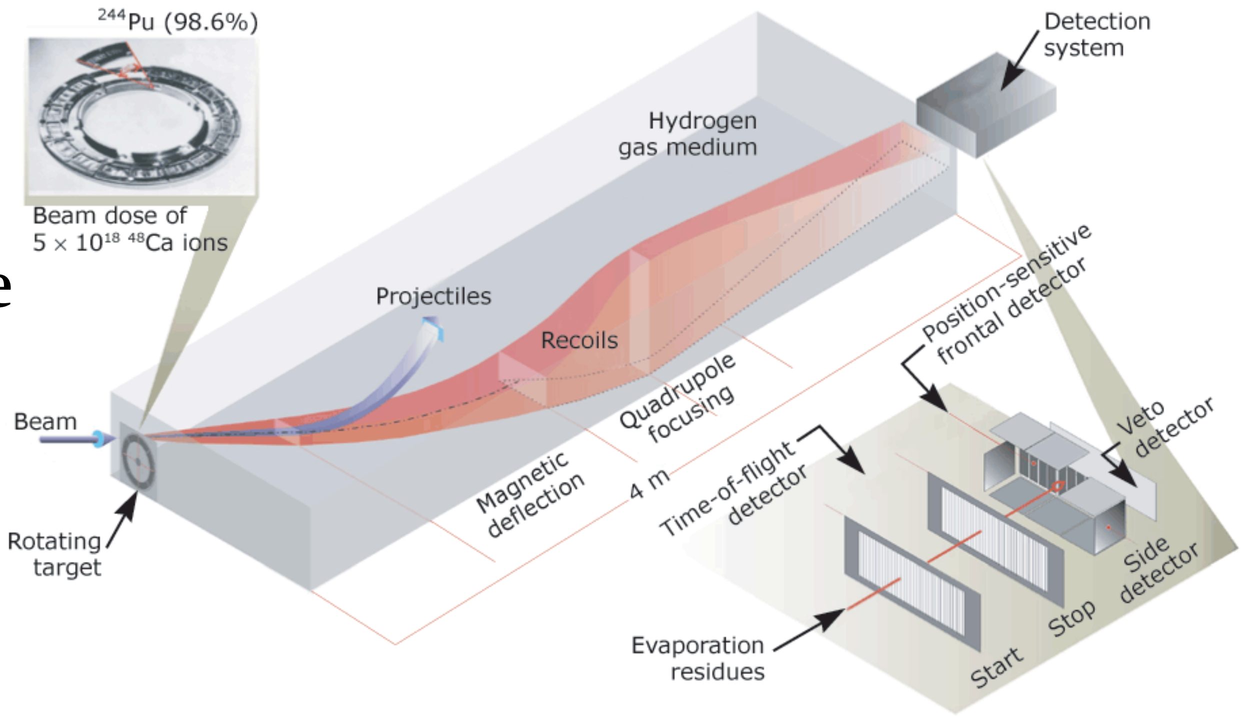
Can we actually reach the "Island of Stability"?

- 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?

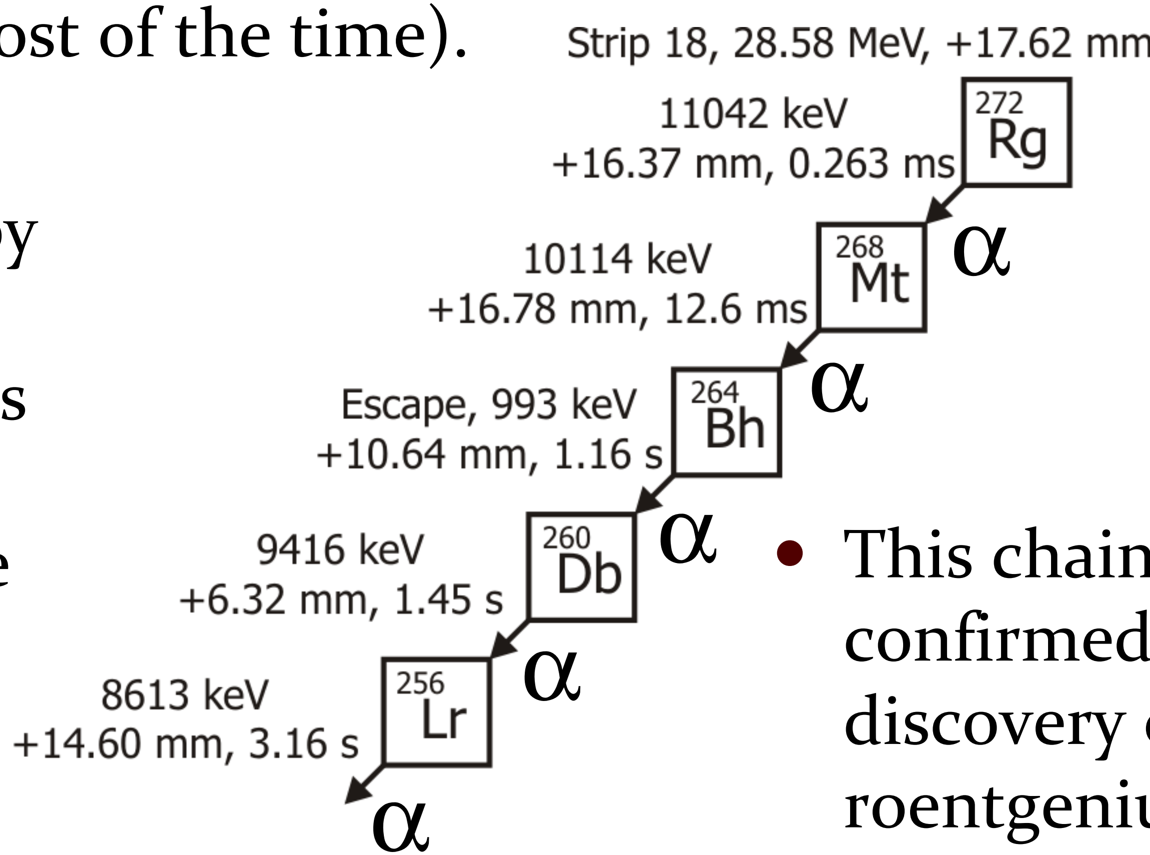
- We use very intense beams, rotating target wheels (to spread out the heat), and a *separator* to filter away the projectiles after the reaction. Beamtimes can last as long as one month or more.
- The separator removes the beam because exposing it to the ultra-sensitive detectors would damage them permanently.



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

- We observe rare isotopes through their radioactive decay. We can observed 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.



- This chain confirmed the discovery of roentgenium.

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):
  - $^{54}Cr + ^{248}Cm \rightarrow ^{298}120 + 4n$
  - $^{50}Ti + ^{249}Cf \rightarrow ^{295}120 + 4n$

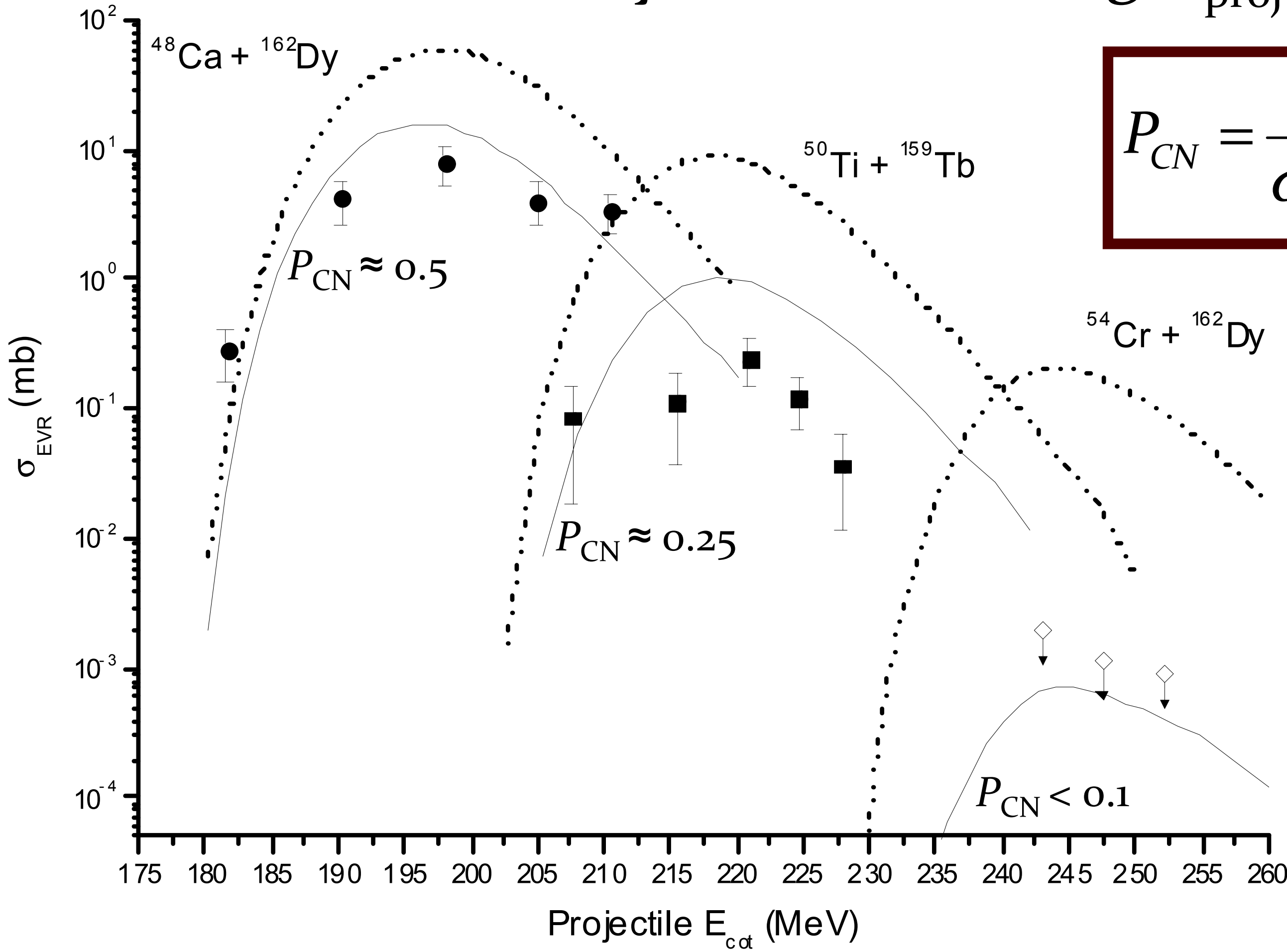
- The success of these experiments likely depends on two factors:
  - The probability that the two nuclei will fuse.
  - The size of the fission barrier.

- All theoretical predictions indicate very low production rates in either case.

Experimental P_{CN} Values

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

Preliminary Results



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

Figure courtesy of D. A. Mayorov.

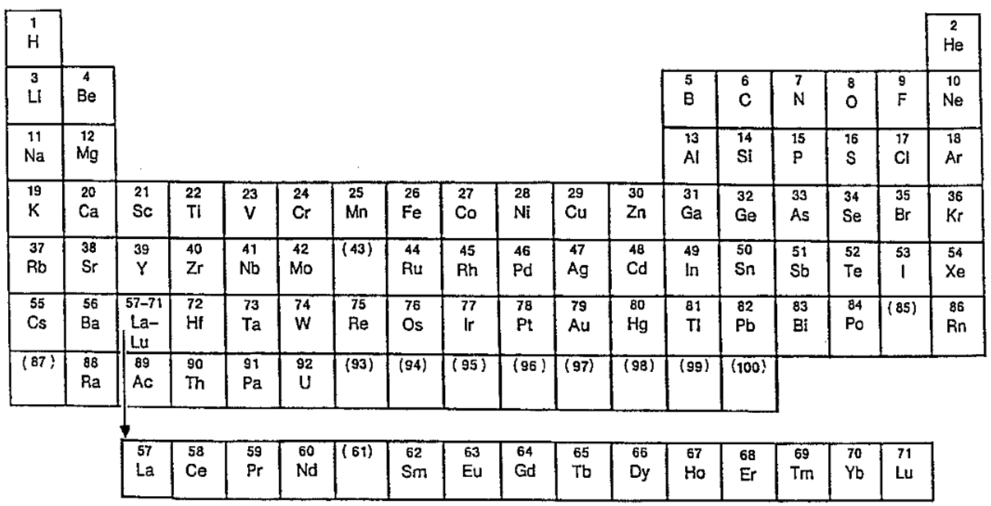
Implications for Reactions with Projectiles Heavier Than ^{48}Ca

- The change from ^{48}Ca to ^{50}Ti or ^{54}Cr affects the cross section:
- Good Things:
  - σ_{cap} is flat at best.
  - Slight increase in separator efficiency.
- Bad Things:
  - Substantial decrease in P_{CN}.
  - Substantial decrease in W_{sur}.
  - (Possibly) slight decrease in beam intensity.

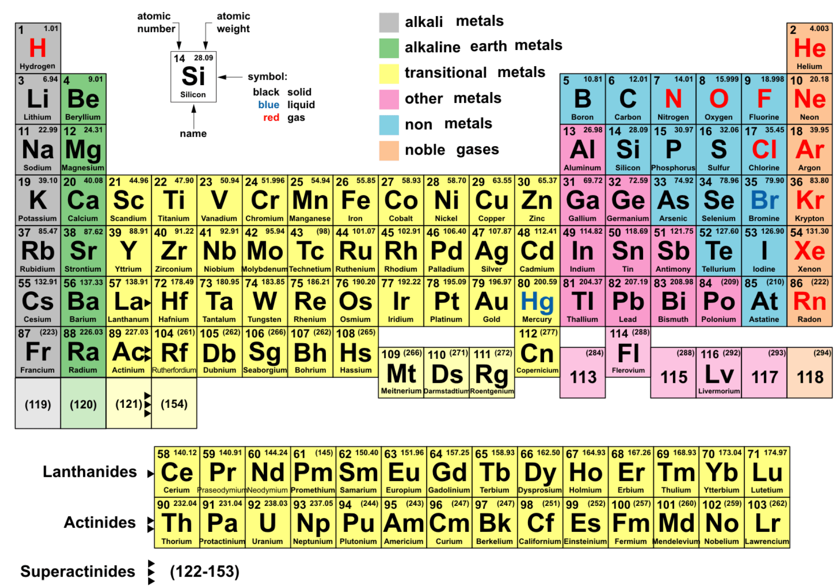
- We may discover elements 119 and 120, but after that it is going to be very difficult.

What has heavy element chemistry told 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



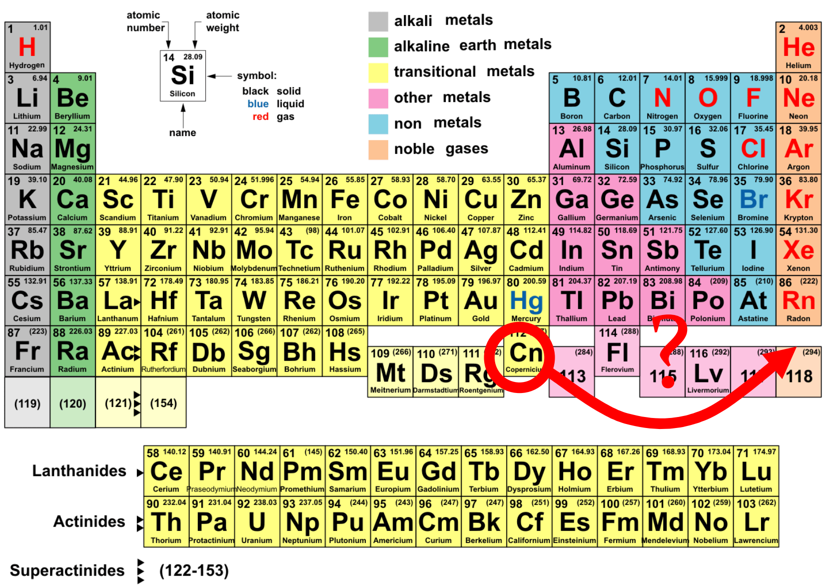
Modern Periodic Table

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?



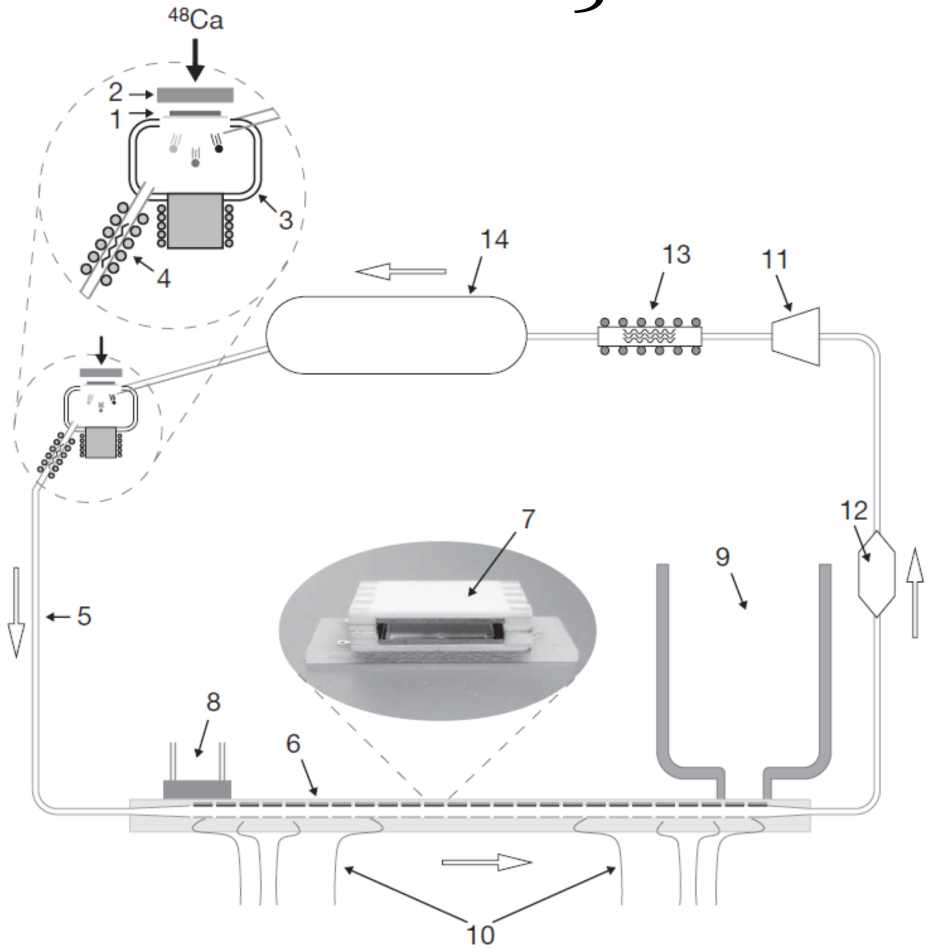
Modern Periodic Table

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 mol = 6.022×10^{23} 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

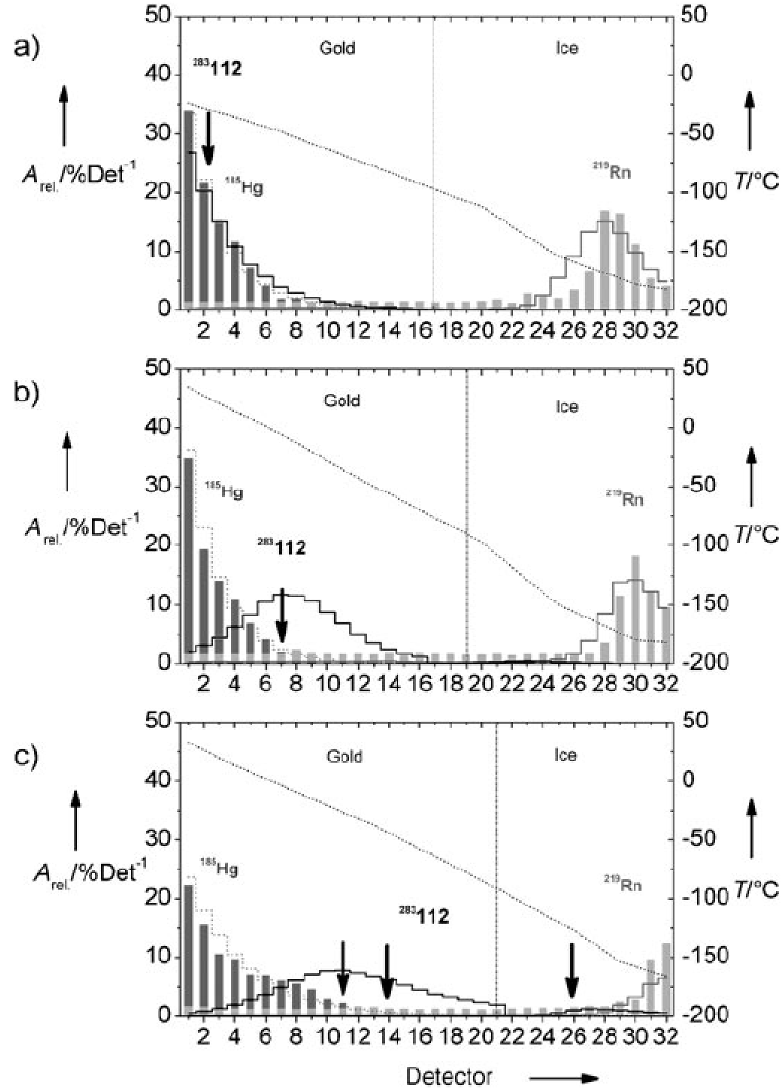
- The *nuclear* reaction is $^{48}Ca + ^{238}U \rightarrow ^{283}Cn + 3n$.
- The reaction products are stopped in a mixture of He and Ar.
- They go through a purification step into a closed-loop system with minimal oxygen and water.
- The main component is *thermochromatography column.*



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: $\Delta H_{ads} = -98 \pm 3$ kJ/mol Rn: -27 ± 3 kJ/mol
- Cn: $\Delta H_{ads} = -52 \pm 4$ 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!