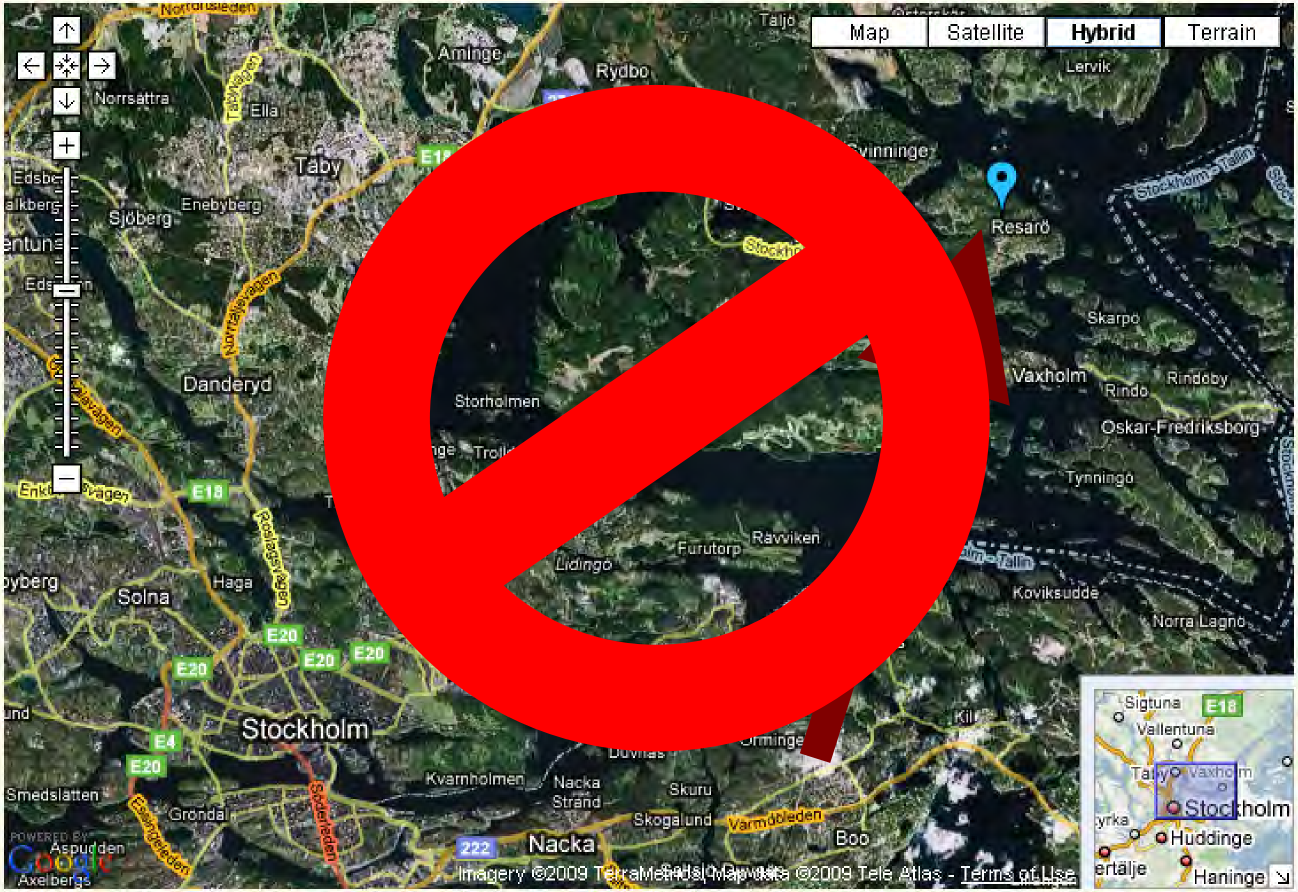
The Heaviest Elements in the Universe

Cody Folden

January 31, 2009

They keep finding new elements. Where are they?

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



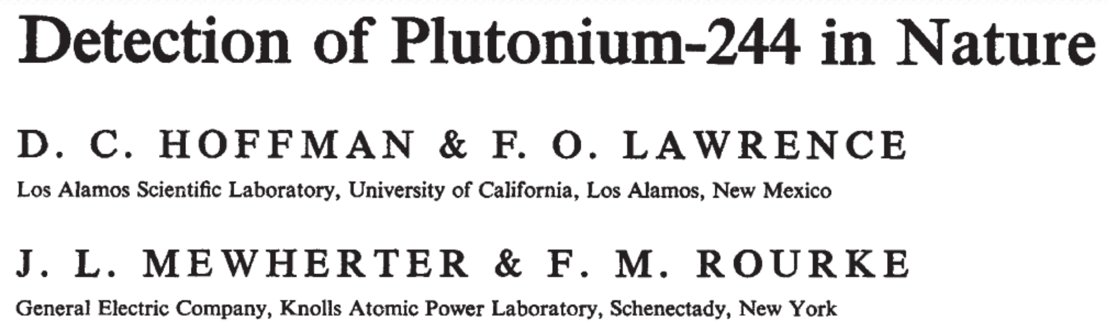
The Elements: 2009

- 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.
  - Plutonium-244 (^{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 117.

^{244}Pu in Nature (1971)

- 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.



Detection of Plutonium-244 in Nature

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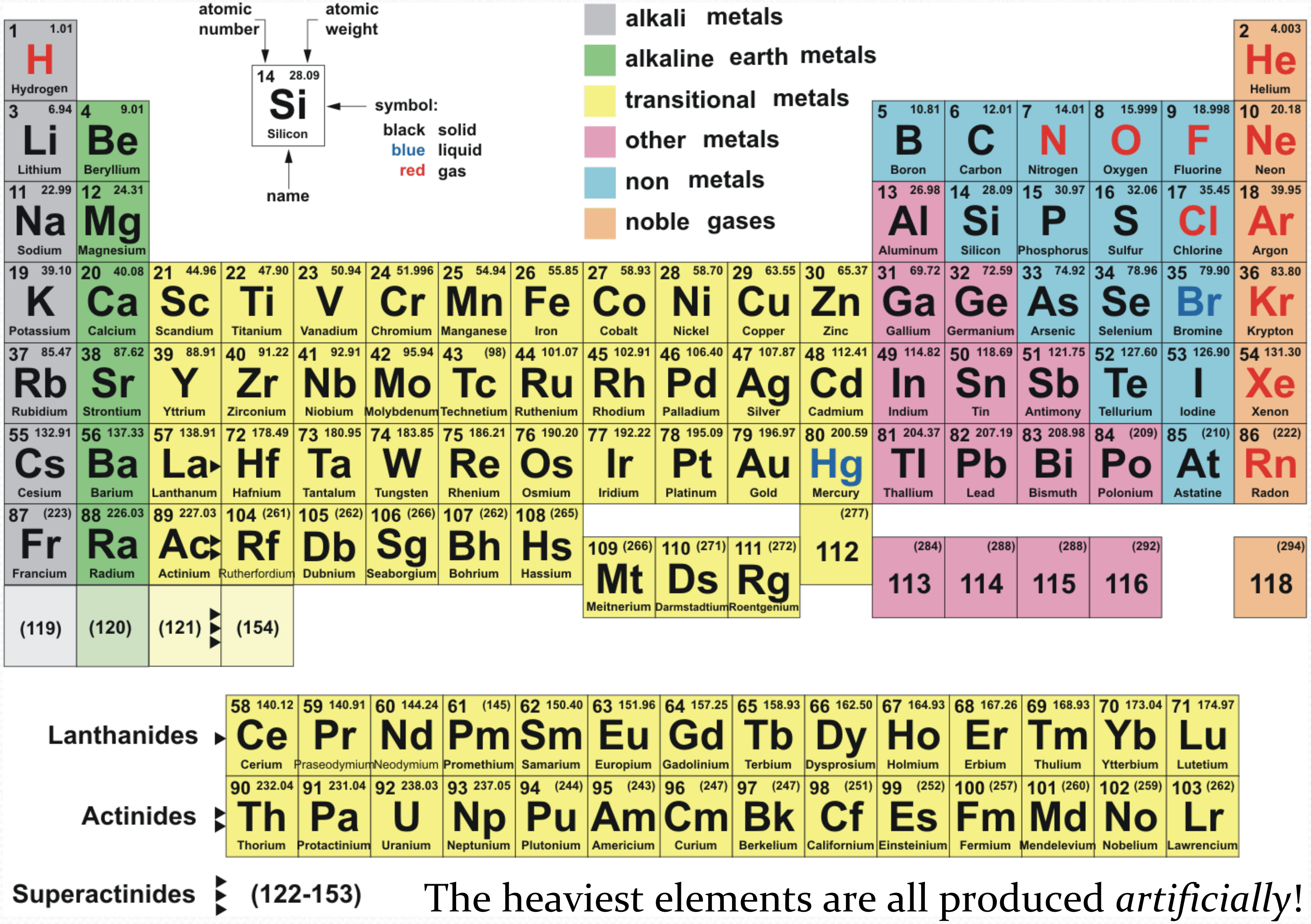
The Periodic Table 2009



atomic number

atomic weight

14 28.09
Si
Silicon

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																	2 4.003 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium											13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	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	109 (266) Mt Meitnerium	110 (271) Ds Darmstadtium	111 (272) Rg Roentgenium	(277) 112	(284) 113	(288) 114	(288) 115	(292) 116		(294) 118
(119)	(120)	(121) ▸	(154)														

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

Superactinides ▸ (122-153)

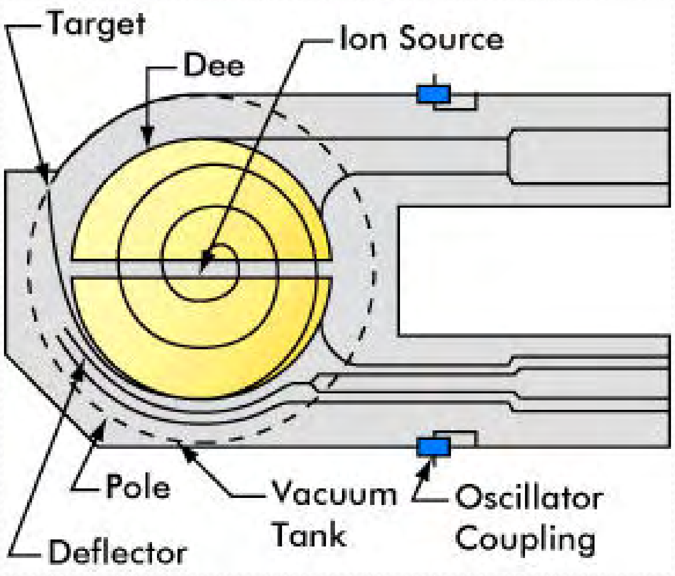
The heaviest elements are all produced *artificially*!

What are all these new elements good for?

- The search for the heaviest elements answers questions like:
  - What is the heaviest element that can be formed?
  - What mechanism is involved in their production?
  - Does the periodicity of the elements continue for very high atomic numbers?
  - What are their chemical properties?
- We also train future nuclear scientists.

How are new elements created?

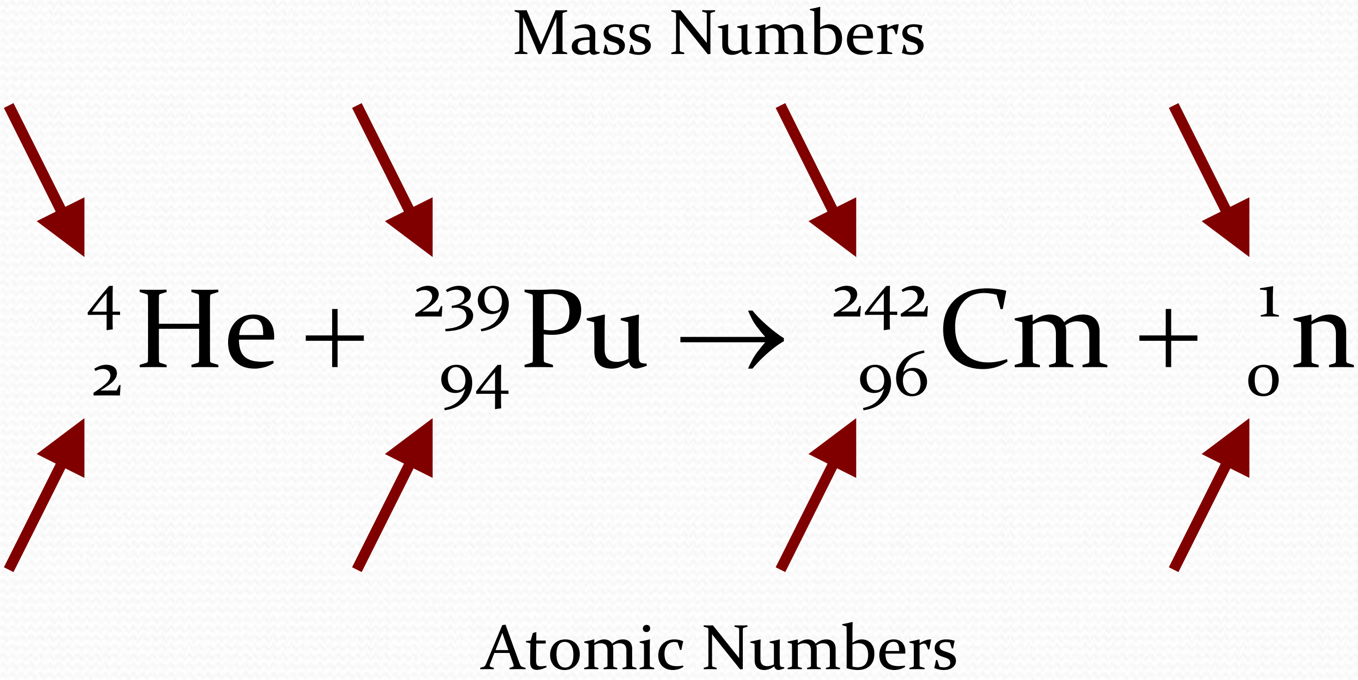
- We build up heavy elements by fusing two lighter elements together.
- Unfortunately, all nuclei are positively charged, so they repel each other very strongly. The answer is to force them together by accelerating one to a high energy.
- A common type of *accelerator* is the *cyclotron*, which uses electric and magnetic fields to accelerate ions.
- A *beam* of accelerated particles is directed at a *target* where the nuclear reaction occurs.



Cyclotron Schematic

How do we balance a nuclear reaction?

- Nuclear reactions have to be balance just like chemical ones.
- The atomic numbers and the mass numbers must be balanced on each side of the equation:



Mass Numbers

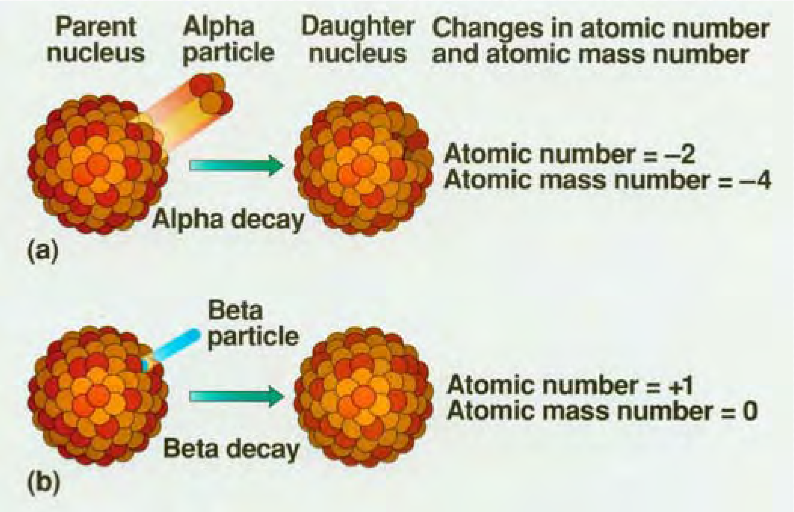
$$ {}^{4}_{2}\mathrm{He} + {}^{239}_{94}\mathrm{Pu} \rightarrow {}^{242}_{96}\mathrm{Cm} + {}^{1}_{0}\mathrm{n} $$

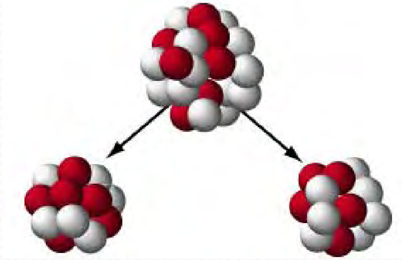
Atomic Numbers

- I've gone ahead and balanced the reactions in this presentation.

What is radioactive decay?

- All of the isotopes that we are talking about are *radioactive*—their nuclei are unstable and release energy, usually by emitting particles.
- *Alpha* decay: Emission of a ^{4}He nucleus.
- *Beta* decay: Converts a neutron into a proton (or vice versa).
- *Gamma* decay: Emission of a high-energy photon.
- Spontaneous *Fission*: When a nucleus splits into two, more stable pieces.





Spontaneous Fission

History of Element Discoveries: The Early Days

- Several elements were discovered using irradiation with neutrons from nuclear reactors followed by beta decay (half-lives in parentheses):
  - $n + {}^{238}U \rightarrow {}^{239}U$ (23 min) $\rightarrow {}^{239}Np$ (2.4 days) $\rightarrow {}^{239}Pu$

First Am Sample

- Some elements were produced by light-ion bombardments:
  - ${}^{4}He + {}^{239}Pu \rightarrow {}^{242}Cm + n$ (atomic number 96)
  - ${}^{4}He + {}^{241}Am \rightarrow {}^{244}Bk + n$ (atomic number 97)
  - ${}^{4}He + {}^{242}Cm \rightarrow {}^{245}Cf + n$ (atomic number 98)
- The next elements were discovered very unexpectedly!

History of Element Discoveries: Glenn T. Seaborg (1912-1999)

- Seaborg was leader of the Berkeley group that discovered so many elements. He was also:
- Nobel Prize Winner
- Eponym of Seaborgium
- Chairman of the AEC
- Chancellor of Berkeley
- Friend to Ten Presidents
- World record holder for the longest entry in "Who's Who"

History of Element Discoveries: New Techniques

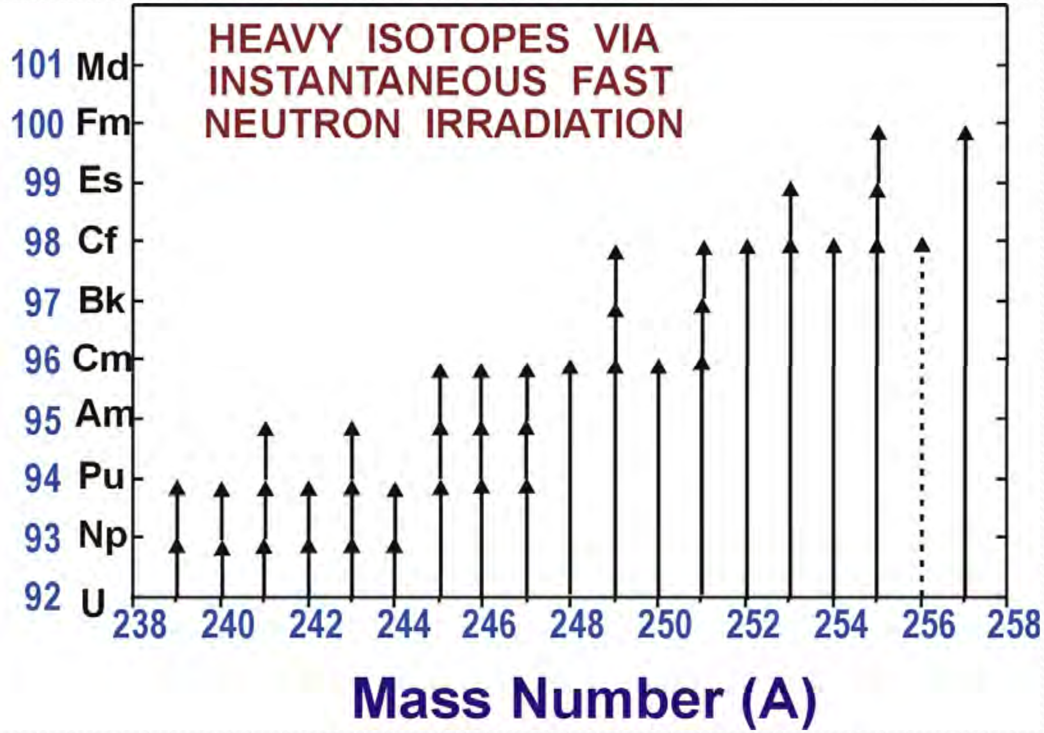
The “Mike” Test
November 1, 1952
Enewetak Atoll

Before

After

History of Element Discoveries: New Techniques

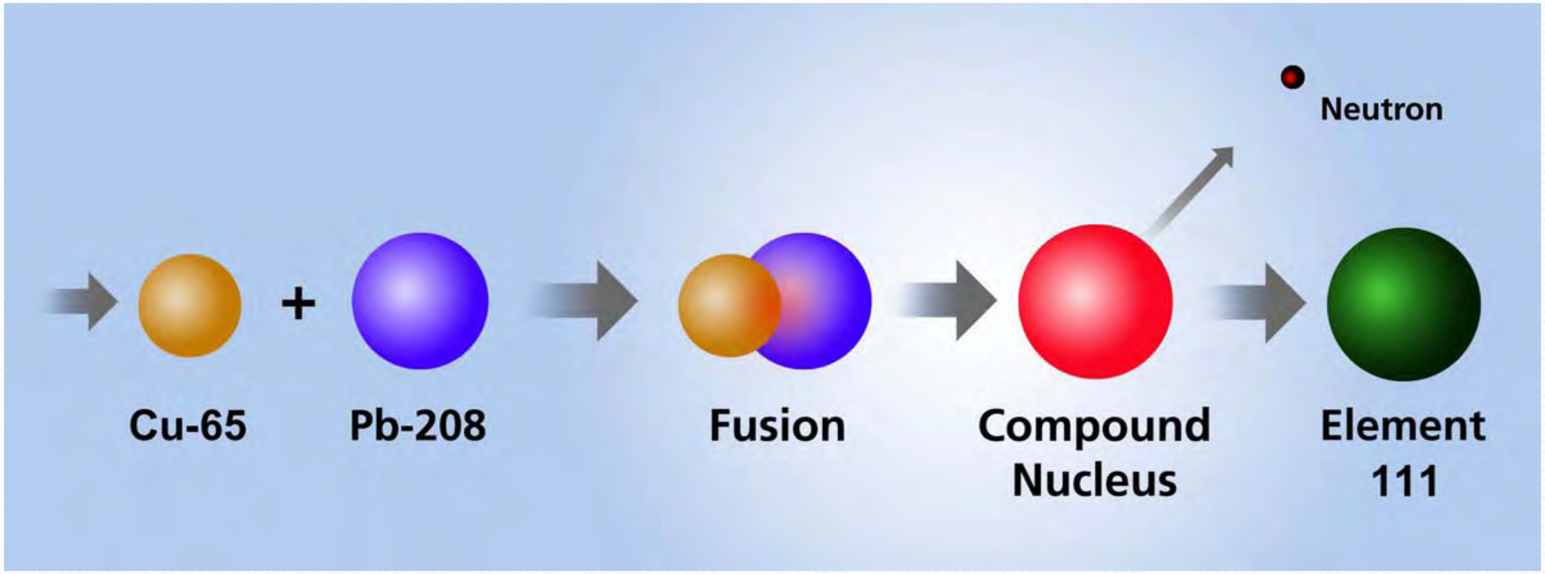
- It is estimated that some ^{238}U nuclei captured 17 neutrons to make ^{255}U and beta-decayed to give two new elements: Es (99) and Fm (100).
- ^{238}U is at the lower left of the diagram on the right. It captures neutrons from the "device," moving right. Beta decay moves you up according to the arrows.



History of Element Discoveries: The Modern Accelerator Era

- 1970s: Heavy Ions + Actinide:
  - ex. $^{12}C + {}^{249}Cf \rightarrow {}^{257}Rf + 4n$ (atomic number 104)
- 1980s and 1990s: Heavy Ion + Pb, Bi
  - ex. $^{58}Fe + {}^{209}Bi \rightarrow {}^{266}Mt + n$ (atomic number 109)
- 2000s: ^{48}Ca + Actinide:
  - ex. $^{48}Ca + {}^{243}Am \rightarrow {}^{288}115 + 3n$ (atomic number 115)
- Note that we just use "115" rather than "ununpentium." (Everyone hates that nonsense).

How does the nuclear reaction work?

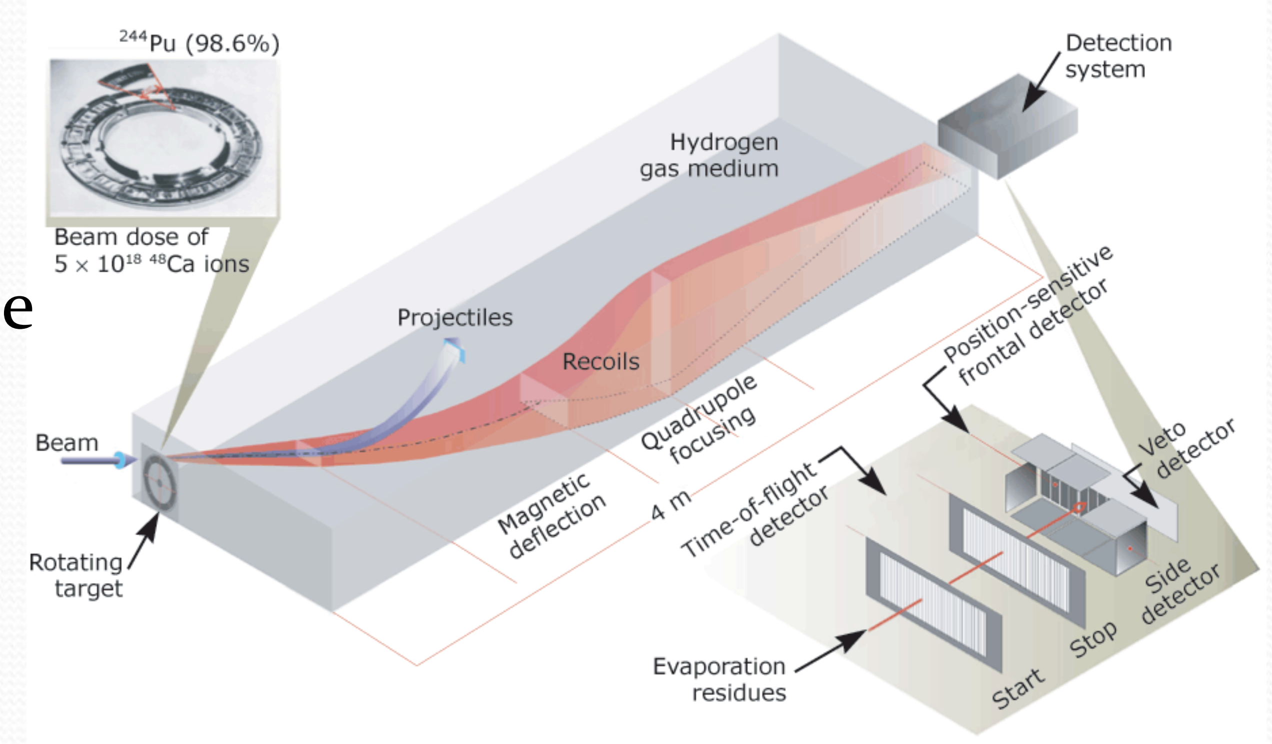


Beam:	Fusion:	Survival:	Residual Nucleus:
$\sim 10^{12}$ per second	(Net Effect: 10^{-8})	$(\sim 10^{-5})^{x}$ x = neutrons	0.1 per second

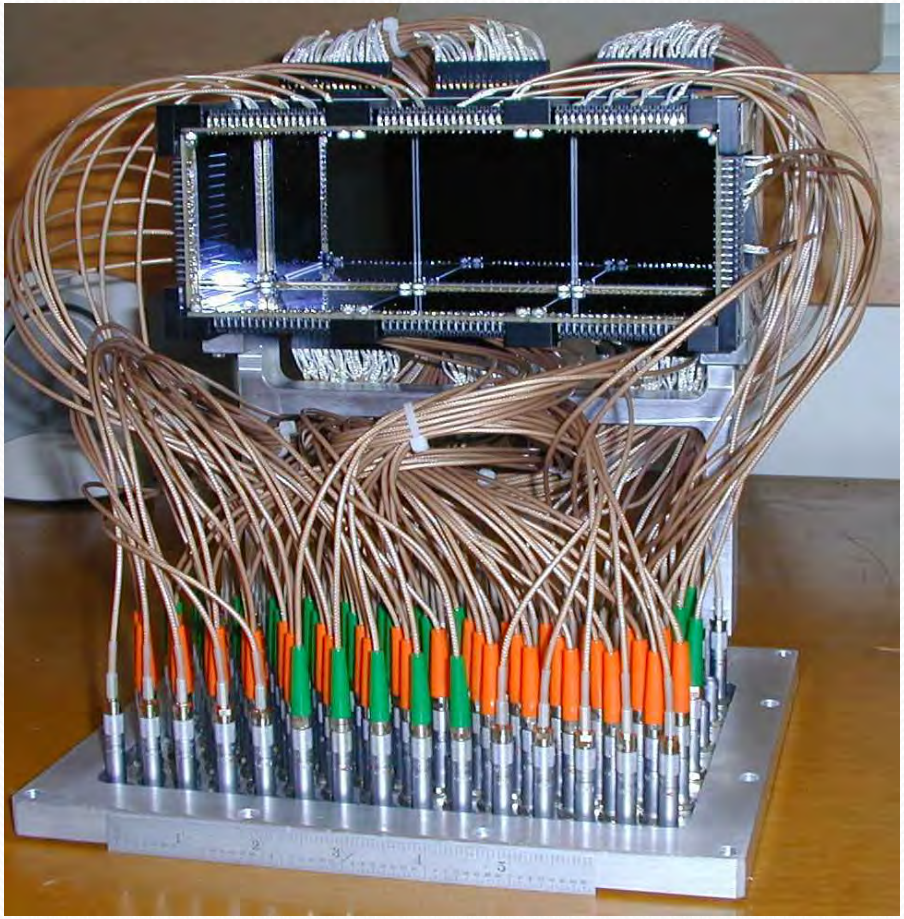
- In reality, it’s not that easy. There is an additional nuclear physics issue that reduces the rate by another 10^{-5}. (We won’t worry about it, though).

How do the experiments work?

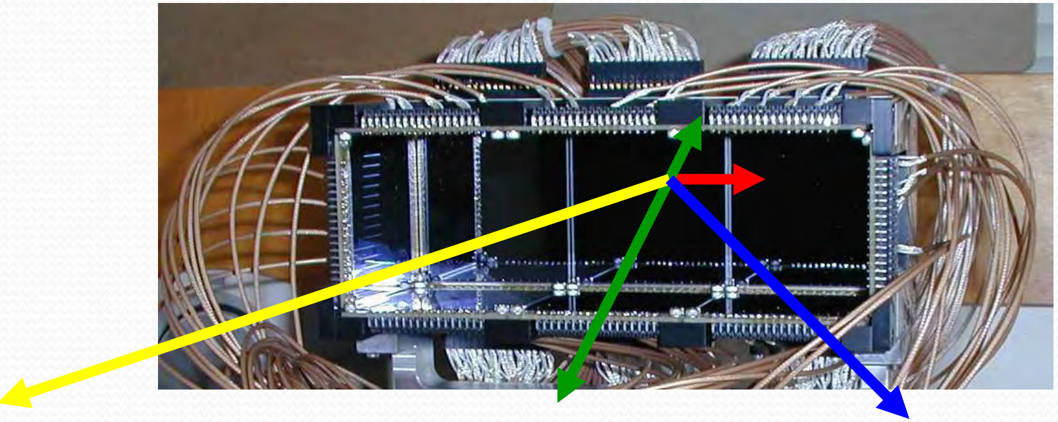
- We use very intense beams, rotating target wheels (to spread out the heat), and a *separator* to filter away the projectiles after the reaction. Beamtimes can last as long as one month.
- The separator removes the beam because exposing it to the ultra-sensitive detectors would damage them permanently.



What does the detector look like?



- ☑ 48 Position-Sensitive Si Strips
- ☑ 32 “Upstream” Detectors
- ☑ 12 “Punch-through” Detectors
- ☑ 18 cm x 6 cm x 6 cm
- ☑ 75-80% Geometric Efficiency

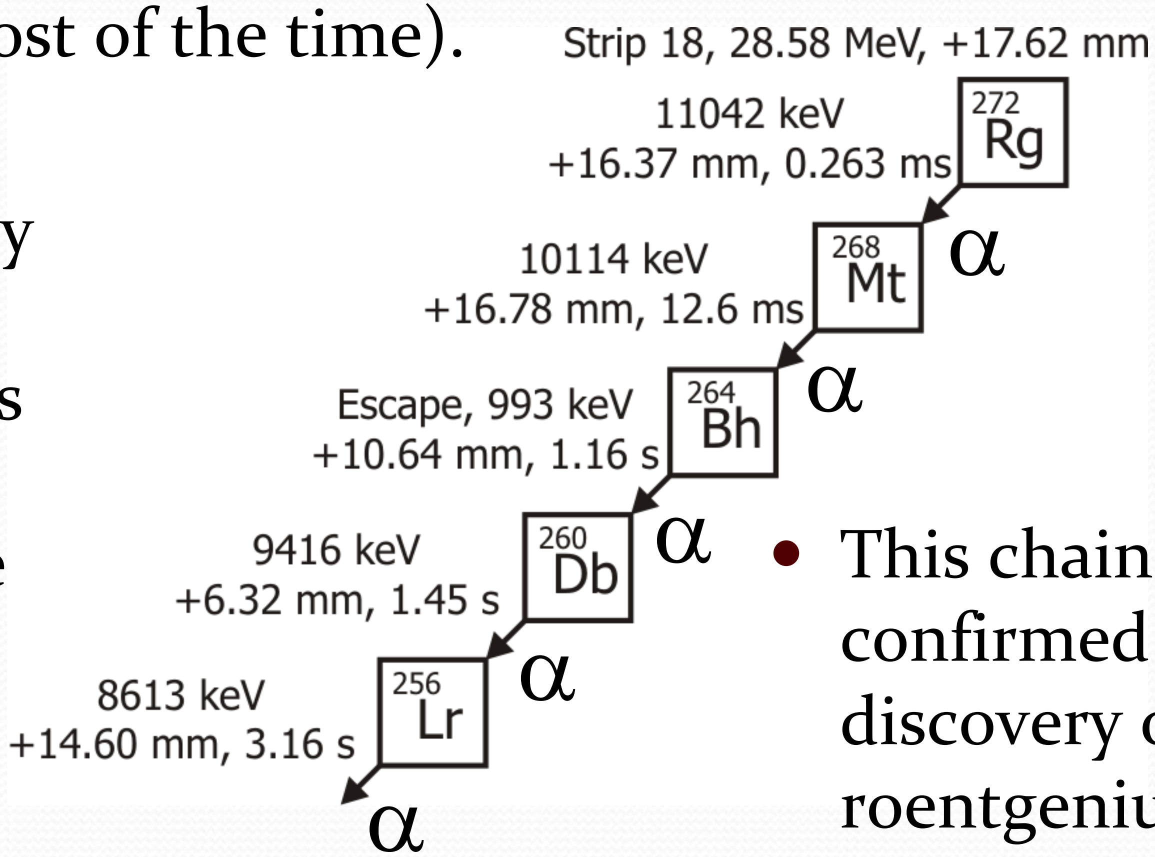


Observable Events:

- “Focal Plane” Alpha
- “Reconstructed” Alpha
- Escape Alpha
- Fission

How do we know when we have made a new element?

- 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.



Strip 18, 28.58 MeV, +17.62 mm

^{272}Rg

11042 keV
+16.37 mm, 0.263 ms

α

^{268}Mt

10114 keV
+16.78 mm, 12.6 ms

α

^{264}Bh

Escape, 993 keV
+10.64 mm, 1.16 s

α

^{260}Db

9416 keV
+6.32 mm, 1.45 s

α

^{256}Lr

8613 keV
+14.60 mm, 3.16 s

α

- 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.

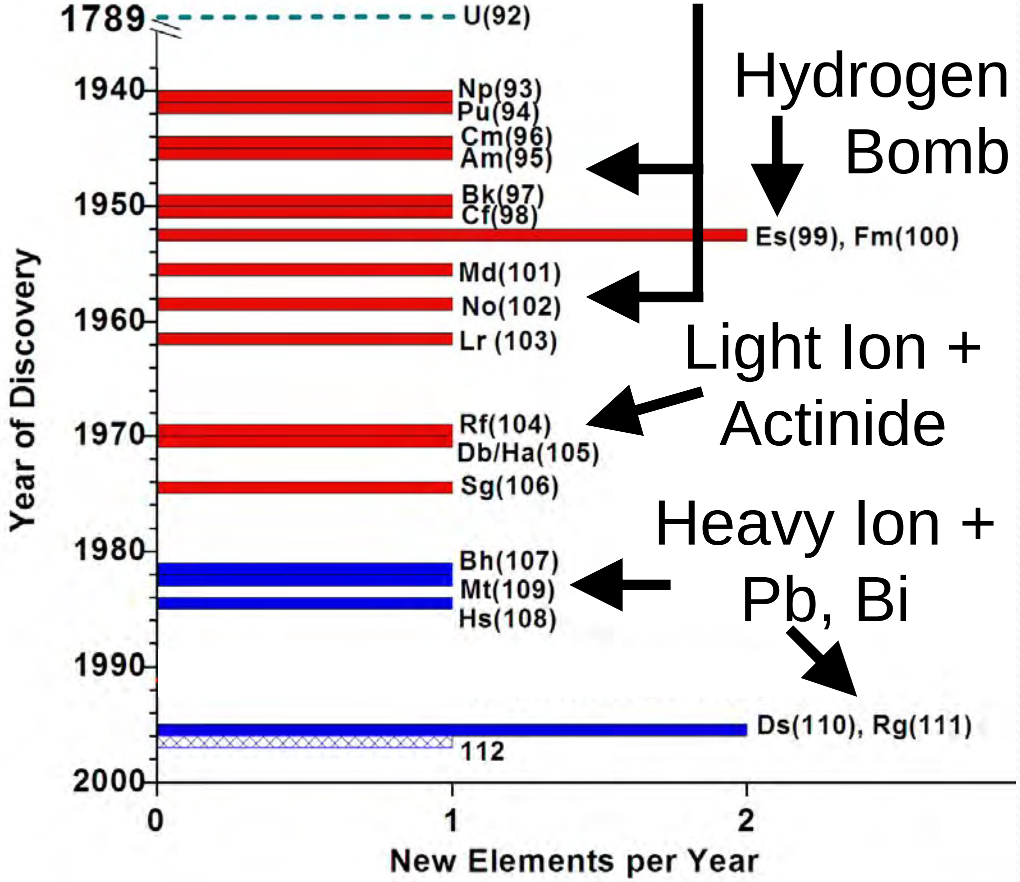
Who holds the record for discovering the most elements?

- Al Ghiorso holds the world record for discovering the most elements: 12!

- He contributed to the discoveries of all elements from 95 to 106.
- The photo is at a celebration of his 90th birthday.
- He intends to live to be 106 (since seaborgium is 106).

New Elements per Year

Either neutron or light-ion irradiations



Hydrogen Bomb

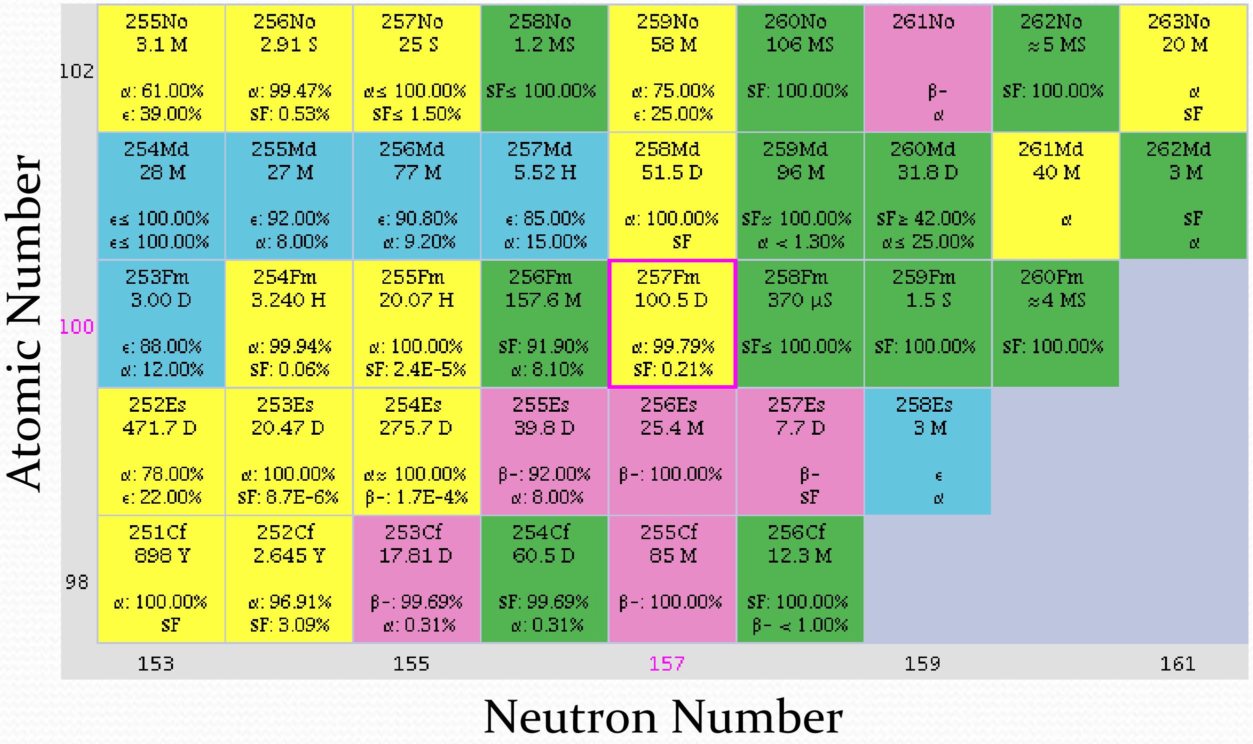
Light Ion + Actinide

Heavy Ion + Pb, Bi

- The discovery of new elements is driven by new technology: new accelerators, separators, etc.
- The favored reaction type changes over time.
- Not shown: Elements 113-116 and 118: ^{48}Ca + actinides

Are these really the heaviest elements in the universe?

- The elements formed by the Hydrogen Bomb resulted from several neutron captures (right on this diagram) followed by beta decay (up and to the left). Unfortunately, no Fm isotopes beta decay. This creates a “fermium wall.”
- Using accelerators we jump over the wall. But. . . .
- A neutron star *might* have more protons. (It’s like a giant nucleus).



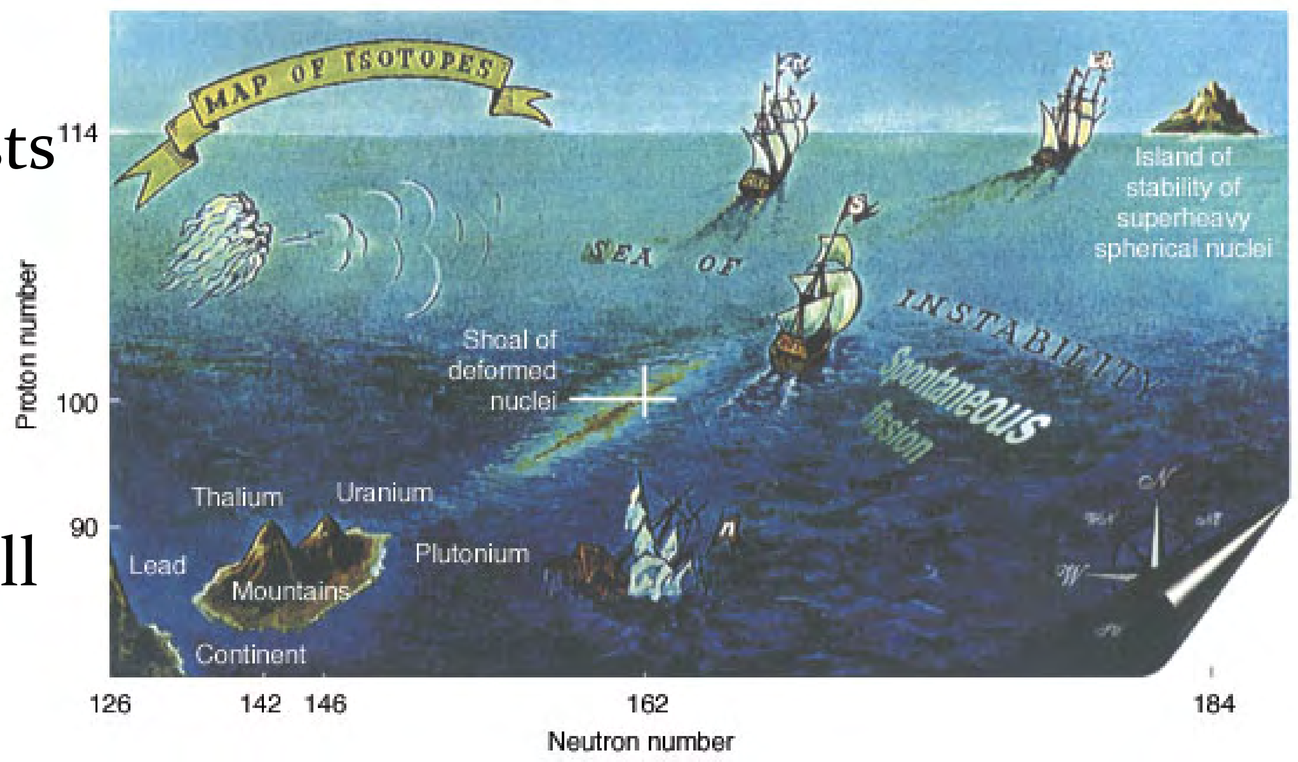
Atomic Number

102	255No 3.1 M α: 61.00% ε: 39.00%	256No 2.91 S α: 99.47% SF: 0.53%	257No 25 S α≤ 100.00% SF≤ 1.50%	258No 1.2 MS SF≤ 100.00%	259No 58 M α: 75.00% ε: 25.00%	260No 106 MS SF: 100.00%	261No β- α	262No ≈5 MS SF: 100.00%	263No 20 M α SF
	254Md 28 M ε≤ 100.00% ε≤ 100.00%	255Md 27 M ε: 92.00% α: 8.00%	256Md 77 M ε: 90.80% α: 9.20%	257Md 5.52 H ε: 85.00% α: 15.00%	258Md 51.5 D α: 100.00% SF	259Md 96 M SF≈ 100.00% α < 1.30%	260Md 31.8 D SF≥ 42.00% α≤ 25.00%	261Md 40 M α	262Md 3 M SF α
100	253Fm 3.00 D ε: 88.00% α: 12.00%	254Fm 3.240 H α: 99.94% SF: 0.06%	255Fm 20.07 H α: 100.00% SF: 2.4E-5%	256Fm 157.6 M SF: 91.90% α: 8.10%	257Fm 100.5 D α: 99.79% SF: 0.21%	258Fm 370 µS SF≤ 100.00%	259Fm 1.5 S SF: 100.00%	260Fm ≈4 MS SF: 100.00%	
	252Es 471.7 D α: 78.00% ε: 22.00%	253Es 20.47 D α: 100.00% SF: 8.7E-6%	254Es 275.7 D α≈ 100.00% β-: 1.7E-4%	255Es 39.8 D β-: 92.00% α: 8.00%	256Es 25.4 M β-: 100.00%	257Es 7.7 D β- SF	258Es 3 M ε α		
98	251Cf 898 Y α: 100.00% SF	252Cf 2.645 Y α: 96.91% SF: 3.09%	253Cf 17.81 D β-: 99.69% α: 0.31%	254Cf 60.5 D SF: 99.69% α: 0.31%	255Cf 85 M β-: 100.00%	256Cf 12.3 M SF: 100.00% β- < 1.00%			
	153		155		157		159		161

Neutron Number

The “Island of Stability”

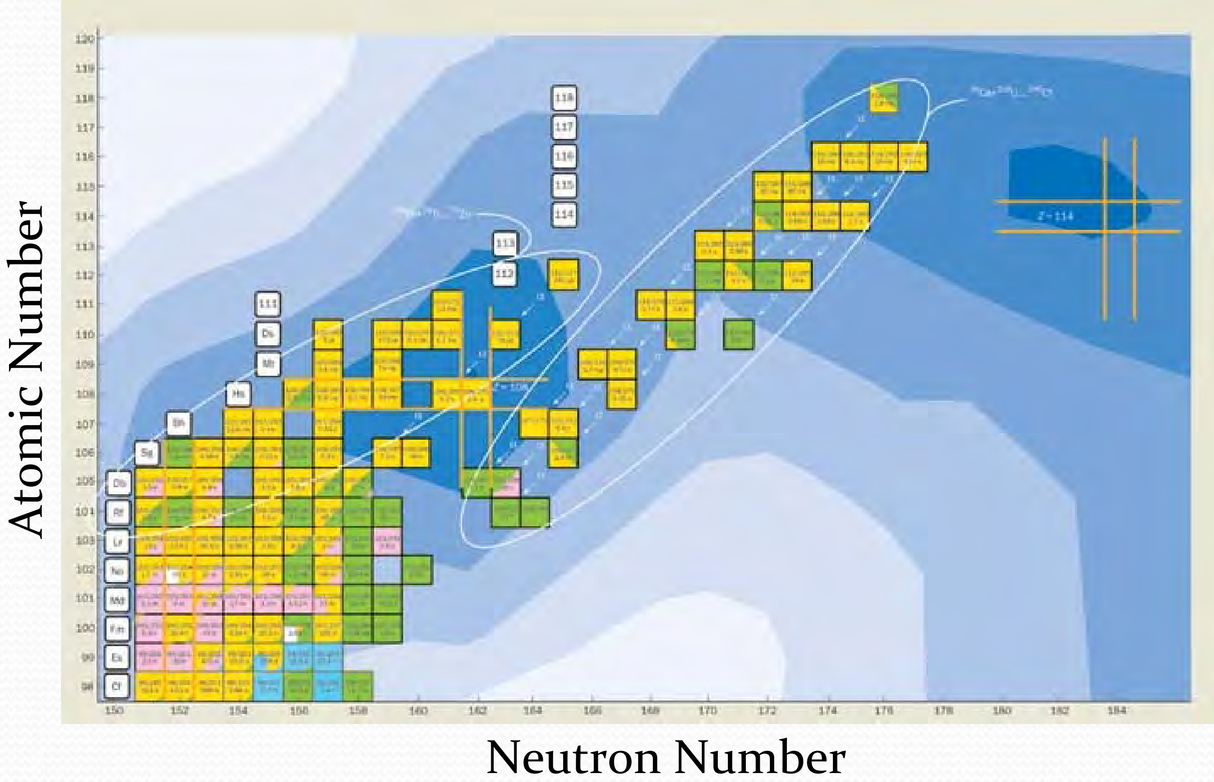
- The “Island of Stability” is a way of stating a theory that there may be a region of nuclei that might have very long half-lives (years or more). Most heavy elements have half-lives of less than a few seconds.
- Theoretical nuclear physicists have been speculating on the location of the Island since 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 it with current technology.

- The problem is that we need higher ratios of protons to neutrons that are not available with current beams and targets.

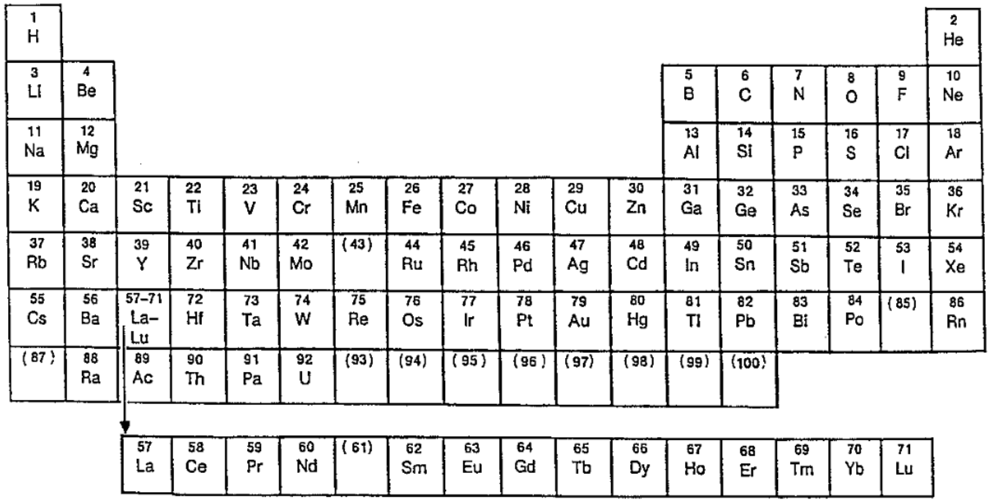


You can't escape. . . .

CHEMISTRY

What has heavy element chemistry told us?

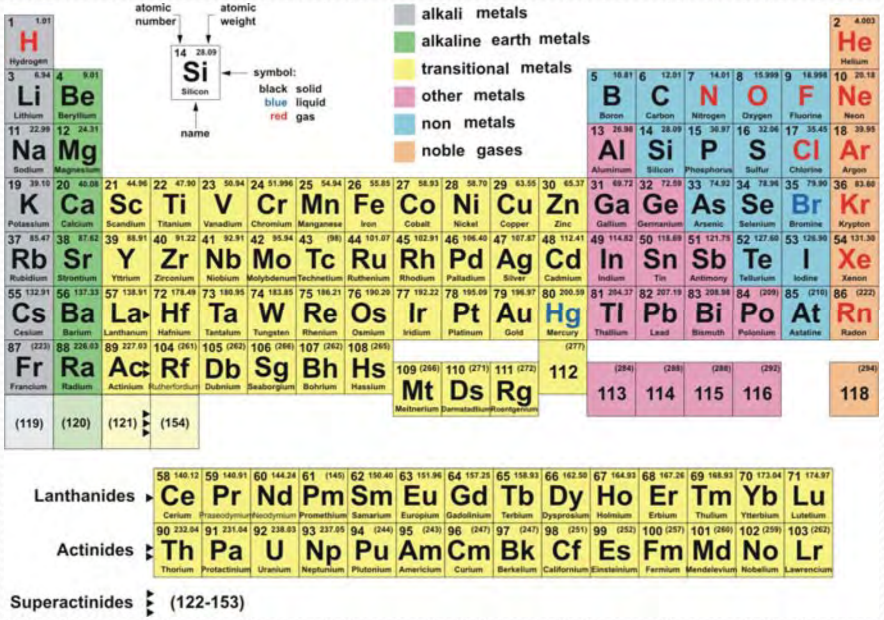
- The chemistry of the heavy elements has been critical to our understanding of the periodic table.
- Seaborg developed the *actinide concept*, which places certain elements in a separate *actinide series*.



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											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)	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)	86 Rn
(87)	88 Ra	89 Ac	90 Th	91 Pa	92 U	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)				

57 La	58 Ce	59 Pr	60 Nd	(61)	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Pre-World War II Periodic Table



atomic number

atomic weight

14 28.09 Si Silicon

symbol:

black solid

blue liquid

red gas

name

▨	alkali metals
🟩	alkaline earth metals
🟨	transitional metals
▨	other metals
🟦	non metals
🟧	noble gases

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											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 La	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 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	113	114	115	116		118
(119)	(120)	(121)	(154)														

Lanthanides	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
Actinides	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

Superactinides (122-153)

Modern Periodic Table

What can heavy element chemistry tell us?

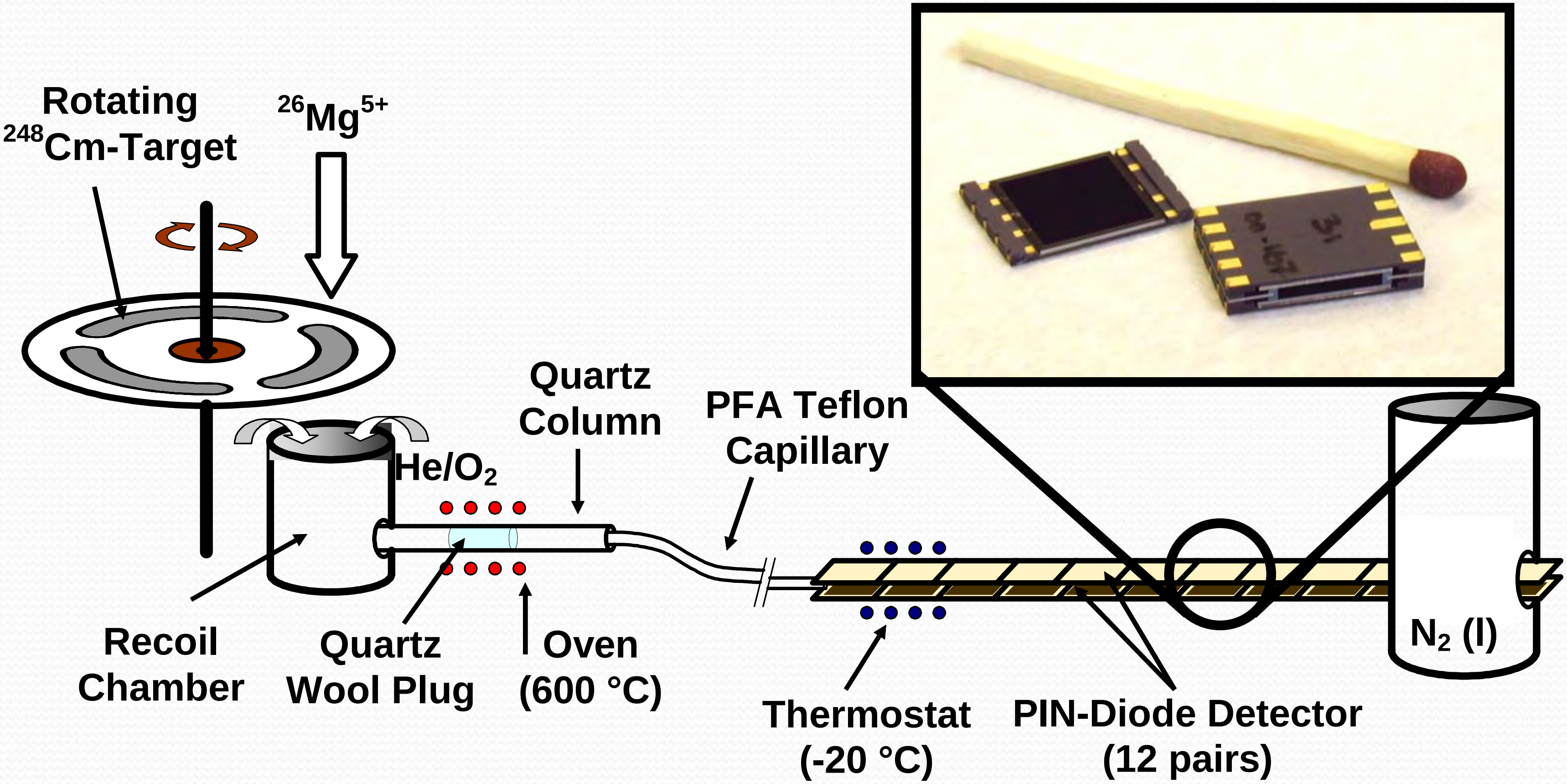
- More recently, we have begun to wonder whether the periodic table still works for very high atomic numbers. (It’s not guaranteed).
- The problem is *relativistic effects*, the result of the fact that all the positive charge in the nucleus can accelerate the electrons to speeds near the speed of light.
- 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.

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.

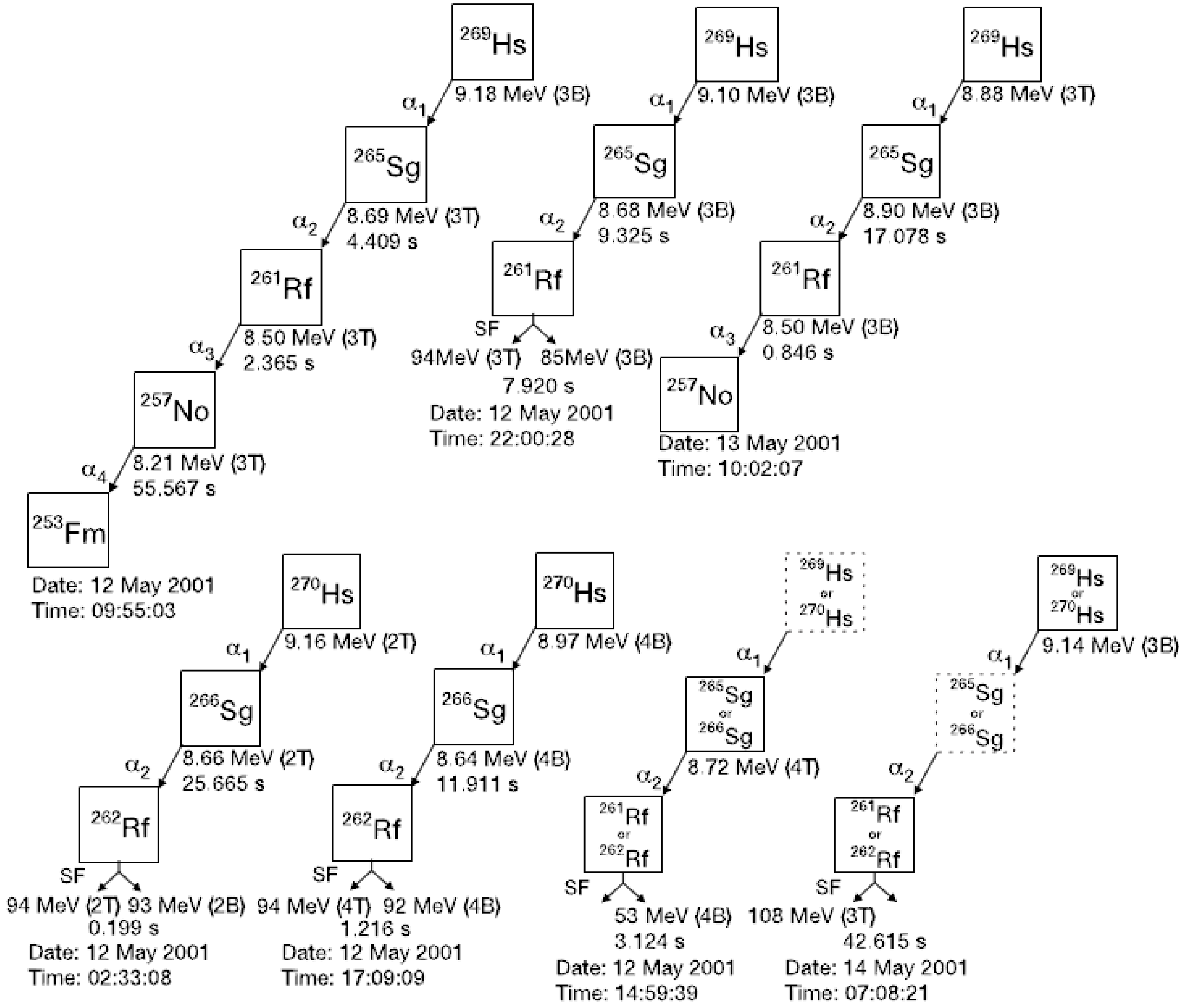
Hassium Chemistry Experiment

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

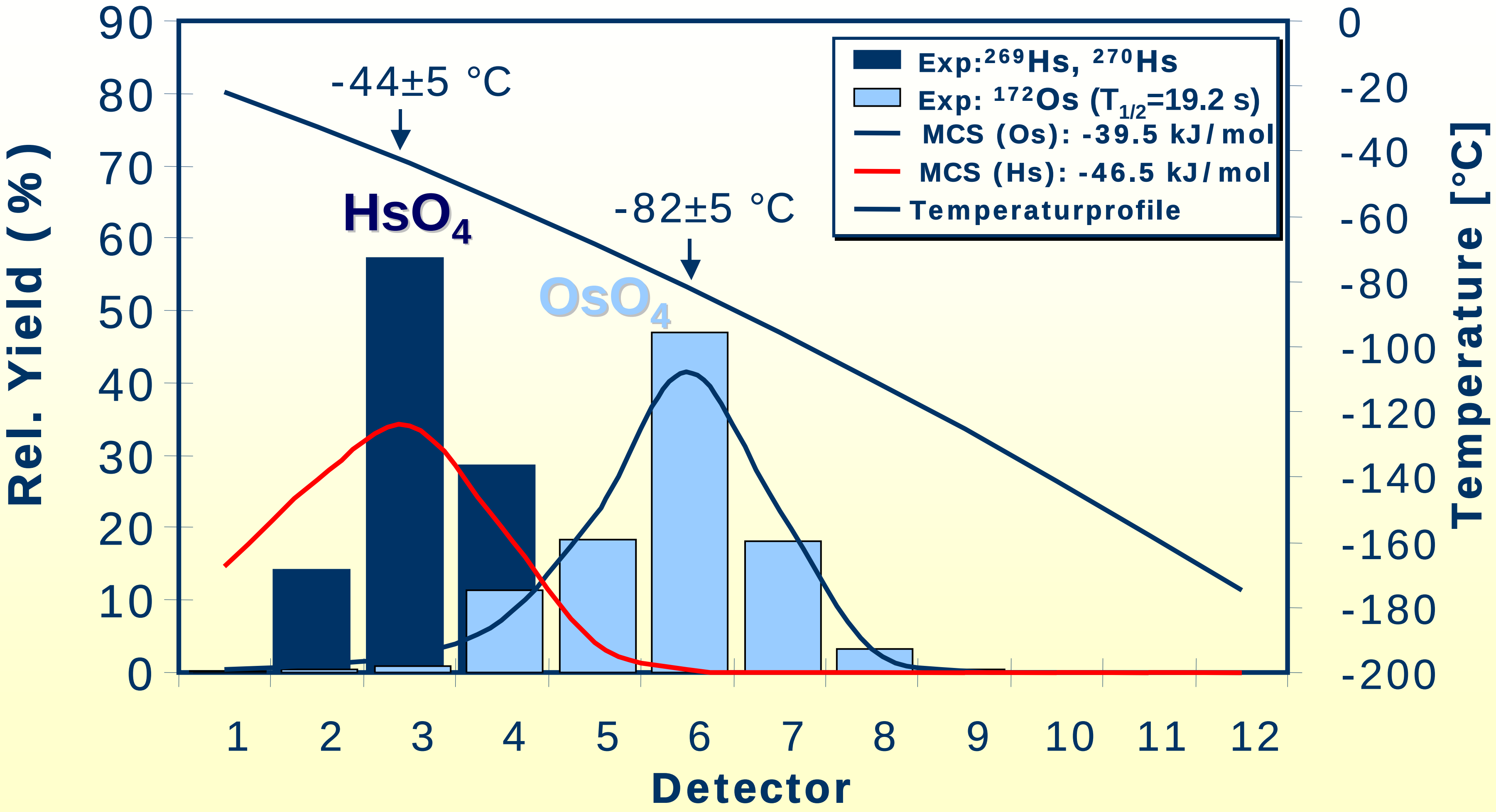


What was observed?

- Seven decay chains were observed, the same way that they are in a “physics” experiment.
- Remember that there are many more homolog atoms than transactinides.



Comparison with the Lighter Homolog Osmium



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 tetroxides on the detector surface (Si_4N_3) that is most likely to give you the observed distribution.
- OsO_4: $\Delta H_{ads} = -39 \pm 1$ kJ/mol
- HsO_4: $\Delta H_{ads} = -46 \pm 2$ kJ/mol
- Notice that this experiment give you the energy *per mole*, even though we only had seven molecules.
- The element is placed on the periodic table!

What are all these new 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: So far they are like their homologs, but we need more data.
- The future of transactinides looks bright!