The Heaviest Elements in the Universe

Cody Folden
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They keep finding new elements. Where are they?

- Ytterby, Sweden is the namesake of four elements: ytterbium, yttrium, erbium, and terbium.
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 (\(^{244}\text{Pu}\)) has been discovered in nature! (This isotope has a half-life of “only” 80 million years).

The artificial elements bring the total to 117.
Sample: $1.0 \times 10^{-18}$ g $^{244}$Pu per gram of sample.

Crust: $5 \times 10^{-25}$ 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

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
The heaviest elements are all produced \textit{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.
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:

\[
\begin{align*}
\text{Mass Numbers} \\
^4_2\text{He} + ^{239}_{94}\text{Pu} & \rightarrow ^{242}_{96}\text{Cm} + ^1_0\text{n}
\end{align*}
\]

- 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.
Several elements were discovered using irradiation with neutrons from nuclear reactors followed by beta decay (half-lives in parentheses):

- $n + ^{238}\text{U} \rightarrow ^{239}\text{U} \ (23 \text{ min}) \rightarrow ^{239}\text{Np} \ (2.4 \text{ days}) \rightarrow ^{239}\text{Pu}$

Some elements were produced by light-ion bombardments:

- $^4\text{He} + ^{239}\text{Pu} \rightarrow ^{242}\text{Cm} + n \text{ (atomic number 96)}$
- $^4\text{He} + ^{241}\text{Am} \rightarrow ^{244}\text{Bk} + n \text{ (atomic number 97)}$
- $^4\text{He} + ^{242}\text{Cm} \rightarrow ^{245}\text{Cf} + n \text{ (atomic number 98)}$

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 $^{238}\text{U}$ nuclei captured 17 neutrons to make $^{255}\text{U}$ and beta-decayed to give two new elements: Es (99) and Fm (100).

- $^{238}\text{U}$ 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. $^{12}\text{C} + ^{249}\text{Cf} \rightarrow ^{257}\text{Rf} + 4\text{n}$ (atomic number 104)

- **1980s and 1990s: Heavy Ion + Pb, Bi**
  - ex. $^{58}\text{Fe} + ^{209}\text{Bi} \rightarrow ^{266}\text{Mt} + \text{n}$ (atomic number 109)

- **2000s: $^{48}\text{Ca} +$ Actinide:**
  - ex. $^{48}\text{Ca} + ^{243}\text{Am} \rightarrow ^{288}\text{115} + 3\text{n}$ (atomic number 115)

- Note that we just use “115” rather than “ununpentium.” (Everyone hates that nonsense).
How does the nuclear reaction work?

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.

- 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).
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: $^{48}\text{Ca} + \text{actinides}$
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).
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....
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*.

| 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.
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

- $^{26}\text{Mg} + ^{248}\text{Cm} \rightarrow ^{269}\text{Hs} + 5\text{n} \text{ (a nuclear reaction)}$
- $^{269}\text{Hs} + 2\text{O}_2 \rightarrow ^{269}\text{HsO}_4 \text{ (a chemical reaction)}$

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**Rotating Cm-Target**
- $^{248}\text{Cm}$
- $^{26}\text{Mg}^{5+}$

**PFA Teflon Capillary**
- He/O$_2$

**Recoil Chamber**

**Quartz Wool Plug**

**Quartz Column**

**Oven (600 °C)**

**Thermostat (-20 °C)**

**PIN-Diode Detector (12 pairs)**

**N$_2$ (l)**
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**

- **HsO₄**
  - Temperature: -44±5 °C

- **OsO₄**
  - Temperature: -82±5 °C

**Graphical Data**

- **Exp:**
  - $^{269}$Hs, $^{270}$Hs
  - $^{172}$Os ($T_{1/2}=19.2$ s)

- **MCS**:
  - (Os): -39.5 kJ/mol
  - (Hs): -46.5 kJ/mol

- **Temperature Profile**
  - HsOHsO₄

**Diagram Details**

- **Rel. Yield (%)** vs. **Detector**
- **Temperature [°C]** vs. **Temperature [°C]**
- **Bars** for relative yield (%)
- **Graph Lines** for temperature profile

**Notes**

- MCS (Hs): -46.5 kJ/mol
- MCS (Os): -39.5 kJ/mol
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$_4$N$_3$) that is most likely to give you the observed distribution.

- **OsO$_4$:** $\Delta H_{\text{ads}} = -39 \pm 1 \text{ kJ/mol}$
- **HsO$_4$:** $\Delta H_{\text{ads}} = -46 \pm 2 \text{ kJ/mol}$

- 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!