Chemistry 1000 Lecture 3: Nuclear stability

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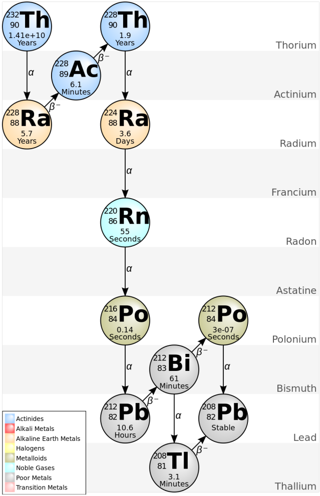
Radioactive decay series



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Forces between nucleons

Electrostatic (Coulomb) force:

- Repulsive force between protons
- Neutrons not involved
- Decreases with distance as $1/r^2$

Strong nuclear force:

- Attractive force between nucleons (neutrons and protons)
- Decreases exponentially with distance (for nucleons)

Forces between nucleons (continued)

Consequences:

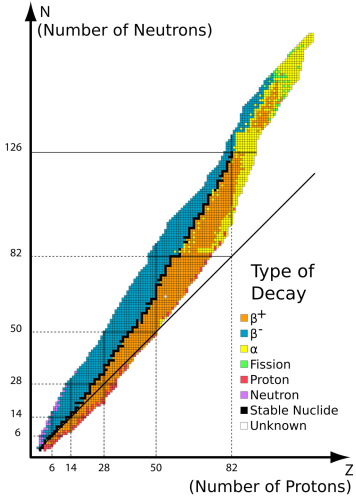
- Large nuclei unstable because strong nuclear force decreases in strength with distance faster than Coulomb force
  Heaviest stable nucleus: ^{208}Pb
- Effect of neutrons: strong-force stabilization *and* increase in average distance between protons $\therefore$ less Coulomb repulsion
- Neutrons and protons are fermions, so they obey the Pauli exclusion principle (to be studied later).
  Putting more nucleons into a nucleus forces the nucleons into higher energy states.
- Having too many neutrons (requiring the use of higher nuclear energy levels) tends to result in beta decay

Nuclear stability rules

Notation: N = number of neutrons = $A - Z$

- For small Z (< 20), $N \approx Z$ for stable nuclei.
  Example: Carbon has two stable isotopes, $^{12}_{6}$C (98.9%) and $^{13}_{6}$C (1.1%).
- For larger Z, $N > Z$, with the N/Z ratio rising slowly from 1 to 1.54 as Z increases from 20 to 82.
- No stable nuclei for $Z > 82$ ($^{208}_{82}$Pb)
- Nuclei with even numbers of neutrons or even numbers of protons or, better still, both, are more likely to be stable
  Examples:
  - Stable nuclei of iron ($Z = 26$): $^{54}_{26}$Fe ($N = 28$), $^{56}_{26}$Fe ($N = 30$), $^{57}_{26}$Fe ($N = 31$), $^{58}_{26}$Fe ($N = 32$)
  - Cobalt has just one stable nucleus: $^{59}_{27}$Co ($N = 32$)

Region of nuclear stability



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Nuclear decay series explained

- Too many neutrons?
  - Beta decay
- Too few neutrons?
  - Positron emission, *or*
  - Electron capture, *or*
  - Alpha emission (esp. for very heavy nuclei)
- Too heavy?
  - Alpha decay
    - especially favored for even proton/even neutron nuclei since alpha decay maintains this favorable parity

Nuclear decay series explained

Examples from the decay series of ${}^{232}_{90}\text{Th}$

${}^{232}_{90}\text{Th}$ has $N/Z = 142/90 = 1.58 > 1.54$, so too many neutrons, but it's also very heavy ($232 > 208$). It has even numbers of both neutrons and protons, so alpha decay would maintain this favorable parity
$\Rightarrow$ alpha decay to ${}^{228}_{88}\text{Ra}$

${}^{228}_{88}\text{Ra}$ has $N/Z = 140/88 = 1.59$, so the preceding alpha decay has made the neutron excess worse
$\Rightarrow$ beta decay to ${}^{228}_{89}\text{Ac}$ ($N/Z = 1.58$)

${}^{228}_{89}\text{Ac}$ still has too many neutrons and an odd number of protons
$\Rightarrow$ beta decay to ${}^{228}_{90}\text{Th}$ ($N/Z = 1.53$)

Nuclear decay series explained

Further examples

$^{18}_{9}$F has $N/Z = 1$ (good) but odd numbers of both protons and neutrons (bad)
$\Rightarrow$ positron emission to form $^{18}_{8}$O

$^{84}_{40}$Zr has $N/Z = 1.1$, which turns out to be below the region of stability (i.e. N is too small)
$\Rightarrow$ electron capture

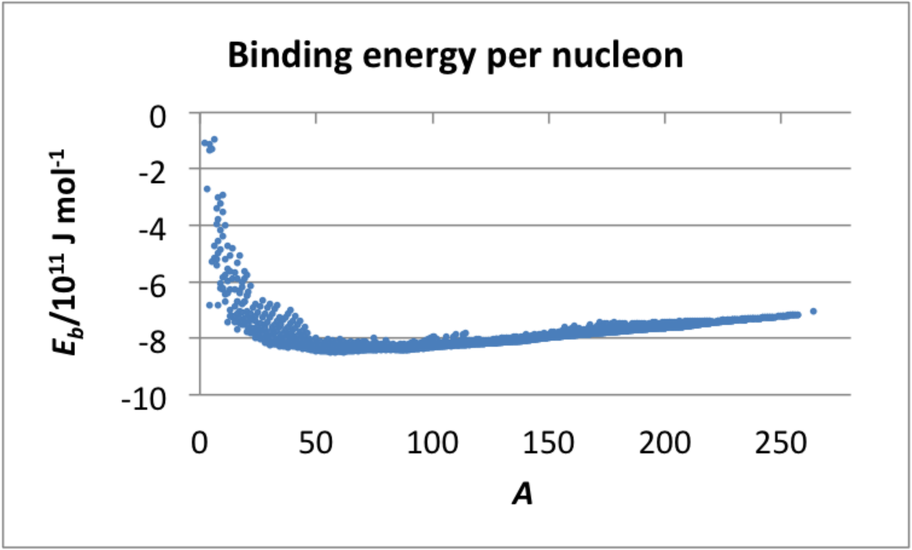
Nuclear binding energy

- Imagine taking initially separated protons, neutrons and electrons and assembling them into an atom.
- This process would be massively exothermic, largely because of the nuclear binding energy, ΔE for this process.
- The nuclear binding energy per nucleon is

$$E_b = \Delta E / A$$

- Important: This is a calculation you do using the mass of a particular isotope, not the average atomic mass.

Nuclear binding energy



Some unusually stable nuclei

- ${}^{4}_{2}\mathrm{He}$: $E_b = -6.83 \times 10^{11}\,\mathrm{J\,mol^{-1}}$
  compared to (e.g.) $-5.14 \times 10^{11}\,\mathrm{J\,mol^{-1}}$ for ${}^{6}_{3}\mathrm{Li}$.
  ⇒ explains alpha particle emission as a common nuclear decay process (rather than some other fragment)
- Minimum of binding energy curve (strongest binding) is ${}^{62}_{28}\mathrm{Ni}$:
  $-8.49 \times 10^{11}\,\mathrm{J\,mol^{-1}}$ [not ${}^{56}_{26}\mathrm{Fe}$ at $-8.48 \times 10^{11}\,\mathrm{J\,mol^{-1}}$]
  ⇒ minimum near these nuclei explains abundance of metals from this part of the periodic table

Fission vs fusion

- To the left of the minimum, fusion can form nuclei closer to the minimum, so this process tends to be energetically favorable.
- To the right of the minimum, fission can form more tightly bound nuclei, so it tends to be energetically favorable.
- Steepest part of curve is at low A, so fusion of light nuclei generates more energy as a rule.