The Nucleus

- Nuclear structure
- Nuclear decay
- Ionizing radiation dangers
- Radioactive half life
- Radioactive dating

Nuclear Structure

- Equal numbers of electrons and protons
  - atomic number
  - Electrons determines chemical properties
- protons have a mass 2000 times that of an electron
- nucleus also contains neutrons
  - approximately same mass as protons
  - neutral (no charge)
- atomic mass is the total number of nucleons
  - nucleons are neutrons or protons
- periodic table lists average atomic mass

Isotopes

- Isotopes are atoms with the same number of protons, but different numbers of neutrons
- Atomic mass number indicated as a superscript before element name
  - $^{10}$B (19.8%) and $^{11}$B (80.2%) are the two naturally occurring isotopes of boron
  - $^{12}$C, $^{13}$C are two important isotopes of carbon
Some Simple Nuclei

- Hydrogen: $^1\text{H}$
- Deuterium: $^2\text{H}$
- Tritium: $^3\text{H}$

The Strong Interaction

- 100 times stronger than electrical force
- Close range (only appreciable in nucleus)
- Only occurs between certain particles
  - Affected: protons, neutrons
  - Not affected: electrons, photons, neutrinos

Nuclear Energy

- Just like atoms and molecules, some nuclear configurations have a lower energy than others.
- Energy released as:
  - Kinetic energy
  - Electromagnetic energy (gamma rays)
- Energy source is nuclear potential energy (mass-energy) present in the nucleus ($E=mc^2$)
- Two processes involved in controlled (and uncontrolled) energy release:
  - Fusion
  - Fission
Fusion

- Smaller nuclei combine to form a larger nucleus, mass-energy released
- Example: $^1_2\text{H} + ^1_1\text{H} \rightarrow ^1_1\text{H} + ^1_0\text{n}
- Raw materials are easily obtained
  - $^1_1\text{H}$ from sea water
  - $^1_3\text{H}$ from bombarding Li with neutrons (which are available in reactors): $n + ^6_3\text{Li} \rightarrow ^4_2\text{He} + ^1_1\text{H}$
- Problems
  - difficult to contain (electromagnetic repulsion of nuclei)
  - large temperatures and pressures involved
  - $30$ to $100$ million degrees C
- Where fusion occurs: sun, hydrogen bomb
- Where fusion doesn’t occur: nuclear reactors

Rollercoaster Analogy

- Atoms must have enough kinetic energy to overcome electromagnetic repulsion for fusion to occur.
- Atoms are barely stable and just need a little nudge for fission to occur.

Fission

- Heavy nucleus breaks up into smaller nuclei and neutrons – mass-energy is released
- nuclear reaction is short range (nucleons on opposite sides don’t feel each other)
- electrostatic repulsion is long range
- This process releases neutrons that can trigger other reactions
- Chain reaction occurs when the process becomes self-sustaining
- Control of the reaction necessary to make this a viable energy source
Fission Process

- Fissile material (fuel rods)
  - $^{235}\text{U}$, $^{239}\text{Pu}$
- Moderator
  - slows neutrons down
- Control rods
  - absorb extra neutrons
- Problems
  - radioactive waste
  - fuel is rare
  - fuel can be misappropriated for weapons
  - mistakes are costly

Fission Reactor

- Coal contains on average 3.3ppm of uranium
- Rocky mountain coal contains 24ppm uranium.
- Uranium levels are as high as 7000ppm.
- A coal plant operating for a day burns 33 to 240 kg of uranium.

Energy comparison

- A 1000 Megawatt power plant for one day requires:
  - 3.2Kg of Uranium
  - 60,000 Kg of propane
  - 10,000,000 kg of coal
  - 10,000,000 gallons of water over a 300 ft high dam.
Nuclear decay

- Most nuclei are very stable
- Some spontaneously change arrangement of nuclear constituents resulting in radioactivity
- Examples of radioactive decay
  - alpha decay
  - beta decay
  - gamma decay
  - electron capture (type of beta decay)
  - positron decay (type of beta decay)

The nuclear strong force is short range, the electromagnetic force is long range.
- As more and more protons are added, the nucleus becomes less stable, and more neutrons are needed to glue the nucleus together.
- Eventually the electromagnetic repulsion between protons is about the same size as the strong force holding the nucleus together.
- These atoms will break apart emitting high energy particles.
  - Any atom heavier than Bismuth is unstable. Regardless of how many neutrons are present.
- Because the high energy particles cause static on radios, they are called Radioactive.

Geiger Counter
Alpha Decay
- helium nucleus emitted, \(^{4}\text{He}\) (has lower mass-energy)
- atomic number decreased by 2
- atomic mass number decreased by 4
- \(^{226}\text{Ra} \rightarrow ^{222}\text{Rn} + ^{4}\text{He}\)

Lighter Nuclei
- Light elements become unstable when they don’t have the right mix of protons and neutrons.
- Only certain isotopes of lighter elements are unstable.
- The atomic mass gives a clue as to what will happen to these atoms.
  - If the atom has too many neutrons, it will change a neutron into a proton and electron by beta decay.
  - If the atom has too few neutrons, it will change a proton into a neutron by electron capture or positron decay.

Beta Decay
- neutron converted to a proton, electron, and neutrino
- atomic number increased by 1
- atomic mass number unchanged
- \(^{14}\text{C} \rightarrow ^{14}\text{N} + ^{0}\text{e} + ^{0}\text{neutrino}\)
Gamma Decay

- high energy photon emitted
- similar to radiation emitted from atoms – the nucleus is in an excited, higher level nuclear state and falls to a lower energy nuclear state
- no change in atomic mass or atomic number
- \(^{87}_{36}\text{Kr} \rightarrow ^{87}_{36}\text{Kr} + \text{photon}\)

Predictions?

- \(^{40}_{19}\text{K} + ^{0}_{-1}\text{e} \rightarrow ^{40}_{18}\text{Ar} + \text{neutrino}\)  (type of beta decay called electron capture)
- \(^{11}_{7}\text{C} \rightarrow ^{11}_{8}\text{B} + ^{0}_{+1}\text{e} + \text{neutrino}\)  (type of beta decay called positron decay)
- \(^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{140}_{54}\text{Xe} + ^{92}_{38}\text{Sr} + ^{3}_{1}\text{n}\)  (fission)
- \(^{193}_{80}\text{Hg} \rightarrow ^{193}_{79}\text{Au} + ^{0}_{+1}\text{e} + \text{neutrino}\)

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Ionizing Radiation

- Energy carried by these particles is more than enough to disrupt many molecules
  - often a million times typical molecular binding energies
- Danger to living cells
  - damage RNA or DNA causing death of cells or mutations
  - disrupt metabolic processes
    - cells with high activity seem more prone to damage than others (cancer therapy)

Half Life

- The half-life is the time it takes half a sample of radioactive nuclei to decay
- Importance examples
  - $^{14}C \rightarrow ^{14}N + e + \text{neutrino}$ (half life of 5730 years)
  - $^{40}K + e \rightarrow ^{40}Ar + \text{neutrino}$ (half life of 1.3 billion years)

Each half-life, half of the remaining atoms are left undecayed.

- One half-life $\rightarrow \frac{1}{2}$
- Two half-lives $\rightarrow \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$
- Three half-lives $\rightarrow \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$

- If the original number of atoms is known, the age of the sample can be determined by the fraction of atoms left.
- This process is known as radioactive dating
Quick Quiz

• A sample of radioactive gas is produced. After 20 minutes, only 1/4 of the original gas remains. What is the half-life of the gas?

• A sample of radioactive material with a half-life of 6 hours sits for a day. How much of the original radioactive material remains?