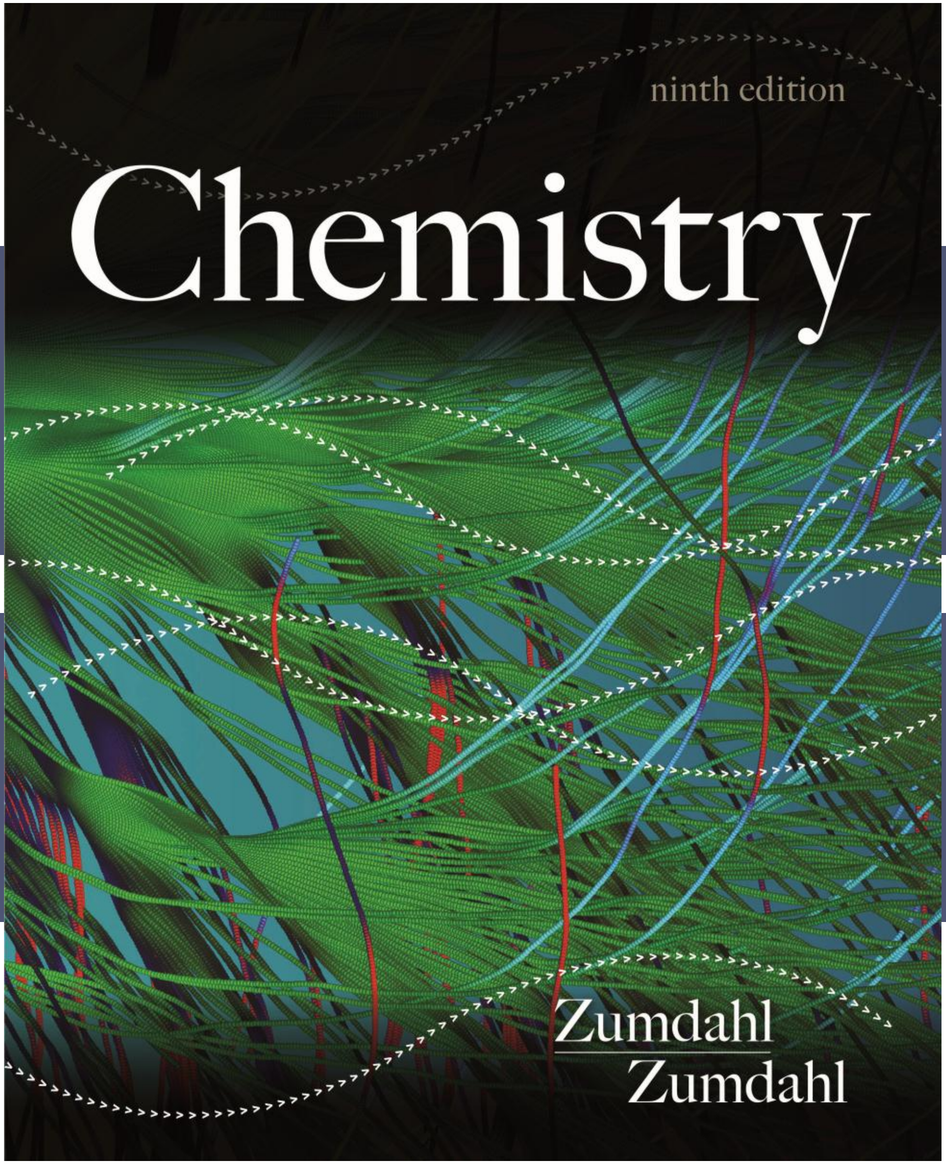


Chapter 19

The Nucleus: A Chemist's View

Table of Contents

Review - Nucleus

- Collection of **nucleons**
  - Subdivided into **neutrons** and **protons**
    - Composed of smaller particles called quarks
    - **Atomic number** (*Z*): Number of protons in a nucleus
    - **Mass number** (*A*): Sum of protons and neutrons in a nucleus
- **Isotopes**: Atoms with identical atomic numbers but different mass number values

Review - Nuclide

- Unique atom that is represented by the following symbol:

$$^{A}_{Z}\mathrm{X}$$

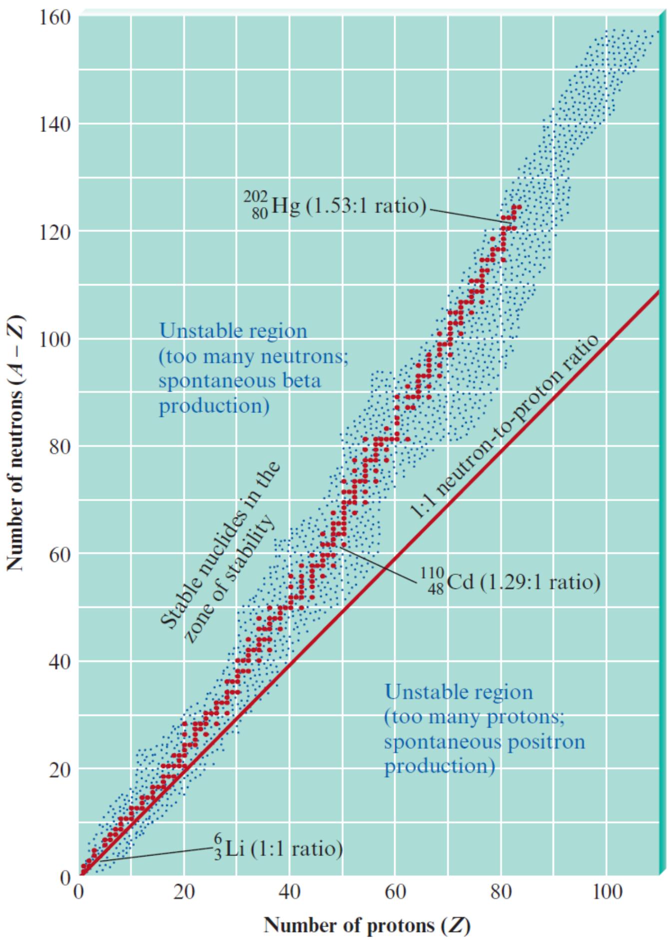
  - X - Symbol of the element
  - *A* - Mass number
  - *Z* - Atomic number

Nuclear Stability

- **Thermodynamic stability**: Potential energy of a nucleus compared with the sum of the potential energies of its constituent neutrons and protons
- **Kinetic stability**: Explains the probability of radioactive decay of a nucleus
  - **Radioactive decay**: Nucleus undergoes decomposition to form a different nucleus

The Zone of Stability

- Area where stable nuclides reside as a function of Z and (A – Z)
  - As the number of protons in the nuclide increases, the neutron-to-proton ratio required for stability increases



Radioactive Decay - Observations

- All nuclides with 84 or more protons are unstable with respect to radioactive decay
- When neutron-to-proton ratio = 1, light nuclides will be stable
  - For heavier elements, neutron-to-proton ratio required for stability is greater than 1 and increases with *Z*

Radioactive Decay - Observations (Continued)

- Certain combinations of protons and neutrons seem to confer special stability
  - Nuclides with even numbers of protons and neutrons are more stable than those with odd numbers
- Certain specific numbers of protons or neutrons produce especially stable nuclides
  - Magic numbers - 2, 8, 20, 28, 50, 82, and 126

Types of Radioactive Decay

- α-particle production
- Spontaneous fission
- β-particle production
- Positron production
- γ-ray production

Alpha-Particle Production

- Involves a change in mass number for the decaying nucleus
  - **Alpha-particle** (**α particle**): A helium nucleus
  - Common mode of decay for heavy radioactive nuclides
  - Example - Decay of uranium-238

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$$

Spontaneous Fission

- Splitting of a heavy nuclide into two lighter nuclides with similar mass numbers
- Occurs at an extremely slow rate

Beta (β)-Particle Production

- Mass number of the decaying nucleus remains constant
- Net effect - To change a neutron to a proton
  - Nuclides that lie above the zone of stability are expected to be β-particle producers
- The emitting nucleus does not contain electrons even though the β particle is an electron

Gamma-Ray Production

- **Gamma ray** (**γ ray**): High-energy photon
  - γ-ray production accompanies nuclear decay and particle reactions
- Example

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th} + 2\,^{0}_{0}\gamma$$

  - In this α-particle decay, two γ rays of different energies and an α particle are produced

Positron Production

- Occurs for nuclides that lie below the zone of stability
  - These nuclides have small neutron/proton ratios
- Positron - Particle with the same mass as the electron but with opposite charge
- Net effect - To change a proton to a neutron
  - Causes the product nuclide to have a higher neutron/proton ratio than the original nuclide

Positron Production (Continued)

- Positron is the antiparticle of electron
  - Annihilation
    - When a positron collides with an electron, particulate matter transforms into electromagnetic radiation in the form of high-energy photons

$$ {}^{0}_{-1}\mathrm{e} + {}^{0}_{1}\mathrm{e} \rightarrow 2\,{}^{0}_{0}\gamma $$

    - Characteristic of antimatter–matter collisions

Electron Capture

- Process by which the nucleus captures one of the inner-orbital electrons

$$ {}^{201}_{80}\mathrm{Hg} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{201}_{79}\mathrm{Au} + {}^{0}_{0}\gamma $$

Inner-orbital electron

  - γ rays are always produced to release excess energy

Interactive Example 19.1 - Nuclear Equations I

- Write balanced equations for each of the following processes:
  a. $^{11}_{6}\mathrm{C}$ produces a positron
  b. $^{214}_{83}\mathrm{Bi}$ produces a β particle
  c. $^{237}_{93}\mathrm{Np}$ produces an α particle

Interactive Example 19.1 - Solution (a)

- We must find the product nuclide represented by $^{A}_{Z}\mathrm{X}$ in the following equation:

$$^{11}_{6}\mathrm{C} \rightarrow \underset{\text{Positron}}{\underset{\uparrow}{^{0}_{1}\mathrm{e}}} + ^{A}_{Z}\mathrm{X}$$

  - We can find the identity of the product nuclide by recognizing that the total of the *Z* and *A* values must be the same on both sides of the equation

Interactive Example 19.1 - Solution (a) (Continued)

- Therefore,

$$^{A}_{Z}\mathrm{X} = {}^{11}_{5}\mathrm{B}$$

  - The fact that *Z* is 5 tells us that the nuclide is boron
- Thus, the balanced equation is

$$^{11}_{6}\mathrm{C} \rightarrow {}^{0}_{1}\mathrm{e} + {}^{11}_{5}\mathrm{B}$$

Interactive Example 19.1 - Solution (b)

- Knowing that a β particle is represented by ${}^{0}_{-1}\text{e}$ and that *Z* and *A* are conserved, we can write

$${}^{214}_{83}\text{Bi} \rightarrow {}^{0}_{-1}\text{e} + {}^{214}_{84}\text{X}$$

$$\text{Therefore, } {}^{A}_{Z}\text{X} \text{ must be } {}^{214}_{84}\text{Po}$$

Interactive Example 19.1 - Solution (c)

- Since an α particle is represented by $^{4}_{2}\text{He}$, the balanced equation must be

$$^{237}_{93}\text{Np} \rightarrow {}^{4}_{2}\text{He} + {}^{233}_{91}\text{Pa}$$

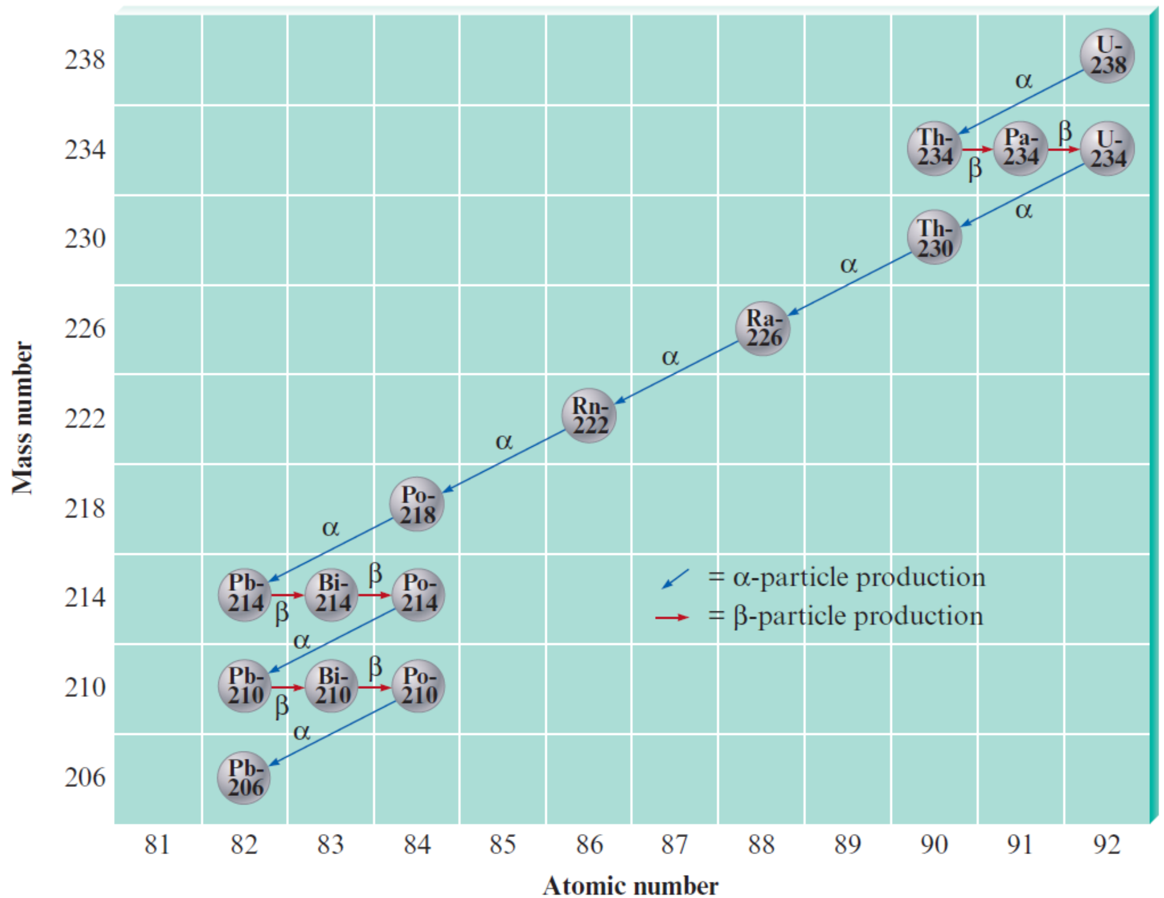
Decay Series

- When a radioactive nucleus cannot reach a stable state via a single radioactive decay process, a **decay series** occurs until a stable nuclide is formed
- Examples

$$^{235}_{92}\text{U} \xrightarrow[\text{decays}]{\text{Series of}} {}^{207}_{82}\text{Pb}$$

$$^{232}_{90}\text{Th} \xrightarrow[\text{decays}]{\text{Series of}} {}^{208}_{82}\text{Pb}$$

Figure 19.2 - Decay Series from Uranium-238 to Lead-206



Critical Thinking

- What if a nuclide were to undergo two successive decays such that it became the original nuclide?
  - Which decays could account for this?
    - Provide an example

Rate of Decay

- Defined as the negative of the change in number of nuclides per unit time

$$\left(-\frac{\Delta N}{\Delta t}\right)$$

  - The rate is directly proportional to the number of nuclides, *N*, in a given sample

$$\text{Rate} = -\frac{\Delta N}{\Delta t} \propto N$$

Rate of Decay (Continued 1)

- Negative sign indicates that the number of nuclides is decreasing

- Rate law for a first-order process

$$\text{Rate} = -\frac{\Delta N}{\Delta t} = kN$$

Rate of Decay (Continued 2)

- Integrated first-order rate law

$$\ln\left(\frac{N}{\mathrm{N}_0}\right) = -kt$$

  - N_0 - Original number of nuclides (at $t = 0$)
  - t - Time
  - N - Number of nuclides remaining at time t

Half-Life ($t_{1/2}$)

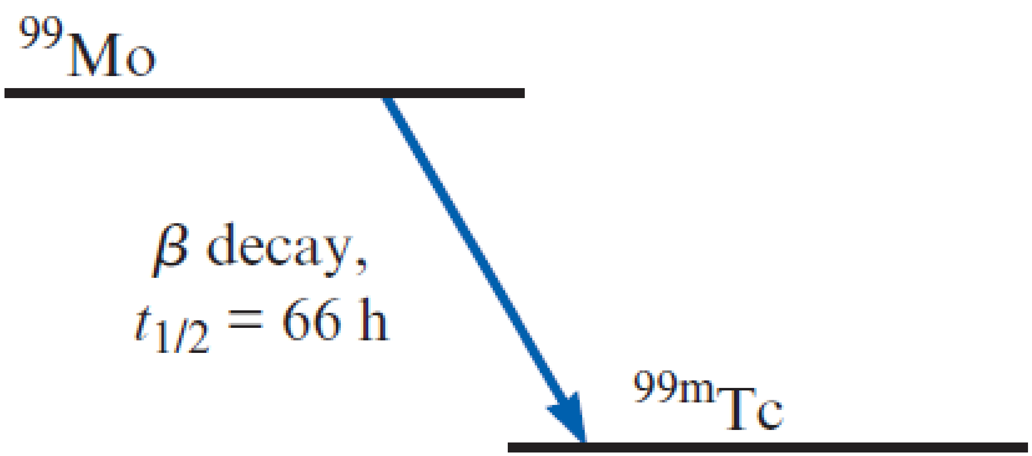
- Time required for the number of nuclides to reach half the original value ($N_0/2$)

$$t_{1/2} = \frac{\ln(2)}{k} = \frac{0.693}{k}$$

  - Helps in the determination of rate constant
- In a first-order process, $t_{1/2}$ is constant

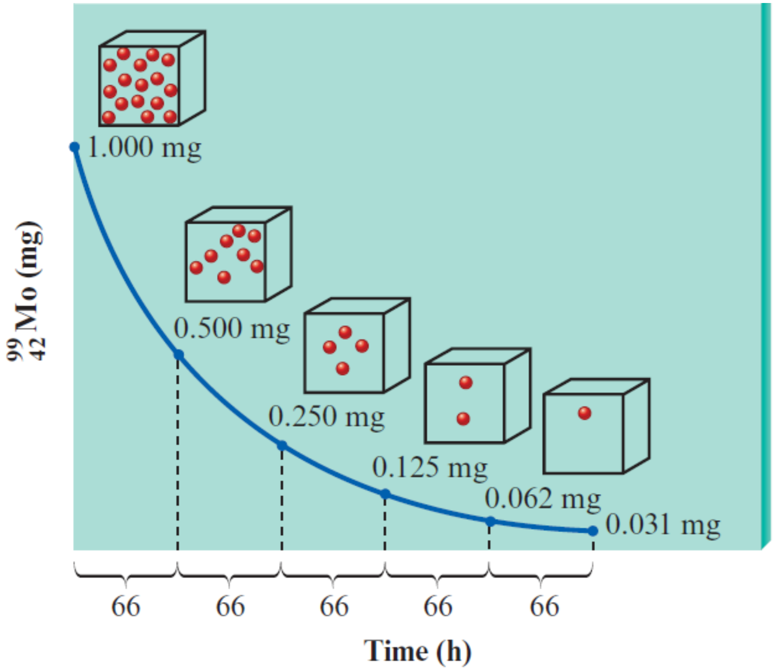
Example 19.4 - Kinetics of Nuclear Decay II

- The half-life of molybdenum-99 is 66.0 h
  - How much of a 1.000-mg sample of molybdenum-99 is left after 330 h?



Example 19.4 - Solution

- Recognize that 330 h represents five half-lives for molybdenum-99 ($330 = 5 \times 66.0$)



Thus, after 330 h, 0.031 mg of molybdenum-99 remains

Exercise

- Krypton consists of several radioactive isotopes, some of which are listed in the following table:

	Half-Life
^{73}Kr	27 s
^{74}Kr	11.5 min
^{76}Kr	14.8 h
^{81}Kr	2.1×10^5 yr

  - Which of these isotopes is most stable, and which isotope is "hottest"? How long does it take for 87.5% of each isotope to decay?

Exercise - Solution

- Most stable isotope
  - Krypton-81, since it has the longest half-life
- Hottest isotope
  - Krypton-73, since it decays rapidly due to a very short half-life
- Time taken for 87.5% of each isotope to decay
  - Krypton-73 = 81s
    Krypton-74 = 34.5 min
  - Krypton-76 = 44.4 h
    Krypton-81 = 6.3×10^5 yr

Nuclear Transformation

- Change of one element into another
  - Observed by Lord Rutherford when he bombarded nitrogen-14 with α particles

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

- Example - Transformation of aluminum to phosphorus

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{30}_{15}\mathrm{P} + \underbrace{{}^{1}_{0}\mathrm{n}}_{\text{Neutron}}$$

Particle Accelerator

- Device used to provide particles high velocities
- Facilitates nuclear transformation when positive ions are used as bombarding particles
  - Enabled by the presence of electrostatic repulsion between the target nucleus and the positive ion
  - Transformation occurs when the particle overcomes the repulsion and penetrates the target nucleus

Cyclotron - A Particle Accelerator

- An ion is introduced at the center of the device
  - The device accelerates the ion in a spiral path by using alternating electric fields in the presence of a magnetic field

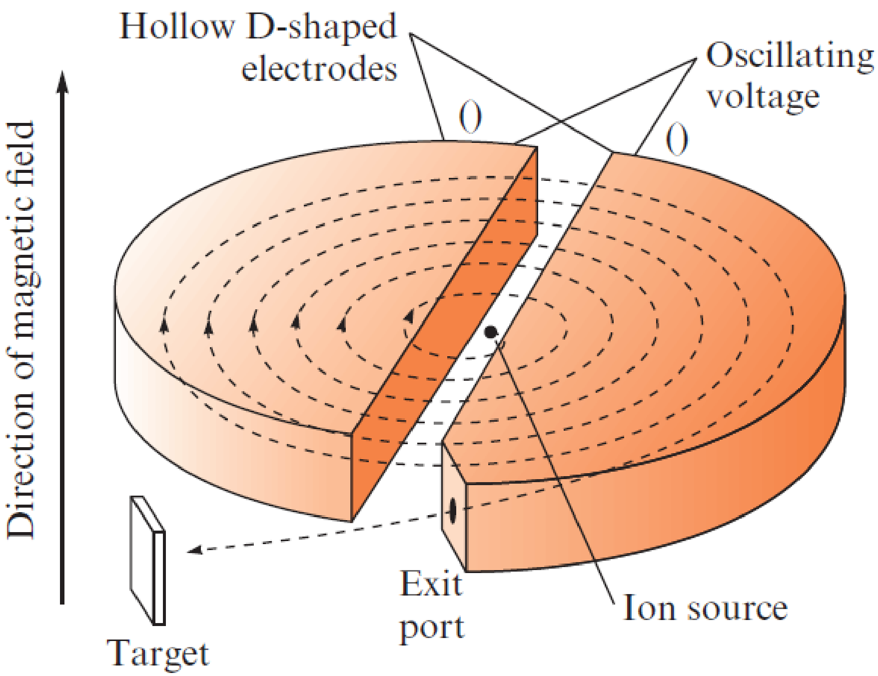
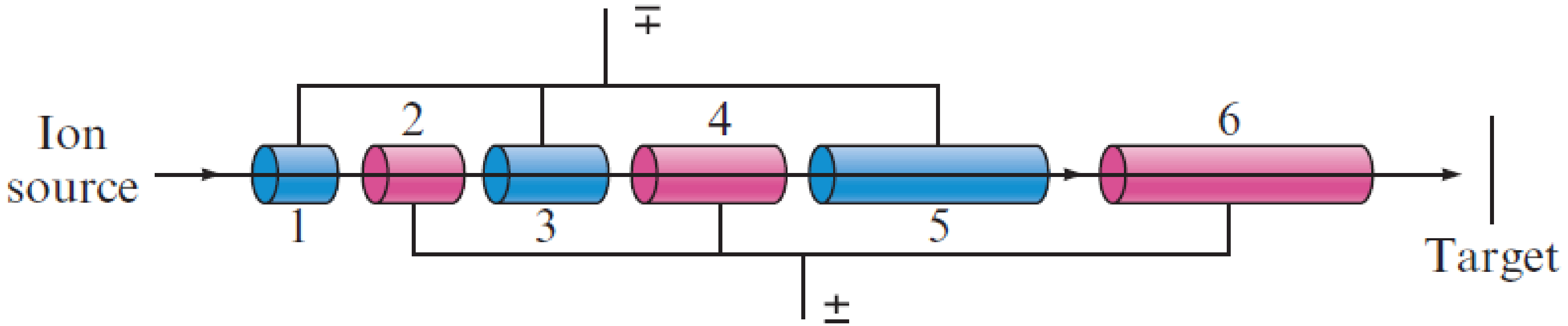


Figure 19.6 - Linear Accelerator

- A device that uses changing electric fields to attain high velocities on a linear pathway



Fission Reactors

- Most common source of neutrons that can be used as bombarding particles to effect nuclear transformations
  - Neutrons are uncharged and cannot be repelled by electrostatic force
    - Easily absorbed by many nuclei leading to new nuclides

Neutron and Positive-Ion Bombardment

- Enabled scientists to extend the periodic table
- **Transuranium elements**: Have atomic numbers that are greater than 92 and have short half-lives
  - Chemical characterization of these elements is difficult

Table 19.4 - Syntheses of Some of the Transuranium Elements

Element	Neutron Bombardment	Half-Life
Neptunium ($Z = 93$)	${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$	2.36 days (${}^{239}_{93}Np$)
Plutonium ($Z = 94$)	${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$	24,110 years (${}^{239}_{94}Pu$)
Americium ($Z = 95$)	${}^{239}_{94}Pu + 2\,{}^{1}_{0}n \longrightarrow {}^{241}_{94}Pu \longrightarrow {}^{241}_{95}Am + {}^{0}_{-1}e$	433 years (${}^{241}_{95}Am$)
Element	**Positive-Ion Bombardment**	**Half-Life**
Curium ($Z = 96$)	${}^{239}_{94}Pu + {}^{4}_{2}He \longrightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$	163 days (${}^{242}_{96}Cm$)
Californium ($Z = 98$)	${}^{242}_{96}Cm + {}^{4}_{2}He \longrightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$ or ${}^{238}_{92}U + {}^{12}_{6}C \longrightarrow {}^{246}_{98}Cf + 4\,{}^{1}_{0}n$	45 minutes (${}^{245}_{98}Cf$)
Rutherfordium ($Z = 104$)	${}^{249}_{98}Cf + {}^{12}_{6}C \longrightarrow {}^{257}_{104}Rf + 4\,{}^{1}_{0}n$	
Dubnium ($Z = 105$)	${}^{249}_{98}Cf + {}^{15}_{7}N \longrightarrow {}^{260}_{105}Db + 4\,{}^{1}_{0}n$	
Seaborgium ($Z = 106$)	${}^{249}_{98}Cf + {}^{18}_{8}O \longrightarrow {}^{263}_{106}Sg + 4\,{}^{1}_{0}n$	

Measuring Radioactivity Levels

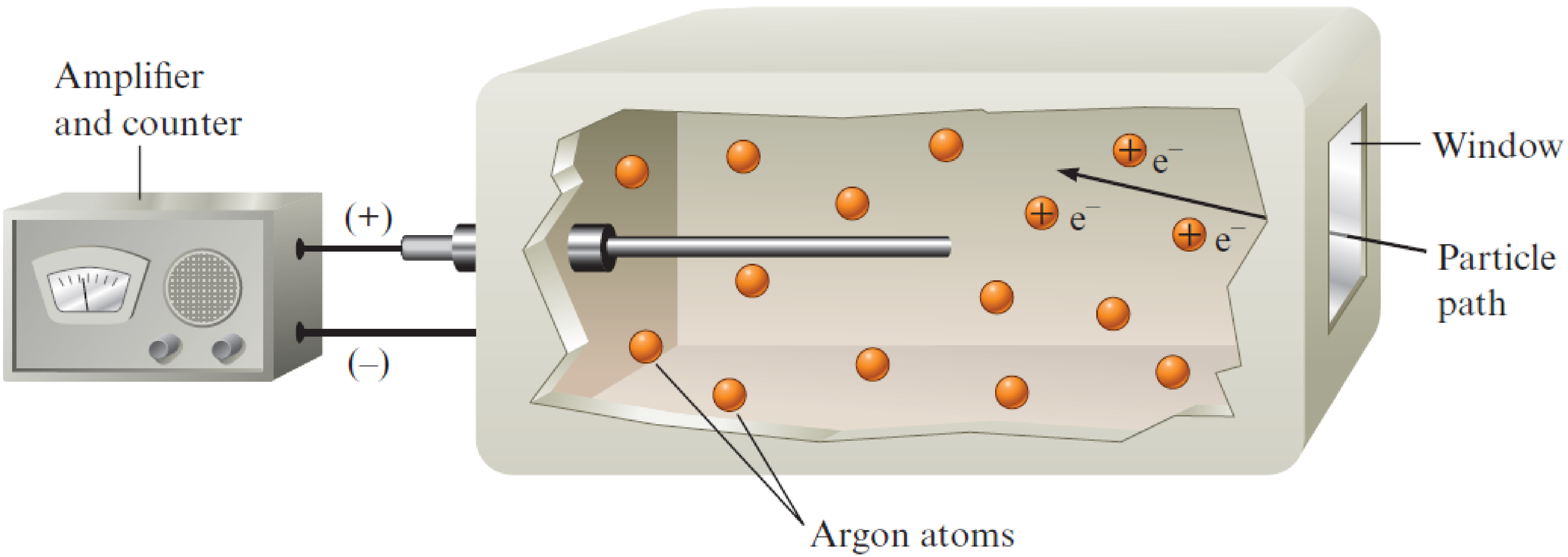
- **Geiger counter** (**Geiger–Müller counter**)
  - Capitalizes on the fact that high-energy particles from radioactive decay produce ions when they travel through matter
  - The probe is filled with argon gas, which can be ionized by a rapidly moving particle

$$\mathrm{Ar}(g) \xrightarrow[\text{particle}]{\text{High-energy}} \mathrm{Ar}^{+}(g) + \mathrm{e}^{-}$$

Measuring Radioactivity Levels (Continued)

- Formation of ions and electrons by the passage of high-energy particles facilitates a momentary current flow
  - Electronic devices can detect this current flow, and the number of these events can be counted to determine the decay rate
- **Scintillation counter**: Capitalizes on the fact that some substances emit light when they are struck by high-energy radiation

Figure 19.7 - Geiger–Müller Counter



Carbon-14 Dating (Radiocarbon Dating)

- Based on the radioactivity of carbon-14 nuclide that decays by β-particle production

$$^{14}_{6}\mathrm{C} \rightarrow \ ^{0}_{-1}\mathrm{e} + \ ^{14}_{7}\mathrm{N}$$

- Carbon-14 is continuously produced in the atmosphere when high-energy neutrons from space collide with nitrogen-14

$$^{14}_{7}\mathrm{N} + \ ^{1}_{0}\mathrm{n} \rightarrow \ ^{14}_{6}\mathrm{C} + \ ^{1}_{1}\mathrm{H}$$

Carbon-14 Dating (Radiocarbon Dating) (Continued)

- Used to date wood and cloth artifacts
- Drawback
  - Process requires a fairly large piece of the sample to be burned to form CO_2
    - This is analyzed for radioactivity
- Mass spectrometer
  - Avoids destruction of the valuable artifact, requires only about 10^{-3} g of the sample

Interactive Example 19.6 - Dating by Radioactivity

- A rock containing uranium-238 and lead-206 was examined to determine its approximate age
  - Analysis showed the ratio of lead-206 atoms to uranium-238 atoms to be 0.115
    - Assume that no lead was originally present, that all the lead-206 formed over the years has remained in the rock, and that the number of nuclides in intermediate stages of decay between uranium-238 and lead-206 is negligible
    - Calculate the age of the rock when the half-life of uranium-238 is 4.5×10^9 years

Interactive Example 19.6 - Solution

- This problem can be solved using the integrated first-order rate law

$$\ln\left(\frac{N}{N_0}\right) = -kt = -\left(\frac{0.693}{4.5\times10^9\ \text{years}}\right)t$$

  - N/N_0 represents the ratio of uranium-238 atoms now found in the rock to the number present when the rock was formed

Interactive Example 19.6 - Solution (Continued 1)

- Assume that each lead-206 nuclide present must have come from decay of a uranium-238 atom

$$^{238}_{92}\text{U} \rightarrow {}^{206}_{82}\text{Pb}$$

$$\boxed{\text{Number of } ^{238}_{92}\text{U atoms originally present}} = \boxed{\text{number of } ^{206}_{82}\text{Pb atoms now present}} + \boxed{\text{number of } ^{238}_{92}\text{U atoms now present}}$$

$$\frac{\text{Atoms of } ^{206}_{82}\text{Pb now present}}{\text{Atoms of } ^{238}_{92}\text{U now present}} = 0.115 = \frac{0.115}{1.000} = \frac{115}{1000}$$

Interactive Example 19.6 - Solution (Continued 2)

- Think carefully about what this means
  - For every 1115 uranium-238 atoms originally present in the rock, 115 have been changed to lead-206 and 1000 remain as uranium-238

Now present

$$\frac{N}{N_0} = \underbrace{\frac{{}^{238}_{92}\text{U}}{{}^{206}_{82}\text{Pb} + {}^{238}_{92}\text{U}}}_{\text{Uranium-238 originally present}} = \frac{1000}{1115} = 0.8969$$

Interactive Example 19.6 - Solution (Continued 3)

$$\ln\left(\frac{N}{N_0}\right) = \ln(0.8969) = -\left(\frac{0.693}{4.5 \times 10^9 \text{ years}}\right)t$$

$$t = 7.1 \times 10^8 \text{ years}$$

- This is the approximate age of the rock, and it was formed sometime in the Cambrian period

Medical Applications of Radioactivity

- **Radiotracers**: Radioactive nuclides that can be introduced into organisms via food or drugs
  - Pathways can be traced by monitoring the substance's radioactivity
  - Provide a sensitive and noninvasive method to:
    - Learn about biological systems
    - Detect diseases
    - Monitor action and effectiveness of drugs
    - Detect pregnancy in its early stages

Table 19.5 - Radiotracers

Nuclide	Half-Life	Area of the Body Studied
^{131}I	8.0 days	Thyroid
^{59}Fe	44.5 days	Red blood cells
^{99}Mo	66 hours	Metabolism
^{32}P	14.3 days	Eyes, liver, tumors
^{51}Cr	27.7 days	Red blood cells
^{87}Sr	2.8 hours	Bones
^{99m}Tc	6.0 hours	Heart, bones, liver, and lungs
^{133}Xe	5.2 days	Lungs
^{24}Na	15.0 hours	Circulatory system

Nucleus - Thermodynamic Stability

- Ascertained by calculating change in potential energy that would result if a nucleus were formed from its constituent neutrons and protons

$$E = mc^2$$

  - This equation shows that energy should be considered as a form of matter

Thermodynamic Stability and Mass

- When a system gains or loses energy, it also gains or loses a quantity of mass
  - Mass of a nucleus is less than that of its nucleons since the process is exothermic

$$\text{Energy change} = \Delta E = \Delta mc^2$$

  - **Mass defect** (Δm): Change in mass
    - Used to ascertain the value of ΔE

Interactive Example 19.7 - Nuclear Binding Energy I

- Calculate the change in energy if 1 mole of oxygen-16 nuclei was formed from neutrons and protons

Interactive Example 19.7 - Solution

- We have already calculated that 0.1366 g of mass would be lost in the hypothetical process of assembling 1 mole of oxygen-16 nuclei from the component nucleons
  - We can calculate the change in energy for this process from

$$\Delta E = \Delta mc^2$$

Interactive Example 19.7 - Solution (Continued)

- Where,

$$c = 3.00 \times 10^{8} \text{ m/s}$$

$$\Delta m = -\,0.1366 \text{ g/mol} = -1.366 \times 10^{-4} \text{ kg/mol}$$

$$\Delta E = \left(-1.366 \times 10^{-4} \text{ kg/mol}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)^{2}$$

$$= -1.23 \times 10^{13} \text{ J/mol}$$

- The negative sign for the Δ*E* value indicates that the process is exothermic
  - Energy, and thus mass, is lost from the system

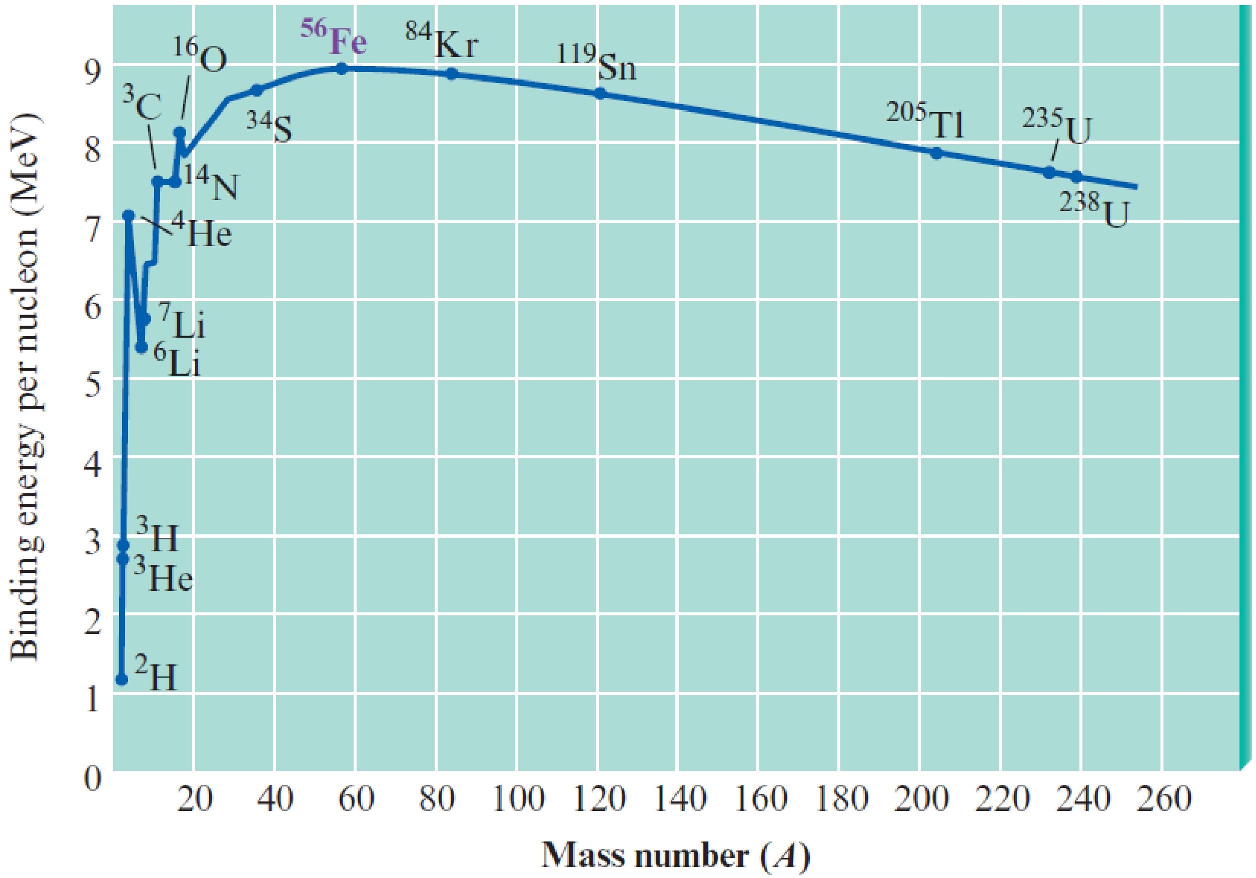
Computing Thermodynamic Stability of a Nucleus

- First, calculate ΔE
  - Divide molar mass value of the nucleus by Avogadro's number
  - Amount is calculated in million electronvolts (MeV), where 1 MeV = 1.60×10^{-13} J
- Next, calculate ΔE per nucleon by dividing by A, the sum of neutrons and protons

Binding Energy

- Energy required to decompose a nucleus into its component nucleons
- Iron-56 is the most stable nucleus and has a binding energy per nucleon of 8.79 MeV

Figure 19.9 - Binding Energy per Nucleon as a Function of Mass Number



Interactive Example 19.8 - Nuclear Binding Energy II

- Calculate the binding energy per nucleon for the helium-4 nucleus
  - Atomic masses:

Helium-4 = 4.0026 amu

Hydrogen-1 = 1.0078 amu

Interactive Example 19.8 - Solution

- First, we must calculate the mass defect (Δm) for helium-4
  - Since atomic masses (which include the electrons) are given, we must decide how to account for the electron mass

$$4.0026 = \text{mass of } {}^{4}_{2}\text{He atom} = \text{mass of } {}^{4}_{2}\text{He nucleus} + 2m_\text{e}$$

Electron mass

$$1.0078 = \text{mass of } {}^{1}_{1}\text{H atom} = \text{mass of } {}^{1}_{1}\text{H nucleus} + m_\text{e}$$

Interactive Example 19.8 - Solution (Continued 1)

- Thus, since a helium-4 nucleus is synthesized from two protons and two neutrons, we see that

$$\Delta m = \underbrace{\left(4.0026 - 2m_e\right)}_{\text{Mass of helium-4 nucleus}} - \left[\underbrace{2\left(1.0078 - m_e\right)}_{\text{Mass of hydrogen-1 nucleus (proton)}} + \underbrace{2\left(1.0087\right)}_{\text{Mass of neutron}}\right]$$

$$= 4.0026 - 2m_e - 2(1.0078) + 2m_e - 2(1.0087)$$

$$= 4.0026 - 2(1.0078) - 2(1.0087)$$

$$= -0.0304 \text{ u}$$

Interactive Example 19.8 - Solution (Continued 2)

- Note that in this case the electron mass cancels out in taking the difference
  - This will always happen in this type of calculation if the atomic masses are used both for the nuclide of interest and for hydrogen-1
  - Thus, 0.0304 of mass is lost per helium-4 nucleus formed
- The corresponding energy change can be calculated from

$$\Delta E = \Delta mc^2$$

Interactive Example 19.8 - Solution (Continued 3)

$$\Delta m = -0.0304\,\frac{\text{u}}{\text{nucleus}} = \left(-0.0304\,\frac{\text{u}}{\text{nucleus}}\right)\left(1.66 \times 10^{-27}\,\frac{\text{kg}}{\text{u}}\right)$$

$$= -5.04 \times 10^{-29}\,\frac{\text{kg}}{\text{nucleus}}$$

and $c = 3.00 \times 10^{8}$ m/s

$$\Delta E = \left(-5.04 \times 10^{-29}\,\frac{\text{kg}}{\text{nucleus}}\right)\left(3.00 \times 10^{8}\,\frac{\text{m}}{\text{s}}\right)^2$$

$$= -\,4.54 \times 10^{-12}\ \text{J/nucleus}$$

Interactive Example 19.8 - Solution (Continued 4)

- This means that 4.54×10^{-12} J of energy is released per nucleus formed and that 4.54×10^{-12} J would be required to decompose the nucleus into the constituent neutrons and protons
  - Thus the binding energy (BE) per nucleon is

$$\text{BE per nucleon} = \frac{4.54 \times 10^{-12}\ \text{J/nucleus}}{4\ \text{nucleons/nucleus}}$$

$$= 1.14 \times 10^{-12}\ \text{J/nucleon}$$

Interactive Example 19.8 - Solution (Continued 5)

$$\text{BE per nucleon} = \left(1.14 \times 10^{-12}\ \frac{\text{J}}{\text{nucleon}}\right)\left(\frac{1\ \text{MeV}}{1.60 \times 10^{-13}\ \text{J}}\right)$$

$$= 7.13\ \text{MeV/nucleon}$$

Nuclear Fission and Fusion

- **Fusion**: Combining two light nuclei to form a heavier, more stable nucleus
- **Fission**: Splitting a heavy nucleus into two nuclei with smaller mass numbers
- Large binding energies hold the nucleus together
  - Fusion and fission involve energy changes that are more than a million times larger than those that occur during a chemical reaction

Nuclear Fission

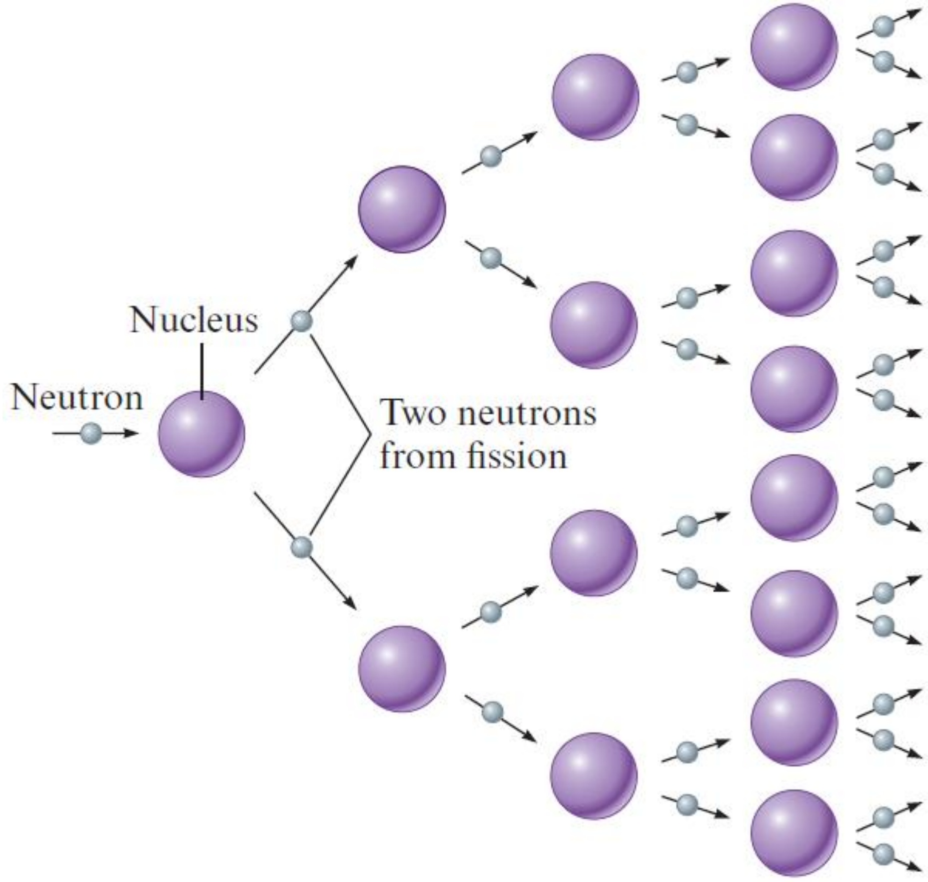
- Discovered when uranium-235 nuclides bombarded with neutrons were observed to split into lighter elements

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} $$

  - This process releases 3.5×10^{-11} J of energy per event

Chain-Reaction

- Self-sustaining fission process
  - Requires one neutron from each fission event to split another nucleus



Chain-Reaction - Possible Outcomes

- **Subcritical**: When less than one neutron causes another fission event
  - Result - Reaction dies out
- **Critical**: When one neutron from each fission event causes another fission event
  - Result - Process sustains itself

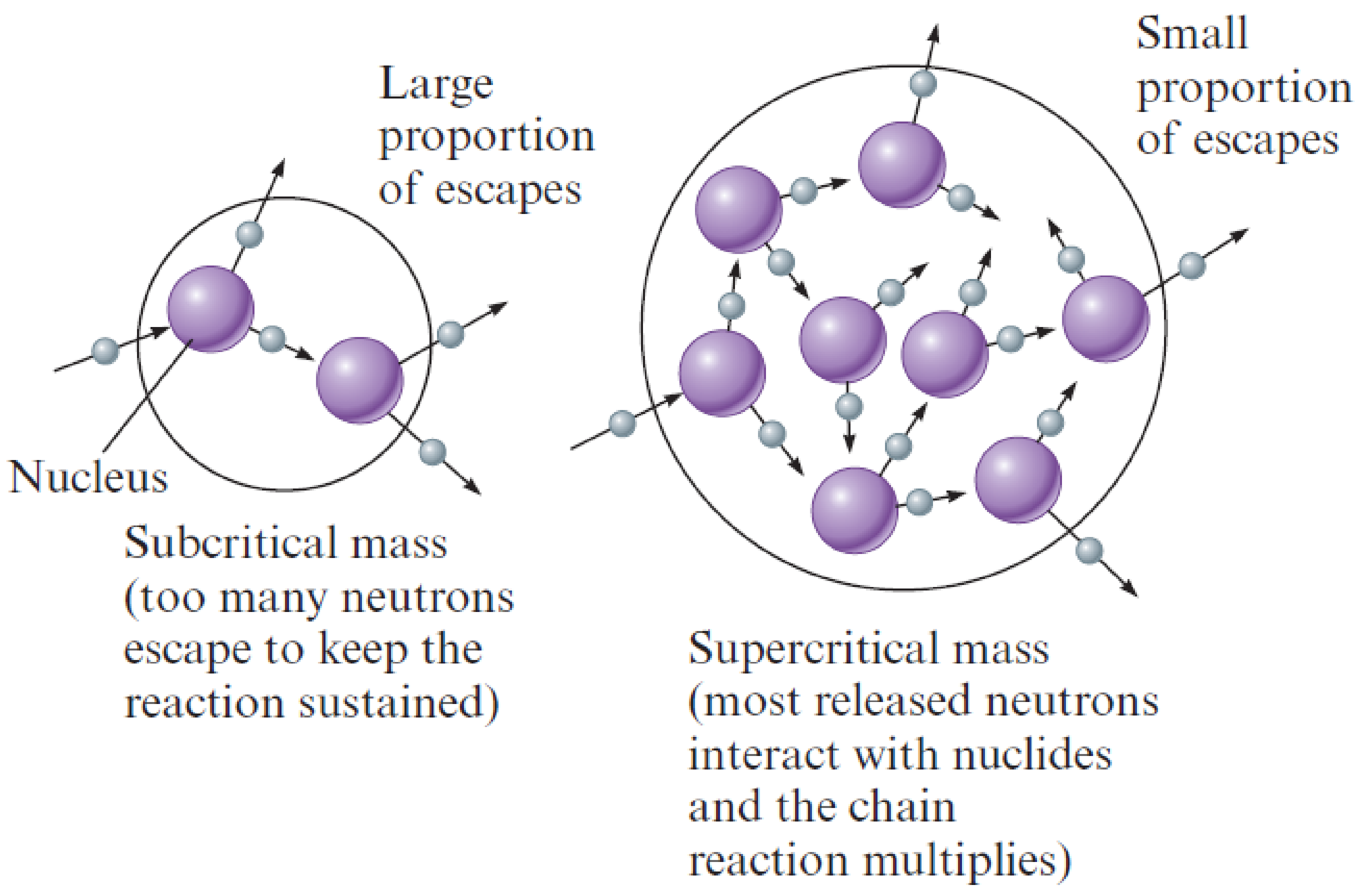
Chain-Reaction - Possible Outcomes (Continued)

- **Supercritical**: When more than one neutron from each event causes another fission event
  - Results
    - Process rapidly escalates
    - Heat buildup causes a violent explosion

Critical Mass

- Specific mass of a fissionable material that aids in achieving the critical state
- When a sample is too small, neutrons escape before they can cause a fission event
  - Process stops

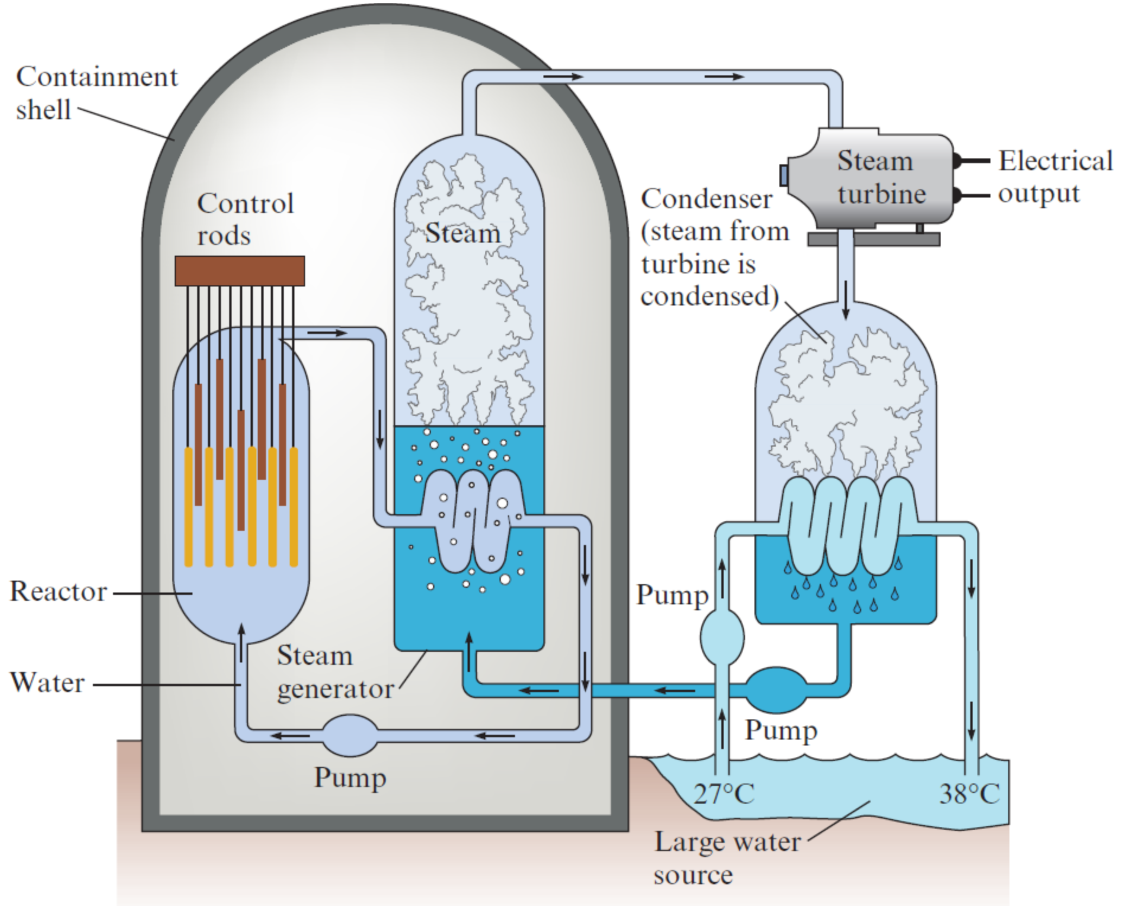
Figure 19.13 - Critical Mass



Nuclear Reactors

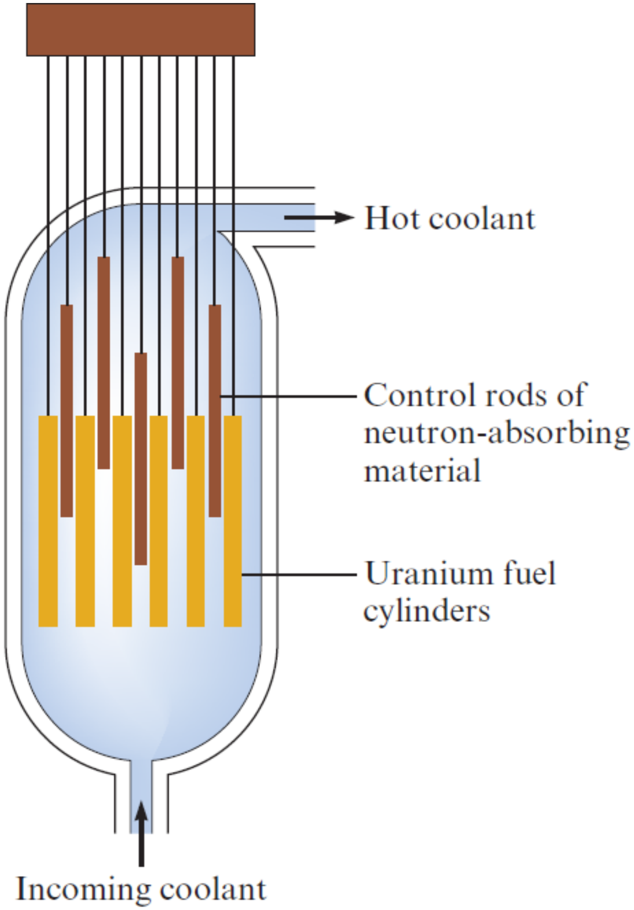
- Devices used to conduct controlled fission reactions
  - The resulting energy is used to heat water to produce steam to run turbine generators
- Used for the production of electricity

Figure 19.14 - Schematic Diagram of a Nuclear Power Plant



Reactor Core

- Houses uranium-235, enriched to approximately 3%, in cylinders
- **Moderator**: Device that surrounds the cylinders and slows down neutrons
  - Enables uranium fuel to capture the neutrons efficiently



Control Rods

- Regulate the power level of the reactor
- Composed of substances that absorb neutrons
- Help control malfunction in any fission event
  - Rods are inserted into the core to stop the reaction

Breeder Reactor

- Device that produces fissionable fuel while the reactor runs
- Reaction involves absorption of a neutron and production of two β particles

$$^{1}_{0}\text{n} + {}^{238}_{92}\text{U} \rightarrow {}^{239}_{92}\text{U}$$

$$^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e}$$

$$^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$$

Breeder Reactor (Continued)

- Reaction process
  - As the reactor runs, uranium-235 is split
  - Excess neutrons are absorbed by uranium-238 to produce plutonium-239
  - Plutonium-239 is separated out and used as fuel for another reactor
    - The reaction breeds nuclear fuel as it operates
- Disadvantage - Hazards in handling plutonium

Fusion Reactions

- Capable of producing tremendous amounts of energy
- The sun produces large quantities of energy from the fusion of protons to form helium

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e} $$

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} $$

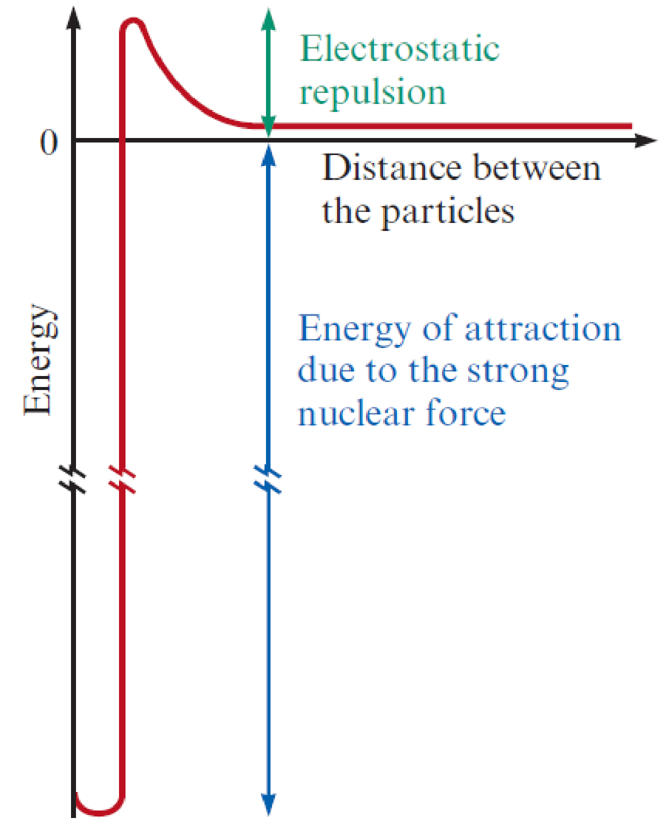
$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{1}\mathrm{e} $$

Stumbling Blocks with Fusion Energy Production

- High temperature is required to initiate fusion
- Protons should be closely bound together to release energy
  - Protons are identically charged and they repel each other electrostatically
    - They must be shot at each other at a speed that can overcome the repulsion

Plot of Energy versus Separation Distance

- Hydrogen-2 nuclei must have sufficient velocities to get over the electrostatic repulsion hill
  - Should be close for the nuclear binding forces to effectively fuse the particles into a new nucleus
    - Large quantities of energy will be released



Critical Thinking

- Nuclear fission processes can provide a lot of energy, but they also can be dangerous
  - What if Congress decided to outlaw all processes that involve fission?
    - How would that change our society?

Effects of Radiation - Classification

- **Somatic damage**: Occurs to the organism itself
  - Results in sickness or death
  - Effects appear immediately if high doses of radiation are received
- **Genetic damage**: Occurs to the genetic machinery of an organism
  - Causes malfunction in the organism's offspring

Biological Effects of a Source of Radiation

- Depend on:
  - Energy of the radiation
  - Penetrating ability of the radiation
  - Ionizing ability of the radiation
  - Chemical properties of the radiation source

rem (Roentgen Equivalent for Man)

- Accounts for the energy of the dose of the radiation and its effectiveness in causing biological damage

$$\text{Number of rems} = (\text{number of rads}) \times \text{RBE}$$

  - RBE - Relative effectiveness of the radiation in causing biological damage

Table 19.6 - Effects of Short-Term Exposures to Radiation

Dose (rem)	Clinical Effect
0–25	Nondetectable
25–50	Temporary decrease in white blood cell counts
100–200	Strong decrease in white blood cell counts
500	Death of half the exposed population within 30 days after exposure

Radiation Hazards

- Nuclear power plants pose a serious potential for radiation hazards that can be caused due to:
  - Accidents that permit the release of radioactive materials
  - Improper disposal of radioactive products

Models for Radiation Damage

- Linear model
  - Damage from radiation is proportional to the dose, even at low exposure levels
    - Any exposure is dangerous
- Threshold model
  - No significant damage occurs below the level of threshold exposure

Figure 19.17 - The Two Models for Radiation Damage