Chapter 22: Atomic and Nuclear Physics

The Structure of Matter and Nuclear Processes

Mr. Gullo

NANMO Physics 12

Winter 2025

Outline

Learning Objectives: 22.1

By the end of this section, you will be able to:

- Describe Rutherford's experiment and his model of the atom

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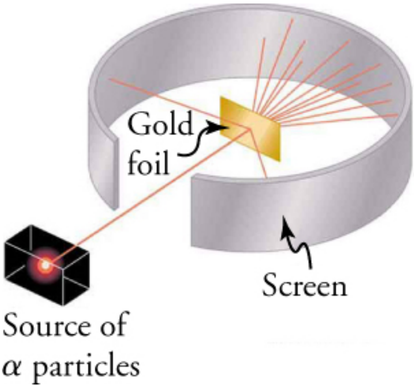
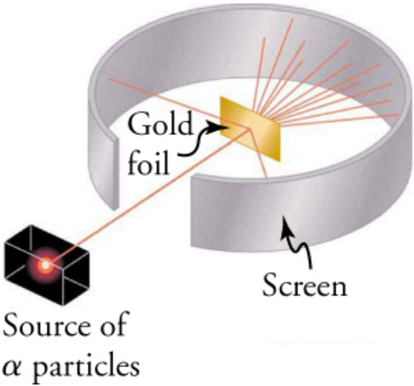
- Calculate the frequency and wavelength of emitted photons
- Describe the quantum model of the atom

22.1 Rutherford's Gold Foil Experiment



The Setup (1909):

- Radioactive source shoots alpha particles
- Thin gold foil target
- Phosphorescent screen detects scattered particles



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Expected: Slight deflection (plum pudding model)

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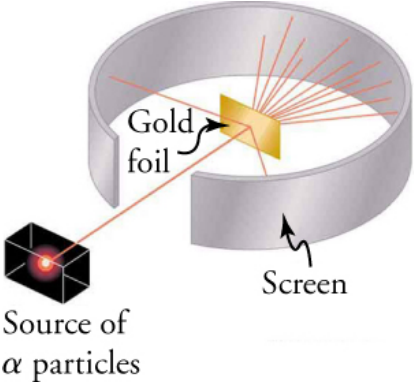


The Setup (1909):

- Radioactive source shoots alpha particles
- Thin gold foil target
- Phosphorescent screen detects scattered particles

Expected: Slight deflection (plum pudding model)
Observed: Some particles bounced straight back!

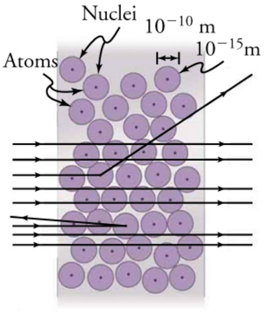
Rutherford's Revolutionary Conclusion

The atom has a tiny, dense nucleus
surrounded by mostly empty space

22.1 The Nuclear Atom

Rutherford's Revolutionary Conclusion

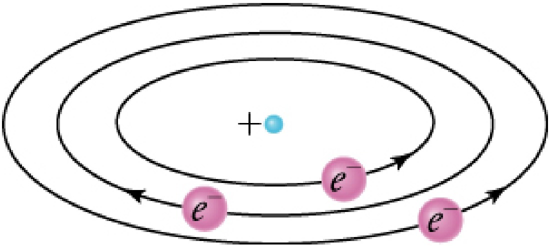
The atom has a tiny, dense nucleus
surrounded by mostly empty space



Key Facts:

- Nucleus: $\sim 10^{-15}$ m
- Atom: $\sim 10^{-10}$ m
- Nucleus is 100,000 times smaller!
- Density: 10^{15} g/cm^3

22.1 The Planetary Model



The Analogy

Low-mass electrons orbit massive nucleus
like planets orbit the Sun

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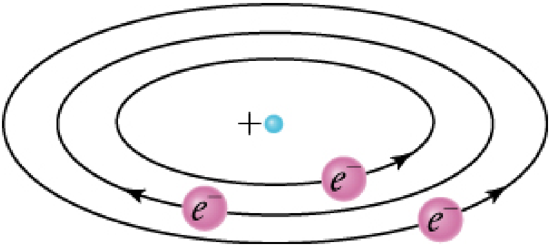

The Analogy

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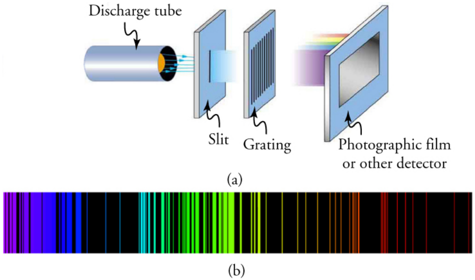
The Problem

Classical physics predicts orbiting electrons should radiate energy and spiral into the nucleus in 10^{-10} seconds!

22.1 Emission and Absorption Spectra



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- Heat a gas
- It emits discrete wavelengths
- Not continuous spectrum!

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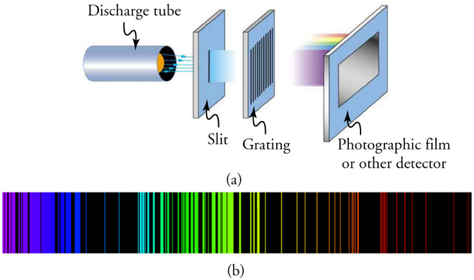

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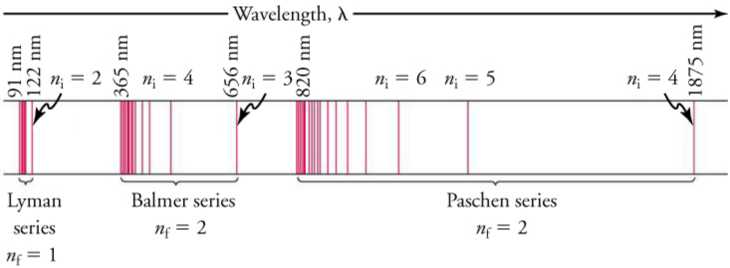
Each Element Has a Unique Spectral Fingerprint

Iron, hydrogen, helium - all produce different line patterns

22.1 The Hydrogen Spectrum



Three Series:

- **Lyman series:** Ultraviolet (electrons drop to $n = 1$)
- **Balmer series:** Visible light (electrons drop to $n = 2$)
- **Paschen series:** Infrared (electrons drop to $n = 3$)

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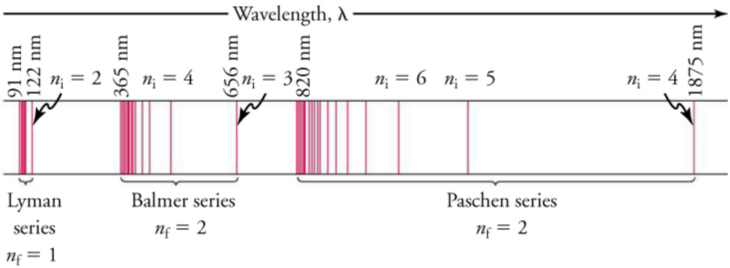

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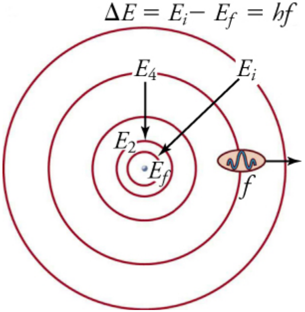
The Pattern

The wavelengths follow precise mathematical relationships.
But why?

22.1 Bohr's Quantum Atom (1913)



Bohr's Radical Ideas

1. Only certain orbits allowed (quantized!)
2. Electrons don't radiate while in orbit
3. Energy emitted/absorbed when electron jumps

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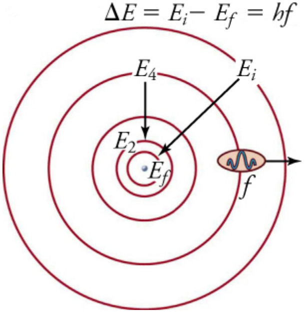

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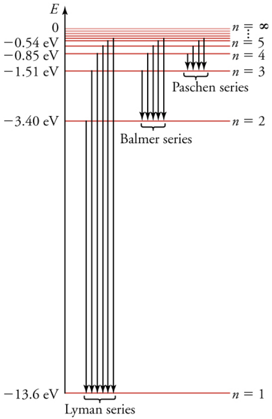
Energy Levels for Hydrogen

$$E_n = -\frac{13.6\text{ eV}}{n^2} \quad (n = 1, 2, 3, \ldots)$$

22.1 Energy Level Diagram



Reading the Diagram

- Arrow down: photon emitted
- Arrow up: photon absorbed
- Longer arrow: higher energy photon

Attempt: Electron Energy Transition

Try this on your own (3 min, silent):
A hydrogen atom absorbs a photon. The electron jumps from the ground state ($n = 1$) to the third energy level ($n = 3$).
Given:

- Initial state: $n_i = 1$
- Final state: $n_f = 3$
- $E_n = -\frac{13.6\text{ eV}}{n^2}$

Find: How much energy must the photon have?

Work individually. Show your GUESS steps.

Compare: Energy Transition Approach

Turn and talk (2 min):

1. What equation did you use first?
2. Did you get a positive or negative result?
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Name wheel: One pair share your approach (not your answer).

Reveal: Solution

Self-correct in a different color:

U - Unknown: $\Delta E = ?$

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$$E_n = -\frac{13.6\ \text{eV}}{n^2}, \quad \Delta E = E_f - E_i$$

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$$E_i = -\frac{13.6}{1^2} = -13.6 \text{ eV}$$

$$E_f = -\frac{13.6}{3^2} = -1.51 \text{ eV}$$

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$$\boxed{\Delta E = 12.1 \text{ eV}}$$

Check: Positive means absorption. Photon must provide energy!

Energy-Frequency Relationship

$$E = hf = \frac{hc}{\lambda}$$

22.1 Photon Energy and Wavelength

Energy-Frequency Relationship

$$E = hf = \frac{hc}{\lambda}$$

Where:

- $h = 6.626 \times 10^{-34}$ J·s (Planck's constant)
- $c = 3.00 \times 10^{8}$ m/s (speed of light)
- f = frequency (Hz)
- λ = wavelength (m)

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The Connection

Higher energy transition $\rightarrow$ shorter wavelength photon

22.1 The Rydberg Formula

Wavelength of Emitted Light

$$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right)$$

Where:

- $R = 1.097 \times 10^7\ \text{m}^{-1}$ (Rydberg constant)
- n_i = initial quantum number (higher)
- n_f = final quantum number (lower)

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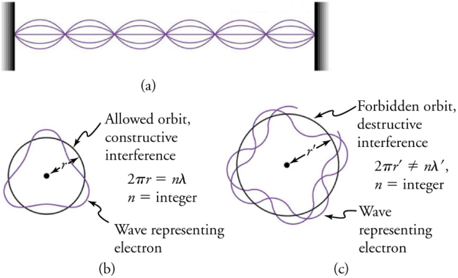
Historical Note

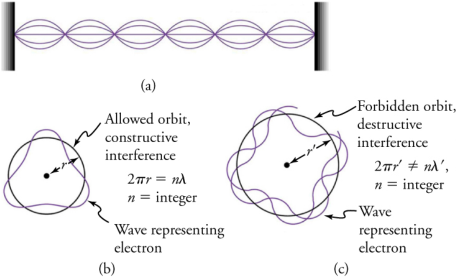
Rydberg discovered this formula empirically in 1888.
Bohr explained why it works in 1913!

22.1 De Broglie's Matter Waves



De Broglie (1924)

If light can be particles,
can particles be waves?



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Yes!

$$\lambda = \frac{h}{p}$$

Only certain wavelengths fit in orbit $\rightarrow$ quantization!

The Fundamental Limit

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

22.1 Heisenberg Uncertainty Principle

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You cannot simultaneously know exact position AND exact momentum. This is not a measurement problem - it's reality!

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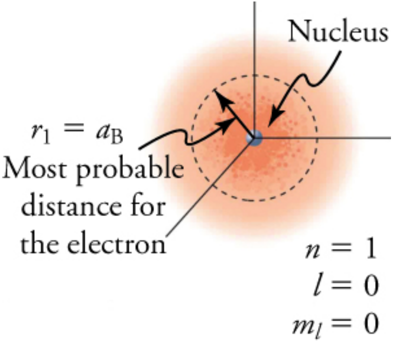
Implication for Atoms

Electrons don't have well-defined orbits.
They exist as probability clouds.

22.1 The Quantum Model



Electron Cloud

- Each dot: one position measurement
- Darker region: higher probability
- No defined orbit - only probability distribution

Learning Objectives: 22.2

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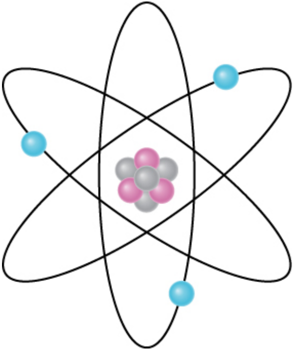
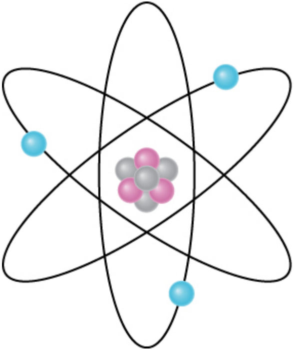
- Describe the structure and forces present within the nucleus
- Explain the three types of radiation
- Write nuclear equations associated with radioactive decay



Nucleons:

- Protons: $+1e$ charge
- Neutrons: neutral
- Mass ≈ 1 u (atomic mass unit)



Nucleons:

- Protons: $+1e$ charge
- Neutrons: neutral
- Mass $\approx$ 1 u (atomic mass unit)

Notation:

$$^{A}_{Z}X_{N}$$

- Z = atomic number (protons)
- A = mass number (protons + neutrons)
- $N = A - Z$ (neutrons)

22.2 Isotopes

Same Element, Different Neutrons

Isotopes have same Z (same element) but different A

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Hydrogen Isotopes:

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- ^{3}H: 1 proton, 2 neutrons (tritium - radioactive)

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- ^{3}H: 1 proton, 2 neutrons (tritium - radioactive)

Chemistry vs. Physics

Chemistry: Isotopes behave nearly identically (same electrons)
Physics: Isotopes have very different nuclear stability

The Problem

Protons repel via Coulomb force.
Why doesn't nucleus explode?

22.2 The Strong Nuclear Force

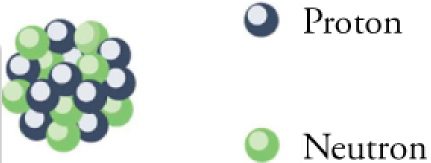
The Problem

Protons repel via Coulomb force.
Why doesn't nucleus explode?

The Solution

Strong nuclear force:

- Attractive between nucleons
- Much stronger than EM force
- Very short range ($\sim 10^{-15}$ m)



22.2 Discovery of Radioactivity (1896)

Becquerel's Accident

- Uranium ore placed on wrapped photographic plate
- Plate darkened - even in complete darkness!
- Uranium emitting invisible, penetrating rays

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The Resolution

Einstein's $E = mc^2$ explains it:
Mass converts to energy in nuclear reactions

22.2 Three Types of Nuclear Radiation

Alpha (α) Radiation

2 protons + 2 neutrons (helium nucleus)

Charge: +2e, Penetration: cm in air, stopped by paper

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Electron (or positron) from nucleus

Charge: −e (or +e), Penetration: m in air, stopped by aluminum

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Alpha (α) Radiation

2 protons + 2 neutrons (helium nucleus)
Charge: +2e, Penetration: cm in air, stopped by paper

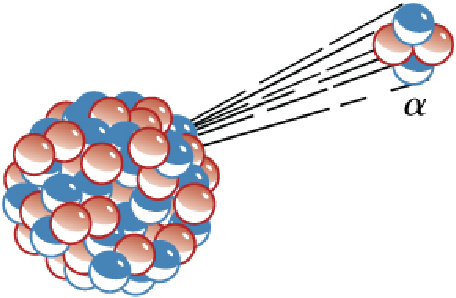
Beta (β) Radiation

Electron (or positron) from nucleus
Charge: −e (or +e), Penetration: m in air, stopped by aluminum

Gamma (γ) Radiation

High-energy photon
Charge: 0, Penetration: km in air, reduced by lead

22.2 Alpha Decay



Nuclear Equation

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}Y_{N-2} + {}^{4}_{2}He_{2} $$

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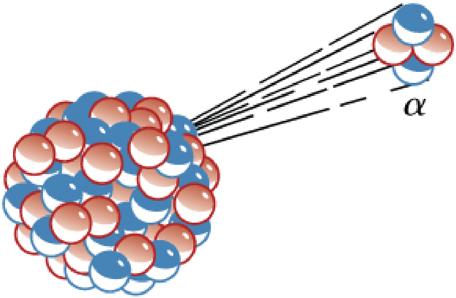
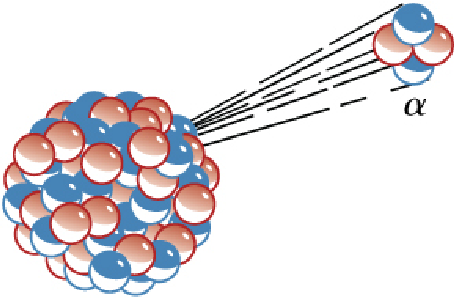


Nuclear Equation

$$^{A}_{Z}X_{N} \rightarrow ^{A-4}_{Z-2}Y_{N-2} + ^{4}_{2}He_{2}$$

Example: Uranium-238

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



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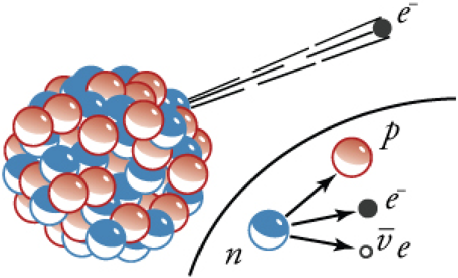
Conservation:

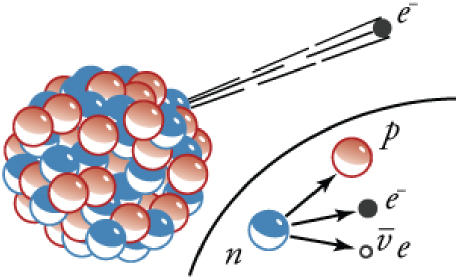
- Mass number: $238 = 234 + 4$ ✓
- Charge: $92 = 90 + 2$ ✓



β^- Decay (most common)

Neutron $\rightarrow$ proton $+$ electron $+$ antineutrino

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-} + \bar{\nu}_e$$



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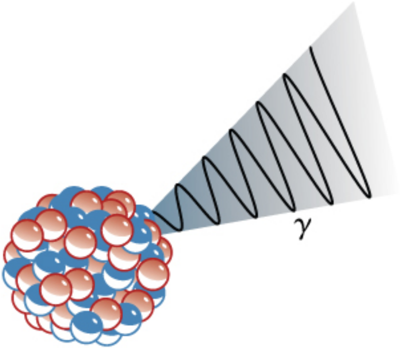
Example: Carbon-14

$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^- + \bar{\nu}_e$$

22.2 Gamma Decay

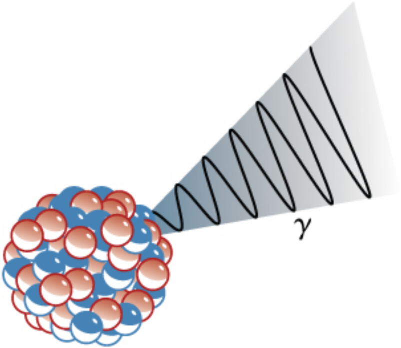


Excited Nucleus

Nucleus drops from excited state to ground state

$$^A_Z X^* \rightarrow ^A_Z X + \gamma$$

22.2 Gamma Decay



Excited Nucleus

Nucleus drops from excited state to ground state

$$^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + \gamma$$

Key Points:

- A and Z unchanged
- Pure energy release
- Often follows α or β decay
- MeV energies (vs. eV for atoms)

Attempt: Write Nuclear Equation

Try this on your own (3 min, silent):

Plutonium-239 undergoes alpha decay.

Given:

- Parent nucleus: $^{239}_{94}Pu$
- Type: alpha decay
- Periodic table for atomic numbers

Find:

1. Complete nuclear equation
2. Identity of daughter nucleus

Remember to conserve mass number and charge!

Turn and talk (2 min):

1. What did you subtract from A and Z?
2. How did you identify the daughter element?
3. Did you check conservation?

Compare: Nuclear Equation Strategy

Turn and talk (2 min):

1. What did you subtract from A and Z?
2. How did you identify the daughter element?
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Name wheel: One pair share their method.

Reveal: Alpha Decay Solution

Self-correct in a different color:
General form:

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2} Y + ^{4}_{2} He$$

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Apply to Pu-239:

$$A_{daughter} = 239 - 4 = 235$$

$$Z_{daughter} = 94 - 2 = 92$$

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Identify element: $Z = 92$ is Uranium (U)

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Identify element: $Z = 92$ is Uranium (U)

$$\boxed{^{239}_{94}Pu \rightarrow ^{235}_{92}U + ^{4}_{2}He}$$

Check: $239 = 235 + 4 \checkmark, \quad 94 = 92 + 2 \checkmark$

Learning Objectives: 22.3

By the end of this section, you will be able to:

- Explain radioactive half-life and its role in radiometric dating

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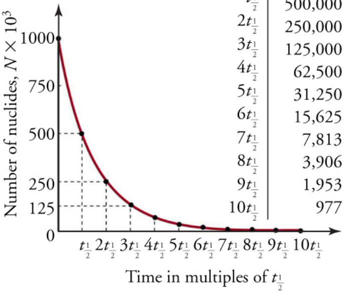
- Explain radioactive half-life and its role in radiometric dating
- Calculate radioactive half-life and solve problems associated with radiometric dating

Time	N
0	1,000,000
$t_{\frac{1}{2}}$	500,000
$2t_{\frac{1}{2}}$	250,000
$3t_{\frac{1}{2}}$	125,000
$4t_{\frac{1}{2}}$	62,500
$5t_{\frac{1}{2}}$	31,250
$6t_{\frac{1}{2}}$	15,625
$7t_{\frac{1}{2}}$	7,813
$8t_{\frac{1}{2}}$	3,906
$9t_{\frac{1}{2}}$	1,953
$10t_{\frac{1}{2}}$	977



Definition

Half-life ($t_{1/2}$): Time for half the nuclei to decay

22.3 What is Half-Life?

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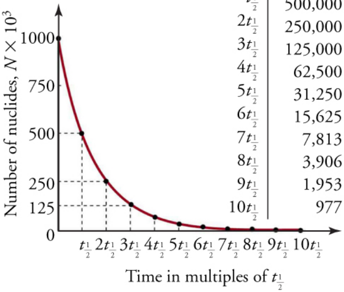

Definition

Half-life ($t_{1/2}$): Time for half the nuclei to decay

- After $t_{1/2}$: $N \rightarrow N/2$
- After $2t_{1/2}$: $N \rightarrow N/4$
- After $3t_{1/2}$: $N \rightarrow N/8$

22.3 Exponential Decay Law

Number of Nuclei vs. Time

$$N(t) = N_0 e^{-\lambda t}$$

Where:

- N_0 = initial number of nuclei
- $N(t)$ = number remaining at time t
- λ = decay constant
- $e = 2.71828\ldots$

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Relationship to Half-Life

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

22.3 Activity (Rate of Decay)

Definition

Activity R**:** Number of decays per unit time

$$R = \frac{\Delta N}{\Delta t} = \lambda N$$

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Units:

- Becquerel (Bq): 1 decay/second (SI unit)
- Curie (Ci): 3.7×10^{10} decays/second (traditional)

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Physical Meaning

More radioactive material $\rightarrow$ higher activity

As sample decays $\rightarrow$ activity decreases

22.3 Carbon-14 Dating

The Method

1. Cosmic rays create ^{14}C in atmosphere
2. Living organisms maintain constant ^{14}C ratio
3. After death: no new ^{14}C absorbed
4. ^{14}C decays with $t_{1/2} = 5,730$ years
5. Measure remaining ^{14}C to find age

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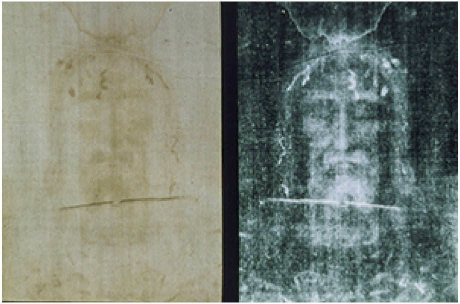
Range

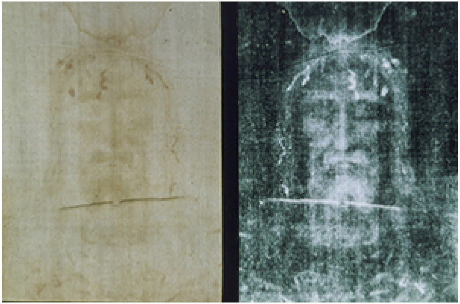
Effective for ages: 100 to 50,000 years
(about 10 half-lives maximum)

22.3 Case Study: Shroud of Turin



The Claim: Burial shroud of Jesus (33 CE)

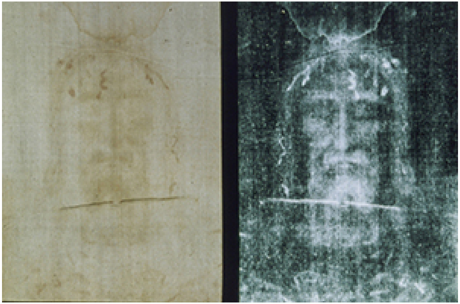
22.3 Case Study: Shroud of Turin



The Claim: Burial shroud of Jesus (33 CE)

The Test (1988):

- Three independent labs
- Found 92% of living ^{14}C
- Calculate age...



The Claim: Burial shroud of Jesus (33 CE)

The Test (1988):

- Three independent labs
- Found 92% of living ^{14}C
- Calculate age...

The Result: Dated to 1320 ± 60 CE
Medieval, not ancient!

Attempt: Half-Life Calculation

Try this on your own (3 min, silent):
A radioactive sample has a half-life of 10 days. You start with 80 g of material.

Given:

- $N_0 = 80$ g
- $t_{1/2} = 10$ days
- Time elapsed: $t = 30$ days

Find: How much material remains after 30 days?

Think: How many half-lives have passed?

Compare: Half-Life Strategy

Turn and talk (2 min):

1. How many half-lives occurred?
2. Did you use repeated halving or a formula?
3. What's your final answer?

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Name wheel: Share your approach.

Reveal: Half-Life Solution

Self-correct in a different color:
Method 1 - Counting Half-Lives:
Number of half-lives: $n = \frac{t}{t_{1/2}} = \frac{30}{10} = 3$

Reveal: Half-Life Solution

Self-correct in a different color:
Method 1 - Counting Half-Lives:
Number of half-lives: $n = \frac{t}{t_{1/2}} = \frac{30}{10} = 3$
After each half-life:

- $t = 10$ days: $80\nabla \cdot 2 = 40$ g
- $t = 20$ days: $40\nabla \cdot 2 = 20$ g
- $t = 30$ days: $20\nabla \cdot 2 = 10$ g

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Method 2 - Formula:

$$N = N_0 \left(\frac{1}{2}\right)^n = 80 \left(\frac{1}{2}\right)^3 = 80 \times \frac{1}{8} = 10 \text{ g}$$

Reveal: Half-Life Solution

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$$\boxed{N = 10 \text{ g}}$$

22.3 Other Radiometric Dating

Uranium-Lead Dating

$^{238}\text{U} \rightarrow {}^{206}\text{Pb}, \quad t_{1/2} = 4.5 \times 10^9$ years

Used for ancient rocks (oldest Earth rocks: 3.5 billion years)

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Used for volcanic rocks, human fossils

The Power

Different isotopes cover different time scales:
Years, millennia, millions of years, billions of years

Learning Objectives: 22.4

By the end of this section, you will be able to:

- Explain nuclear fission

Learning Objectives: 22.4

By the end of this section, you will be able to:

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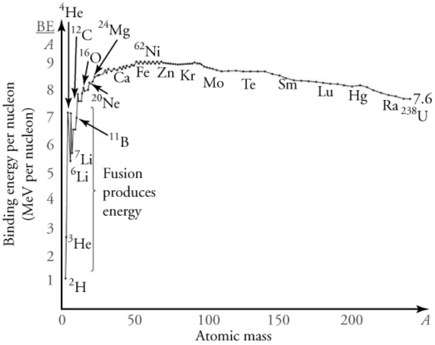
- Explain nuclear fusion

Learning Objectives: 22.4

By the end of this section, you will be able to:

- Explain nuclear fission
- Explain nuclear fusion
- Describe how fission and fusion work in weapons and power generation

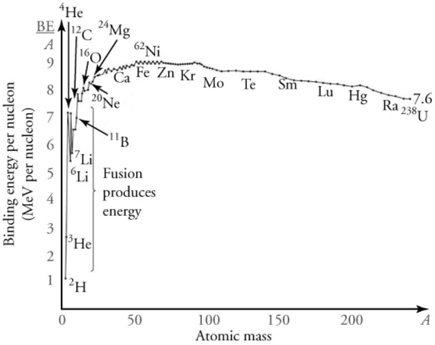
22.4 Nuclear Binding Energy



The Key Insight

Iron-56 has highest binding energy per nucleon
$\rightarrow$ Most stable nucleus

22.4 Nuclear Binding Energy



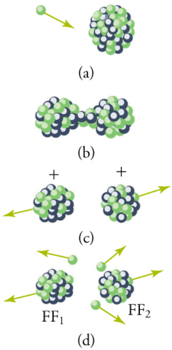
The Key Insight

Iron-56 has highest binding energy per nucleon

$\rightarrow$ Most stable nucleus

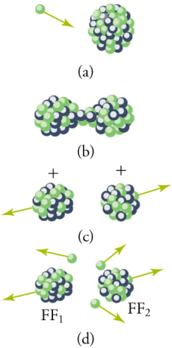
- Heavy nuclei (right of Fe): release energy by **fission**
- Light nuclei (left of Fe): release energy by **fusion**

22.4 Nuclear Fission



The Process

1. Neutron strikes heavy nucleus
2. Nucleus elongates
3. EM repulsion overcomes strong force
4. Nucleus splits
5. Releases energy + more neutrons



Typical energy: 200 MeV per fission (vs. 1 eV per chemical reaction)

The Process

1. Neutron strikes heavy nucleus
2. Nucleus elongates
3. EM repulsion overcomes strong force
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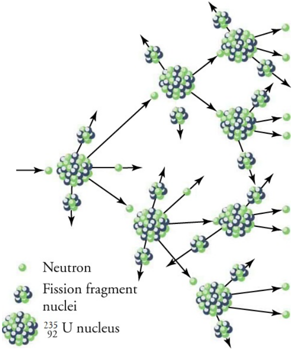
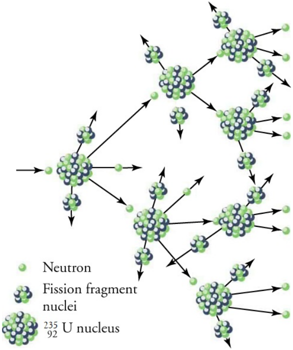


Self-Sustaining Fission

Each fission releases 2-3 neutrons
→ Those neutrons cause more fissions
→ Exponential growth

22.4 Chain Reaction



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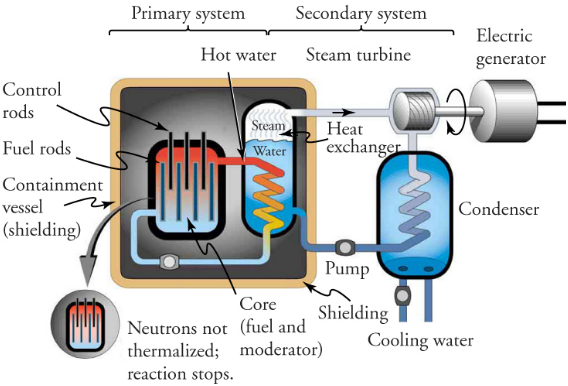
Critical Mass



Key Components:

- Fuel rods: enriched ^{235}U
- Moderator: water (slows neutrons)
- Control rods: absorb excess neutrons
- Heat exchanger: produces steam → turbine → electricity

22.4 Mass-Energy Conversion

Einstein's Equation

$$E = mc^2$$

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Einstein's Equation

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In fission:

- Products have less mass than reactants
- Missing mass $\rightarrow$ converted to energy
- $\Delta m \approx 0.1\%$ of original mass
- Still liberates enormous energy

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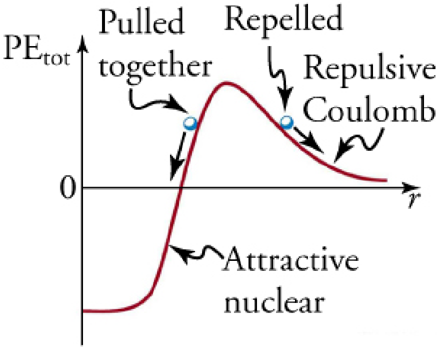
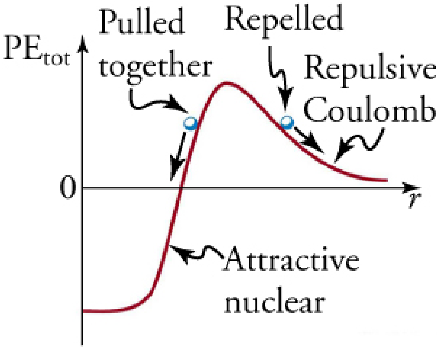
Example

1 kg of ^{235}U fully fissioned:
$E = 8.2 \times 10^{13}$ J $\approx$ 14,000 barrels of oil!



The Process

Combine light nuclei
→ Overcome Coulomb repulsion
→ Strong force binds them
→ Release energy



The Process

Combine light nuclei
→ Overcome Coulomb repulsion
→ Strong force binds them
→ Release energy

Requirements:

- Extreme temperature ($\sim 10^7$ K)
- Extreme pressure
- → Found in star cores!

How the Sun Fuses Hydrogen

$$
\begin{aligned}
{}^{1}\mathrm{H} + {}^{1}\mathrm{H} &\rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e \quad (0.42\ \mathrm{MeV}) \\
{}^{1}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \gamma \quad (5.49\ \mathrm{MeV}) \\
{}^{3}\mathrm{He} + {}^{3}\mathrm{He} &\rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \quad (12.86\ \mathrm{MeV})
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22.4 The Proton-Proton Cycle

How the Sun Fuses Hydrogen

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Net result:

$$4\,^1\text{H} \rightarrow\ ^4\text{He} + 2e^+ + 2\nu_e + 6\gamma \quad (26.7\ \text{MeV})$$

22.4 The Proton-Proton Cycle

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Net result:

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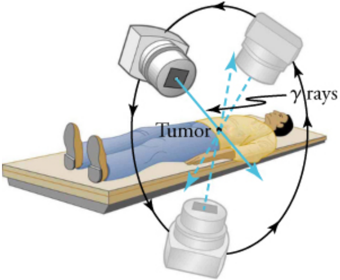
The Wonder

This energy took 32,000 years to reach Sun's surface
Then 8 minutes to reach Earth!

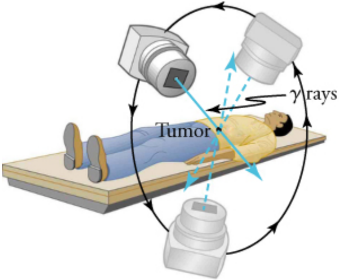
22.4 Fusion Energy Potential



The Promise

- Fuel: deuterium from seawater (virtually unlimited)
- No chain reaction $\rightarrow$ inherently safe
- No long-lived radioactive waste
- 4x more energy per kg than fission

22.4 Fusion Energy Potential



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- No chain reaction $\rightarrow$ inherently safe
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- 4x more energy per kg than fission

The Challenge

22.4 Fission vs. Fusion Summary

Fission	Fusion
Split heavy nuclei	**Combine** light nuclei
Fuel: ^{235}U, ^{239}Pu (rare)	**Fuel:** H isotopes (abundant)
Products: Radioactive waste	**Products:** Helium (inert)
Status: Mature technology	**Status:** Experimental
Use: Power plants, weapons	**Use:** Stars, H-bombs, (future power?)

Summary: Chapter 22 (Sections 1-4)

22.1 Atomic Structure

Rutherford → Bohr → Quantum model
Discrete energy levels explain emission spectra

22.2 Nuclear Forces and Radioactivity

Strong force holds nucleus together
Alpha, beta, gamma decay restore stability

22.3 Half-Life

Exponential decay enables radiometric dating
Carbon-14, U-238 date different timescales

22.4 Fission and Fusion

Binding energy curve: both release enormous energy
Fission mature, fusion promising

Key Equations: Chapter 22

Atomic Structure

$$E_n = -\frac{13.6\ \text{eV}}{n^2}, \quad \Delta E = E_f - E_i, \quad E = hf = \frac{hc}{\lambda}$$

$$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right), \quad \Delta x \Delta p \geq \frac{h}{4\pi}$$

Nuclear Physics

$$E = mc^2$$

Radioactive Decay

$$N(t) = N_0 e^{-\lambda t}, \quad \lambda = \frac{0.693}{t_{1/2}}, \quad R = \lambda N$$

Nuclear Notation

$${}^{A}_{Z}X_N \quad (A = Z + N)$$

Complete the assigned problems

posted on the LMS