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Raipur, Chhattisgarh

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Class 12 Physics - Chapter 13: NUCLEI



NUCLEI

Chapter Overview

This chapter explores the heart of the atom - the nucleus. The nucleus contains more than 99.9% of an atom's mass in a region about 10^4 times smaller than the atom itself!

- Atomic masses and nuclear composition
- Discovery of neutron by James Chadwick (1932)
- Nuclear size and density
- Mass-energy equivalence ($E = mc^2$)
- Nuclear binding energy and stability
- Properties of nuclear force
- Radioactivity (α , β , γ decay)
- Nuclear fission and fusion

1. INTRODUCTION

Scale of the Nucleus

Remarkable Size Comparison:

- **Radius ratio:** Nuclear radius is about 10^4 times smaller than atomic radius
- **Volume ratio:** Nuclear volume is about 10^{-12} times atomic volume
- **Mass concentration:** More than 99.9% of atom's mass is in the nucleus

Visualization: If an atom is enlarged to the size of a classroom, the nucleus would be about the size of a pinhead at the center!

Historical Discoveries

Key Milestones in Nuclear Physics:

- **1897:** J.J. Thomson discovered the electron
- **1911:** Ernest Rutherford established the existence of atomic nucleus
- **1913:** R.A. Millikan measured elementary charge precisely ($e = 1.602 \times 10^{-19}$ C)
- **1932:** James Chadwick discovered the neutron
- **1896:** Henri Becquerel discovered radioactivity



2. ATOMIC MASSES AND COMPOSITION OF NUCLEUS

ATOMIC MASS UNIT (u)

$$1 \text{ u} = (1/12) \times \text{mass of one } ^{12}\text{C atom}$$

$$1 \text{ u} = 1.660539 \times 10^{-27} \text{ kg}$$

$$1 \text{ u} = 931.5 \text{ MeV}/c^2$$

Key Terms and Notation

Nuclide Notation: ${}^A_Z\text{X}$

- **X:** Chemical symbol of element
- **Z:** Atomic number = Number of protons = Number of electrons (in neutral atom)
- **A:** Mass number = Total number of nucleons (protons + neutrons)
- **N:** Neutron number = $A - Z$

$$\mathbf{A = Z + N}$$

(Mass number = Protons + Neutrons)

Example: Gold nucleus ${}^{197}_{79}\text{Au}$ contains 197 nucleons, of which 79 are protons and 118 are neutrons.

💡 Important Nuclear Particles

Particle	Symbol	Mass (u)	Mass (kg)	Charge
Proton	p or ${}^1_1\text{H}$	1.00727 u	1.67262×10^{-27} kg	+e
Neutron	n or ${}^1_0\text{n}$	1.00866 u	1.67490×10^{-27} kg	0 (neutral)
Electron	e^-	0.00055 u	9.109×10^{-31} kg	-e

Note: Elementary charge $e = 1.602 \times 10^{-19}$ C

Discovery of the Neutron (1932)


James Chadwick's Breakthrough:

The Problem:

- Deuterium (${}^2_1\text{H}$) and Tritium (${}^3_1\text{H}$) are hydrogen isotopes with only 1 proton each
- But their masses are in ratio 1:2:3 (not 1:1:1)
- This suggested presence of neutral matter in addition to protons

The Experiment:

- Bombarded beryllium nuclei with α -particles (helium nuclei)
- Observed emission of neutral radiation that could knock out protons from light nuclei
- Applied conservation of energy and momentum to determine mass of new particle
- Found mass of neutron \approx mass of proton

 **Nobel Prize 1935:** James Chadwick was awarded the Nobel Prize in Physics for his discovery of the neutron.

Neutron Properties

Stability of Neutrons:

- **Free neutron:** Unstable - decays with mean life \approx 1000 s
- Decay: $n \rightarrow p + e^- + \bar{\nu}$ (proton + electron + antineutrino)
- **Bound neutron:** Stable inside the nucleus

Isotopes, Isobars, and Isotones

Term	Definition	Example
Isotopes	Same Z (same element), different N Same chemical properties	${}^1_1\text{H}$, ${}^2_1\text{H}$ (Deuterium), ${}^3_1\text{H}$ (Tritium)
Isobars	Same A (mass number), different Z	${}^3_1\text{H}$ and ${}^3_2\text{He}$
Isotones	Same N (neutron number), different Z	${}^{198}_{80}\text{Hg}$ and ${}^{197}_{79}\text{Au}$ (both have 118 neutrons)

Weighted Average Atomic Mass

Problem: Chlorine has two isotopes with masses 34.98 u (75.4% abundance) and 36.98 u (24.6% abundance). Calculate the average atomic mass.

Solution:

$$\text{Average mass} = (\text{abundance}_1 \times \text{mass}_1 + \text{abundance}_2 \times \text{mass}_2)/100$$

$$= (75.4 \times 34.98 + 24.6 \times 36.98)/100$$

$$= (2637.49 + 909.71)/100$$

$$= \mathbf{35.47 \text{ u}}$$

This matches the observed atomic mass of chlorine!

3. SIZE OF THE NUCLEUS

Rutherford's Alpha Scattering

Key Findings:

- Distance of closest approach for 5.5 MeV α -particles to gold nucleus $\approx 4.0 \times 10^{-14}$ m
- This gave an upper limit for nuclear size
- Scattering explained by Coulomb repulsion alone
- At higher energies, deviations occur due to short-range nuclear forces

★ NUCLEAR RADIUS FORMULA ★

$$R = R_0 A^{1/3}$$

R = Nuclear radius

$$R_0 = 1.2 \times 10^{-15} \text{ m} = 1.2 \text{ fm (fermi)}$$

A = Mass number

$$1 \text{ fm} = 10^{-15} \text{ m (femtometer)}$$

▢ Important Consequences of $R \propto A^{1/3}$

Volume Proportionality:

$$\text{Nuclear volume } V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(R_0 A^{1/3})^3$$

$$V = \frac{4}{3}\pi R_0^3 A$$

Therefore: $V \propto A$

Volume is directly proportional to mass number!

Nuclear Density:

$$\text{Density } \rho = \text{Mass/Volume} = (A \times 1u) / [\frac{4}{3}\pi R_0^3 A]$$

$$\rho = 1u / [\frac{4}{3}\pi R_0^3]$$

Nuclear density $\approx 2.3 \times 10^{17} \text{ kg/m}^3$

🌟 **Amazing Fact:** Nuclear density is constant and independent of A for all nuclei!

💡 Understanding Nuclear Density

Comparison with ordinary matter:

- **Nuclear matter:** $\rho \approx 2.3 \times 10^{17} \text{ kg/m}^3$
- **Water:** $\rho = 10^3 \text{ kg/m}^3$
- **Ratio:** Nuclear matter is about 10^{14} times denser than water!

Neutron Stars: The density of matter in neutron stars is comparable to nuclear density. Matter in these objects has been compressed so much that they resemble a giant nucleus!

NCERT Example 13.1 - Nuclear Density

Problem: Given the mass of iron nucleus as 55.85 u and $A = 56$, find the nuclear density.

Solution:

Step 1: Convert mass to kg

$$m_{\text{Fe}} = 55.85 \text{ u} = 55.85 \times 1.66 \times 10^{-27} \text{ kg} = 9.27 \times 10^{-26} \text{ kg}$$

Step 2: Calculate nuclear volume

$$V = \left(\frac{4}{3}\right)\pi R^3 = \left(\frac{4}{3}\right)\pi(R_0 A^{1/3})^3$$

$$V = \left(\frac{4}{3}\right)\pi(1.2 \times 10^{-15})^3(56)$$

Step 3: Calculate density

$$\rho = m/V = (9.27 \times 10^{-26}) / \left[\left(\frac{4}{3}\right)\pi(1.2 \times 10^{-15})^3(56)\right]$$

$$\rho = 2.29 \times 10^{17} \text{ kg/m}^3$$

⚡ 4. MASS-ENERGY AND NUCLEAR BINDING ENERGY

🌟 Einstein's Mass-Energy Equivalence

Revolutionary Concept (1905):

Before Einstein's theory of special relativity, mass and energy were thought to be conserved separately. Einstein showed that mass is another form of energy.

★ EINSTEIN'S MASS-ENERGY RELATION ★

$$E = mc^2$$

E = Energy equivalent

m = Mass

c = Speed of light = 3×10^8 m/s

NCERT Example 13.2 - Energy Equivalent

Problem: Calculate the energy equivalent of 1 g of substance.

Solution:

$$E = mc^2 = (10^{-3} \text{ kg})(3 \times 10^8 \text{ m/s})^2$$

$$E = 10^{-3} \times 9 \times 10^{16} \text{ J}$$

$$E = 9 \times 10^{13} \text{ J}$$

*** Enormous Energy!** If 1 gram of matter is completely converted to energy, it releases 90 trillion joules!

💡 Useful Energy Conversion

$$1 \text{ u} = 931.5 \text{ MeV}/c^2$$

Derivation:

$$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}$$

$$\text{Energy} = mc^2 = (1.6605 \times 10^{-27})(2.9979 \times 10^8)^2$$

$$= 1.4924 \times 10^{-10} \text{ J}$$

$$= (1.4924 \times 10^{-10}) / (1.602 \times 10^{-19}) \text{ eV}$$

$$= 0.9315 \times 10^9 \text{ eV}$$

$$= \mathbf{931.5 \text{ MeV}}$$

Mass Defect and Binding Energy

Key Concept: Mass Defect (ΔM)

Observation: The mass of a nucleus is ALWAYS less than the sum of masses of its individual protons and neutrons!

Mass Defect:

$$\Delta M = [Zm_p + (A-Z)m_n] - M$$

Z = Number of protons

A-Z = Number of neutrons

M = Actual nuclear mass

Understanding Mass Defect with $^{16}_8\text{O}$

Expected mass calculation:

- Mass of 8 neutrons = $8 \times 1.00866 \text{ u} = 8.06928 \text{ u}$
- Mass of 8 protons = $8 \times 1.00727 \text{ u} = 8.05816 \text{ u}$
- Mass of 8 electrons = $8 \times 0.00055 \text{ u} = 0.00440 \text{ u}$
- **Expected total = 16.13184 u**

Experimental measurement:

- Atomic mass of $^{16}_8\text{O} = 15.99493 \text{ u}$
- Subtracting 8 electron masses: $15.99493 - 0.00440 = 15.99053 \text{ u}$
- **Actual nuclear mass = 15.99053 u**

Mass defect:

$$\Delta M = 16.13184 - 15.99053 = \mathbf{0.14131 \text{ u}}$$

? Where did this mass go? It was converted to binding energy that holds the nucleus together!

★ BINDING ENERGY ★

$$E_b = \Delta M c^2$$

E_b = Binding energy

(energy needed to separate nucleus into individual nucleons)

ΔM = Mass defect

c = Speed of light

💡 Physical Meaning of Binding Energy

Binding Energy (E_b): The energy required to completely separate a nucleus into its individual protons and neutrons.

OR equivalently: The energy released when nucleons come together to form a nucleus.

Binding Energy per Nucleon (E_{bn}):

$$E_{bn} = E_b/A$$

This is the average energy needed to remove one nucleon from the nucleus.

NCERT Example 13.3 - Mass Defect

Problem: Using $1 \text{ u} = 931.5 \text{ MeV}/c^2$, express the mass defect of $^{16}_8\text{O}$ in MeV/c^2 .

Solution:

Mass defect $\Delta M = 0.13691 \text{ u}$ (from NCERT)

In energy units: $\Delta M = 0.13691 \times 931.5 \text{ MeV}/c^2$

$$\Delta M = 127.5 \text{ MeV}/c^2$$

Therefore:

Binding energy $E_b = 127.5 \text{ MeV}$

Binding Energy per Nucleon Curve

Key Features of Binding Energy Curve

1. Middle Region ($30 < A < 170$):

- E_{bn} is practically constant ≈ 8 MeV/nucleon
- Maximum at $A = 56$ (Iron): $E_{bn} \approx 8.75$ MeV
- Most stable nuclei are in this region

2. Light Nuclei ($A < 30$):

- Lower E_{bn} (less stable)
- Can release energy by fusion (combining)
- Exception: ${}^4_2\text{He}$ has unusually high E_{bn}

3. Heavy Nuclei ($A > 170$):

- Lower E_{bn} (less stable)
- Can release energy by fission (splitting)
- For $A = 238$ (Uranium): $E_{bn} \approx 7.6$ MeV

💡 Energy Production - Key Insights

Process	Direction	Energy Release
Fission	Heavy nucleus ($A \approx 240$) \rightarrow Two medium nuclei ($A \approx 120$)	~ 200 MeV per fission
Fusion	Light nuclei ($A \leq 10$) \rightarrow Heavier nucleus	Several MeV per fusion

💪 5. NUCLEAR FORCE

🔑 Why Do We Need Nuclear Force?

The Problem:

- Nucleus contains positively charged protons in tiny volume
- Coulomb repulsion between protons is enormous
- Gravitational force is far too weak
- **Solution:** A new, extremely strong, short-range force - the NUCLEAR FORCE

Properties of Nuclear Force

- 1. Strength:** Much stronger than Coulomb or gravitational force
- 2. Range:** Very short (~few femtometers), falls rapidly to zero beyond 2-3 fm
- 3. Saturation:** Each nucleon interacts only with nearest neighbors
- 4. Charge Independence:** Force between p-p, n-n, and p-n is approximately same
- 5. Distance Dependence:**
 - $r > r_0$ (≈ 0.8 fm): Attractive
 - $r < r_0$ (≈ 0.8 fm): Strongly repulsive

6. RADIOACTIVITY

Discovery by Henri Becquerel (1896)

While studying fluorescence of uranium compounds, Becquerel observed spontaneous emission that could penetrate black paper and expose photographic plates.

Three Types of Radioactive Decay

Type	Particle Emitted	Nature	Penetrating Power
α-decay	Alpha particle (${}^4_2\text{He}$)	2 protons + 2 neutrons	Least - stopped by paper
β-decay	Beta particle (e^- or e^+)	High-speed electron/positron	Moderate - stopped by aluminum
γ-decay	Gamma ray (photon)	High-energy EM radiation	Most - requires thick lead

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⚡ 7. NUCLEAR ENERGY

★ 7.1 Nuclear Fission

NUCLEAR FISSION

Heavy nucleus splits into lighter nuclei with enormous energy release

🧪 Fission of Uranium-235



Key Features:

- 2-3 neutrons released per fission
- Fragment products are radioactive
- **Energy release: ~200 MeV per fission!**

Energy Released in Fission

Consider: $A = 240$ nucleus \rightarrow two $A = 120$ nuclei

From binding energy curve:

- E_{bn} for $A = 240$: ≈ 7.6 MeV/nucleon
- E_{bn} for $A = 120$: ≈ 8.5 MeV/nucleon

Gain per nucleon: $8.5 - 7.6 = 0.9$ MeV

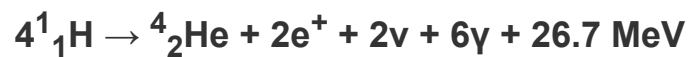
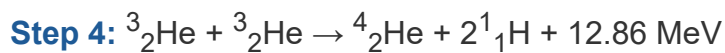
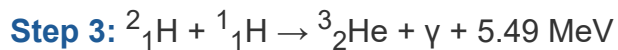
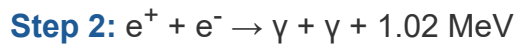
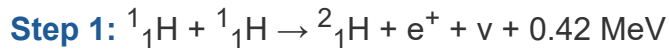
Total energy: $240 \times 0.9 = 216$ MeV ≈ 200 MeV

7.2 Nuclear Fusion

NUCLEAR FUSION

Light nuclei combine to form heavier nucleus with energy release

☀ Proton-Proton Cycle in the Sun



🔥 Conditions for Fusion

Challenge: Nuclei repel each other (Coulomb barrier)

For two protons to fuse:

Coulomb barrier $\approx 400 \text{ keV}$

Temperature required: $T \approx 3 \times 10^9 \text{ K!}$

Sun's Core: $T \approx 1.5 \times 10^7 \text{ K}$ - fusion occurs due to particles with above-average energies



8. KEY FORMULAE

⚡ FUNDAMENTAL CONSTANTS

Constant	Value
1 u	$1.660539 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV}/c^2$
m_p	$1.00727 \text{ u} = 1.67262 \times 10^{-27} \text{ kg}$
m_n	$1.00866 \text{ u} = 1.67490 \times 10^{-27} \text{ kg}$
m_e	$0.00055 \text{ u} = 9.109 \times 10^{-31} \text{ kg}$
e	$1.602 \times 10^{-19} \text{ C}$
c	$3.0 \times 10^8 \text{ m/s}$
R_0	$1.2 \times 10^{-15} \text{ m} = 1.2 \text{ fm}$

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IMPORTANT FORMULAE

Formula	Description
$A = Z + N$	Mass number = Protons + Neutrons
$R = R_0 A^{1/3}$	Nuclear radius ($R_0 = 1.2 \text{ fm}$)
$\rho \approx 2.3 \times 10^{17} \text{ kg/m}^3$	Nuclear density (constant)
$E = mc^2$	Mass-energy equivalence
$\Delta M = [Zm_p + (A-Z)m_n] - M$	Mass defect
$E_b = \Delta M c^2$	Binding energy
$E_{bn} = E_b/A$	Binding energy per nucleon

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! 9. COMMON MISTAKES

✗ MISTAKE 1: Confusing Mass Number with Atomic Mass

Wrong: "Mass number of chlorine is 35.5"

Correct: Mass number is always an integer. Chlorine has isotopes with $A = 35$ and 37 . Average atomic mass = 35.5 u

✗ MISTAKE 2: Forgetting Unit Conversions

Remember: Always convert $1 \text{ u} = 931.5 \text{ MeV}/c^2$ when calculating binding energy in MeV

✗ MISTAKE 3: Incorrect Mass Defect Calculation

Correct Method:

$$\Delta M = [Zm_{\text{H}} + (A-Z)m_{\text{n}}] - M_{\text{atom}}$$

(Using atomic masses, not nuclear masses)

10. PRACTICE QUESTIONS

MCQ Section

Q1. Binding energy per nucleon is maximum for:

- (a) H
- (b) Fe ✓
- (c) Sn
- (d) U

Answer: (b) Maximum at $A \approx 56$ (Iron)

Q2. Nuclear radius is proportional to:

- (a) A
- (b) $A^{1/2}$
- (c) $A^{1/3}$ ✓
- (d) A^2

Answer: (c) $R = R_0 A^{1/3}$

Short Answer Questions

Q3. Define isotopes, isobars, and isotones with examples.

Answer:

- **Isotopes:** Same Z, different A. Example: ${}^1_1\text{H}$, ${}^2_1\text{H}$, ${}^3_1\text{H}$
 - **Isobars:** Same A, different Z. Example: ${}^3_1\text{H}$ and ${}^3_2\text{He}$
 - **Isotones:** Same N, different Z. Example: ${}^{197}_{79}\text{Au}$ and ${}^{198}_{80}\text{Hg}$
-

Q4. Why is nuclear density constant?

Answer:

Since $R = R_0 A^{1/3}$, volume $V \propto A$

Also, mass $M \propto A$

Therefore, density $\rho = M/V \propto A/A = \text{constant} \approx 2.3 \times 10^{17} \text{ kg/m}^3$

Long Answer Questions

Q5. Explain binding energy curve and its significance for fission and fusion.

Answer:

Binding Energy Curve: Shows E_{bn} vs A

Features:

- Maximum at $A \approx 56$ (most stable nuclei)
- Plateau at $30 < A < 170$ ($E_{bn} \approx 8$ MeV)
- Lower for light and heavy nuclei










Significance:

- **Fission:** Heavy nucleus (low E_{bn}) \rightarrow Medium nuclei (high E_{bn}) \rightarrow Energy released
- **Fusion:** Light nuclei (low E_{bn}) \rightarrow Heavier nucleus (high E_{bn}) \rightarrow Energy released



11. EXAM PREPARATION

Must Master Concepts:

-  Atomic mass unit and conversions
-  Nuclear composition (Z , A , N)
-  Isotopes, isobars, isotones
-  Nuclear radius formula
-  Mass defect and binding energy
-  Binding energy curve
-  Properties of nuclear force
-  Radioactive decay types
-  Fission and fusion

EXAM TIPS

For Numerical Problems:

- Always write Given and To Find
- Check units - use $1 \text{ u} = 931.5 \text{ MeV}/c^2$
- Show all steps clearly
- Box final answers

Common Question Types:

1. Calculate binding energy (3-5 marks)
2. Explain binding energy curve (3 marks)
3. Describe fission/fusion (5 marks)
4. Properties of nuclear force (3 marks)
5. Define isotopes/isobars/isotones (2 marks)

Study Material Information

This comprehensive study material on **Nuclei** (Chapter 13, Class 12 Physics) has been prepared following the latest CBSE curriculum. The content includes detailed explanations, NCERT solved examples, practice questions, and exam-focused tips.

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