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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 u = (1/12) × mass of one ^{12}C atom

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

$1\ u = 931.5\ MeV/c^2$

🔑 Key Terms and Notation

Nuclide Notation: $^{A}_{Z}X$

- **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

A = Z + N
(Mass number = Protons + Neutrons)

Example: Gold nucleus $^{197}_{79}Au$ 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 ${}^{1}_{1}H$	1.00727 u	1.67262×10^{-27} kg	+e
Neutron	n or ${}^{1}_{0}n$	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_1H) and Tritium (^3_1H) 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 ≈ 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 ≈ 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	$^{1}_{1}H$, $^{2}_{1}H$ (Deuterium), $^{3}_{1}H$ (Tritium)
Isobars	Same A (mass number), different Z	$^{3}_{1}H$ and $^{3}_{2}He$
Isotones	Same N (neutron number), different Z	$^{198}_{80}Hg$ and $^{197}_{79}Au$ (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:

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

= (75.4 × 34.98 + 24.6 × 36.98)/100

= (2637.49 + 909.71)/100

= 35.47 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 ≈ 4.0×10^{-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

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

A = Mass number

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

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

Volume Proportionality:

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

$V = (4/3)\pi R_0^3 A$

Therefore: $V \propto A$

Volume is directly proportional to mass number!

Nuclear Density:

Density ρ = Mass/Volume = $(A \times 1u)/[(4/3)\pi R_0^3 A]$

$\rho = 1u/[(4/3)\pi R_0^3]$

Nuclear density ≈ 2.3×10^{17} kg/m³

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

💡 Understanding Nuclear Density

Comparison with ordinary matter:

- **Nuclear matter:** $\rho \approx 2.3 \times 10^{17}$ kg/m³
- **Water:** $\rho = 10^3$ kg/m³
- **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

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

Step 2: Calculate nuclear volume

$V = (4/3)\pi R^3 = (4/3)\pi(R_0A^{1/3})^3$

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

Step 3: Calculate density

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

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

⚡ 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:

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

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

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

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

💡 Useful Energy Conversion

$1\ u = 931.5\ MeV/c^2$

Derivation:

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

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

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

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

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

= 931.5 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 $^{16}_{8}O$

Expected mass calculation:

- Mass of 8 neutrons = 8 × 1.00866 u = 8.06928 u
- Mass of 8 protons = 8 × 1.00727 u = 8.05816 u
- Mass of 8 electrons = 8 × 0.00055 u = 0.00440 u
- **Expected total = 16.13184 u**

Experimental measurement:

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

Mass defect:

ΔM = 16.13184 - 15.99053 = **0.14131 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 u = 931.5 MeV/c², express the mass defect of $^{16}_{8}O$ in MeV/c².

Solution:

Mass defect ΔM = 0.13691 u (from NCERT)

In energy units: ΔM = 0.13691 × 931.5 MeV/c²

ΔM = 127.5 MeV/c²

Therefore:

Binding energy E_b = 127.5 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} ≈ 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: ${}^{4}_{2}He$ 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} ≈ 7.6 MeV

💡 Energy Production - Key Insights

Process	Direction	Energy Release
Fission	Heavy nucleus (A≈240) → Two medium nuclei (A≈120)	~200 MeV per fission
Fusion	Light nuclei (A≤10) → 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 ($^{4}_{2}He$)	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

⚡ 7. NUCLEAR ENERGY

💥 7.1 Nuclear Fission

NUCLEAR FISSION

Heavy nucleus splits into lighter nuclei with enormous energy release

⚛️ Fission of Uranium-235

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3\,^{1}_{0}n + 200\ \text{MeV}$$

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 → 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 × 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

Step 1: ${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + e^{+} + \nu + 0.42$ MeV

Step 2: $e^{+} + e^{-} \rightarrow \gamma + \gamma + 1.02$ MeV

Step 3: ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma + 5.49$ MeV

Step 4: ${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2\,{}^{1}_{1}H + 12.86$ MeV

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu + 6\gamma + 26.7 \text{ MeV}$$

🔥 Conditions for Fusion

Challenge: Nuclei repel each other (Coulomb barrier)

For two protons to fuse:

Coulomb barrier ≈ 400 keV

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

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

8. KEY FORMULAE

FUNDAMENTAL CONSTANTS

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

📐 IMPORTANT FORMULAE

Formula	Description
$A = Z + N$	Mass number = Protons + Neutrons
$R = R_0 A^{1/3}$	Nuclear radius (R_0 = 1.2 fm)
$\rho \approx 2.3 \times 10^{17}$ kg/m³	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

⚠️ 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 u = 931.5 MeV/c^2 when calculating binding energy in MeV

❌ MISTAKE 3: Incorrect Mass Defect Calculation

Correct Method:

$\Delta M = [Zm_H + (A-Z)m_n] - M_{atom}$

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

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 $\rho = M/V \propto A/A$ = constant $\approx 2.3 \times 10^{17}$ 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 ≈ 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}) → Medium nuclei (high E_{bn}) → Energy released
- **Fusion:** Light nuclei (low E_{bn}) → Heavier nucleus (high E_{bn}) → 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 u = 931.5 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.