CBSE Class 12 Physics: Nuclei

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1. Introduction: The Heart of the Atom

In the previous study of Atoms, we learned through the Rutherford Scattering Experiment that the majority of an atom's mass and its entire positive charge are concentrated in a tiny central core called the **Nucleus**. While the atom is approximately 10^{-10} m in size, the nucleus is about 10^{-15} m. To put this in perspective, if an atom were the size of a large football stadium, the nucleus would be the size of a small marble in the center.

1.1 Atomic Mass Unit (amu or u)

Because the masses of nuclei are incredibly small, kilograms are impractical. We use the **atomic mass unit (u)**, defined as $1/12^{th}$ of the mass of a carbon-12 (^{12}C) atom.

- $1 \text{ u} = 1.660539 \times 10^{-27}$ kg
- Energy equivalent of 1 u ≈ 931.5 MeV

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2. Composition and Size of Nucleus

A nucleus consists of **nucleons**, which is a collective term for **protons** and **neutrons**.

- **Atomic Number (Z):** The number of protons. It defines the element.
- **Mass Number (A):** The total number of protons and neutrons.
- **Neutron Number (N):** $N = A - Z$.

2.1 Nuclear Radius

Experimental evidence (electron scattering) shows that the volume of a nucleus is directly proportional to its mass number A. Since Volume $\propto R^3$, it follows that $R^3 \propto A$, or:

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

Where $R_0 \approx 1.2 \times 10^{-15}$ m (or 1.2 fermi).

2.2 Nuclear Density

Nuclear density is the mass per unit volume of the nucleus.

$$\text{Density } (\rho) = \frac{\text{Mass}}{\text{Volume}} = \frac{A \times m}{\frac{4}{3}\pi R^3}$$

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

$$\rho = \frac{A \times m}{\frac{4}{3}\pi (R_0 A^{1/3})^3} = \frac{3m}{4\pi R_0^3}$$

Conclusion: The mass number A cancels out. This means nuclear density is **independent of the mass number**. All nuclei, from Hydrogen to Uranium, have approximately the same density ($\approx 2.3 \times 10^{17}$ kg/m^3), which is significantly higher than ordinary matter.

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3. Mass-Energy Equivalence and Nuclear Binding Energy

Einstein's Theory of Special Relativity changed our understanding of mass. Mass is not "lost"; it is simply another form of energy.

3.1 Mass Defect (Δm)

It is observed that the rest mass of any stable nucleus is always **less** than the sum of the masses of its individual constituent nucleons. If a nucleus has Z protons and $(A - Z)$ neutrons, the expected mass is $Zm_p + (A - Z)m_n$. The actual mass is M.

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

3.2 Binding Energy (E_b)

The "missing mass" is converted into energy when nucleons combine to form a nucleus. This same energy must be supplied to the nucleus to break it apart into its individual nucleons.

$$E_b = \Delta m \cdot c^2$$

3.3 Binding Energy per Nucleon (E_{bn})

To determine nuclear stability, we look at $E_{bn} = E_b/A$. This represents the average energy required to remove a single nucleon from the nucleus. Higher E_{bn} indicates greater stability.

[Image of Binding Energy per nucleon curve]

Try drawing this: The Binding Energy Curve

1. **Axes:** Draw a horizontal axis (x-axis) for Mass Number A (0 to 250) and a vertical axis (y-axis) for Binding Energy per Nucleon (E_{bn}) in MeV (0 to 9).
2. **Initial Peak:** Start low for H, then show sharp peaks for ^{4}He, ^{12}C, and ^{16}O. These peaks indicate that these "even-even" nuclei are more stable than their neighbors.
3. **The Plateau:** The curve rises steadily and reaches a maximum of about 8.8 MeV at $A = 56$ (Iron, Fe).
4. **The Gradual Decline:** After $A = 56$, the curve drops slowly, reaching about 7.6 MeV for Uranium ($A = 238$).

Key Observations from the Curve:

- **Saturation of Nuclear Forces:** The fact that E_{bn} is roughly constant (approx. 8 MeV) for $30 < A < 170$ shows that a nucleon only interacts with its nearest neighbors.
- **Nuclear Fission:** A very heavy nucleus ($A = 240$) has lower E_{bn} than middle-range nuclei. If it splits into two smaller nuclei, the nucleons become more tightly bound, and energy is released.
- **Nuclear Fusion:** Very light nuclei ($A \leq 10$) have low E_{bn}. If they join to form a heavier nucleus, the E_{bn} increases significantly, releasing massive amounts of energy.

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4. Nuclear Forces

If protons are all positively charged, why don't they fly apart due to electrostatic repulsion? There must be a stronger, attractive force.

Characteristics of Nuclear Force:

1. **Strongest in Nature:** Roughly 100 times stronger than electromagnetic force.
2. **Short Range:** Only effective at distances of about $1-2$ fm. Beyond this, it drops to zero.
3. **Charge Independent:** The $p-p$, $n-n$, and $p-n$ forces are nearly identical.
4. **Saturation:** A nucleon only attracts those nucleons immediately surrounding it.
5. **Repulsive Core:** If nucleons get closer than 0.8 fm, the force becomes strongly repulsive, preventing the nucleus from collapsing.

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5. Radioactivity

Radioactivity is the spontaneous disintegration of an unstable nucleus by emitting particles or radiation.

5.1 Law of Radioactive Decay

The number of nuclei disintegrating per unit time (Rate of decay) is directly proportional to the total number of nuclei present at that instant.

$$\frac{dN}{dt} = -\lambda N$$

Where λ is the **Decay Constant**.

Derivation of the Decay Equation:

1. Rearrange: $\frac{dN}{N} = -\lambda dt$
2. Integrate both sides: $\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t d\,t$
3. $\ln(N) - \ln(N_0) = -\lambda t$
4. $\ln(N/N_0) = -\lambda t$
5. **Result:** $N(t) = N_0 e^{-\lambda t}$

Try drawing this: Radioactive Decay Curve

1. Draw an L-shaped graph. Y-axis is N (number of nuclei), X-axis is t (time).
2. Mark N_0 on the Y-axis at $t = 0$.
3. Draw a smooth curve that drops rapidly at first and then flattens out, asymptotically approaching the X-axis (it never actually touches the X-axis).

5.2 Half-Life ($T_{1/2}$)

The time in which the number of radioactive nuclei reduces to half of its initial value. Set $N = N_0/2$ in the decay equation: $N_0/2 = N_0 e^{-\lambda T_{1/2}}$ $1/2 = e^{-\lambda T_{1/2}} \Longrightarrow \ln(2) = \lambda T_{1/2}$

$$T_{1/2} = \frac{0.693}{\lambda}$$

6. Nuclear Energy: Fission and Fusion

6.1 Nuclear Fission

The process in which a heavy nucleus ($A > 230$) splits into two or more lighter nuclei of comparable mass when bombarded with neutrons. **Example:** $^{235}\text{U} + ^{1}\text{n} \rightarrow ^{141}\text{Ba} + ^{92}\text{Kr} + 3^{1}\text{n} + Q$ (Energy)

- **Chain Reaction:** The 3 neutrons produced can trigger further fissions.
- **Critical Mass:** The minimum mass of fissionable material required to sustain a chain reaction.
- **Moderators (e.g., Heavy water, Graphite):** Used to slow down fast neutrons to "thermal" speeds to increase fission probability.
- **Control Rods (e.g., Cadmium, Boron):** Absorb excess neutrons to control the reaction rate.

6.2 Nuclear Fusion

The process where two light nuclei combine to form a single heavier nucleus. **Example:** $^{2}\text{H} + ^{2}\text{H} \rightarrow ^{3}\text{He} + n + 3.27$ MeV

- **Conditions:** Requires extremely high temperature (10^7 K) and high pressure to overcome the strong electrostatic repulsion between nuclei. This is why it is called **Thermonuclear Fusion**.
- **Source of Stellar Energy:** Fusion is the reaction powering the Sun and stars (Proton-Proton cycle).

Final Exam Checklist

- ☐ Definition of Atomic Mass Unit and MeV equivalent.
- ☐ Calculation showing Nuclear Density is independent of Mass Number.
- ☐ Definition of Mass Defect and Binding Energy.
- ☐ Sketching and explaining the Binding Energy per Nucleon curve.
- ☐ Listing 4 properties of Nuclear Forces.
- ☐ Derivation of $N = N_0 e^{-\lambda t}$ and $T_{1/2} = 0.693/\lambda$.
- ☐ Differences between Nuclear Fission and Fusion.
- ☐ Role of Moderators and Control Rods in a Nuclear Reactor.