Solution

NUCLEAR PHYSICS

Class 12 - Physics

1. A neutron carries no charge. It easily penetrates even a heavy nucleus without being repelled or attracted by the nucleus and electrons. So it serves as an ideal projectile for starting a nuclear reaction.
2. Nuclear radius, $R \propto A^{1/3}$
   $\frac{R_{Fe}}{R_{Al}} = \left(\frac{A_{Fe}}{A_{Al}}\right)^{1/3} = \left(\frac{125}{27}\right)^{1/3} = \frac{5}{3} = 1.67$
   $R_{Fe} = 1.67 \times R_{Al} = \frac{5}{3} \times 3.6$
   = 6 fermi
3. It is because of the fact that the mass of a nucleus is slightly less than the mass of the constituent nucleons. This decrease in mass is called mass defect. Since the mass defect in case of ${}^{16}_{8}O$ is not exactly twice the mass defect in case of ${}^{8}_{4}Be$, the ratio of the atomic masses is not exactly 2.
4. Radius of nucleus is related to its mass number as
   $R = R_0 A^{1/3}$
   where, R_0 = base radius (= 1.2 Fm) and A = mass number
   $\therefore \quad \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{1/3} = \left(\frac{1}{8}\right)^{1/3} = \frac{1}{2}$
5. B.E. = $[ZM_P + (A - Z)M_n - M_N] \times c^2 = \Delta Mc^2$
6. Yes
7.
   i. Momentum
   ii. Number of nucleons
   iii. Charge
   iv. Energy
8. According to question,
   ${}^2_1\mathrm{H} + {}^2_1\mathrm{H} \longrightarrow {}^3_2\mathrm{He} + {}_0n^1$
   Energy of fusion = Binding energy of ${}^3_2He - 2 \times$ Binding energy of ${}^2_1\mathrm{H}$
   $= 7.73 - 2 \times 2.23 = 3.27\mathrm{MeV}$
9. Binding Energy $= (Zm_p + (A - Z)m_n - M_N) \times 931.5MeV$
   B..E. = $(6 \times 1.007825 + 6 \times 1.008665 - 12.000000) \times 931.5MeV$
   $= (0.09894) \times 931.5MeV$
   B. E. $= 92.16MeV$
10. Nuclear fusion is the process by which two light atomic nuclei combine to form a single heavier one while releasing massive amounts of energy. Inside the Sun, this process begins with protons (which is simply a lone hydrogen nucleus) and through a series of steps, these protons fuse together and are turned into helium. This fusion process occurs inside the core of the Sun, and the transformation results in a release of energy that keeps the sun hot.
11. **Moderator:** Any substance which is used to slow down fast-moving neutrons to thermal energies ($\approx$ 0.0235 eV) is called a moderator. The commonly used moderators are water, heavy water (D_2O), graphite, and beryllium.

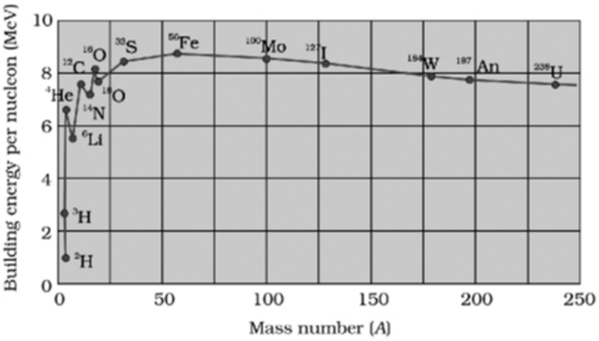
    The action of the moderator. Fast neutrons are passed through substances like paraffin, deuterium, or water, which contain a large number of hydrogen nuclei or protons. Neutrons and protons have nearly the same mass. When fast-moving neutrons are passed through paraffin, they make elastic collisions with protons, which have comparatively much smaller velocities. In few interactions, the velocities of the neutrons get interchanged with those of protons. The final velocities of the neutrons correspond to the random velocities of the atoms or molecules of the moderator at room temperature. Such neutrons are called thermal neutrons.
    About 25 collisions with deuterons (present in heavy water) or 100 collisions with carbon or beryllium are sufficient to slow down a neutron from 2 MeV to thermal energies.
    A good moderator has two properties:
    i. It slows down neutrons by elastic collisions.
    ii. It does remove neutrons from the system by absorbing them.
12.
    i. A nucleus, that spontaneously decays by emitting an electron, and an antineutrino is said to undergo $-\beta$-decay. In beta-minus decay, an energetic negative electron is emitted, producing a daughter nucleus of one higher atomic number and the same mass

number.

Radioactive nuclei can emit β-particles i.e., electrons or positrons even though they do not contain them. The reason is that neutron or proton present in the nucleus gets interconverted and emitting electron or positron. Electrons or positrons are emitted in β-decay process along with neutrino or antineutrino. The energy of these emitted neutrinos or antineutrinos is different which affects the energy of electrons or positrons.

ii. The daughter nuclei have more binding energy per nucleon.

13. Total B.E of ${}^{235}_{92}\mathrm{Y}$ = 7.8 $\times$ 235 = 1833 MeV
Total B.E. of ${}^{231}_{90}\mathrm{X}$ = 7.835 $\times$ 231 = 1809.9 MeV
Total B.E. of ${}^{4}_{2}\mathrm{He}$ = 7.076 $\times$ 4 = 28.28 MeV
Energy released in the decay, Q
Q = B.E of X + B.E of He - B.E of Y
= 1809.9 + 28.28 - 1833
= 5.18 MeV
K.E of a particle, $\frac{1}{2}mv^2$ = Q
$\therefore$ Speed of the emitted α particle is given by, v = $\sqrt{\frac{2Q}{m}}$
v = $\sqrt{\frac{2\times 5.18\times 1.6\times 10^{-13}}{6.68\times 10^{-27}}}$
v = 1.58 $\times$ 10^7 ms^{-1}

14. 

Salient feature of B.E. curve

i. B.E/nucleon is pratically constant i.e. independent of the atomic number for nuclei of middle mass number (30 < A < 17)

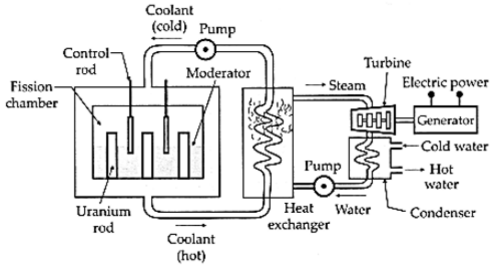
ii. Binding energy per nucleon is lower for both light nuclei (A < 30) and heavy nuclei (A > 70).

Very heavy nucleus has lower B.E./nucleon will undergo fission and split into two medium sized nuclei with large B.E./nucleon and release tremendous amount of energy (Fission process)

When two very light nuclei, having low binding energy per nucleon combine together and form a medium sized nuclei of higher B.E. per nucleon releases enormous amount of energy (Fusion process)

15. ${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{X} + e^{+} + \mathrm{v} + \mathrm{Q}$
${}^{11}_{5}X$ is an isobar of ${}^{11}_{6}\mathrm{C}$ as both have same mass number.
Mass defect,
$\Delta m = m_N\left({}^{11}_{6}\mathrm{C}\right) - m_N\left({}^{11}_{5}B\right) - m_e$
In terms of atomic masses, we can write
Δm = $\left[m\left({}^{11}_{6}\mathrm{C}\right) - 6m_e\right] - \left[m\left({}^{11}_{6}B\right) - 5m_e\right] - m_e$
$= m\left({}^{11}_{6}\mathrm{C}\right) - m\left({}^{11}{}_{6}B\right) - 2m_e$
Ignoring the mass of electrons, we get
$\Delta m = m\left({}^{11}_{6}C\right) - m\left({}^{11}_{6}B\right)$
= (11.011434 - 11.009305)u
= 0.002129 u
Q = Δm $\times$ 931.5 MeV
= 0.002129 $\times$ 931.5 MeV
= 1.98 MeV

16. Nuclear reactor is a device in which a nuclear chain reaction is initiated, maintained and controlled. It works on the principle of controlled chain reaction and provides energy at a constant rate.

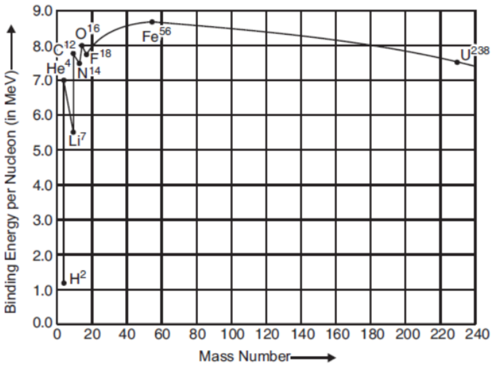


Moderator: In the fission of uranium, fast neutrons of energy 2 MeV are released. These fast neutrons have more tendency to escape instead of triggering another fission reaction. Also, slow neutrons are more efficient in inducing fission in $^{235}_{95}U$ nuclei than fast neutrons. By the use of a moderator, the fast neutrons are slowed to thermal velocities. Usually, heavy water, graphite and beryllium oxide are used as moderators.

Control rods: To start, stop or control the chain reaction, rods of neutron absorbing material like cadmium or boron are inserted into the reactor core. The rate of neutron production is controlled by adjusting the depth of control rods.

Coolant: It is the material used to cool the fuel rods and the moderator and is capable of carrying away large amount of heat produced in the fission process. The coolant transfers heat to the working liquid like water and produces steam. The steam drives a turbine which, in turn, runs a generator to generate electric power. The coolant must have a high boiling point and high specific heat. Heavy water and liquid sodium are good coolants.

17. i. Graphical variation of (BE/A) for nucleons with mass number A. The variation of binding energy per nucleon versus mass number is shown in figure.



 a. Nuclear forces non-central and short-ranged force.
 b. Nuclear forces between proton-neutron and neutron-neutron are strong and attractive in nature.

 ii. Explanation of Nuclear Fission: When a heavy nucleus ($\mathrm{A} \geq 235$ say) breaks into two lighter nuclei (nuclear fission), the binding energy per nucleon increases i.e, nucleons get more tightly bound. This implies that energy would be released in nuclear fission.

 Explanation of Nuclear Fusion: When two very light nuclei ($\mathrm{A} \leq 10$) join to form a heavy nucleus, the binding is energy per nucleon of fused heavier nucleus more than the binding energy per nucleon of lighter nuclei, so again energy would be released in nuclear fusion.

 iii. During decay of a neutron, we have

 $^{1}_{0}n \rightarrow {}^{1}_{1}\mathrm{p} + {}_{-1}{}^{0}\ \mathrm{b} + \mathrm{v\ bar}$

 The detection of neutrinos is very difficult because it shows weak interactions with other particles.

18. a. The decay of a free neutron at rest can be represented as

 ${}_{0}n^{1} \longrightarrow\ {}_{1}H^{1} +_{-1} e^{0}$

 According to the principle of conservation of linear momentum, the electron and proton will acquire equal and opposite momentum. This means the energy of an electron in the above decay is fixed in terms of the masses of the particles involved. Therefore, it is impossible for the electron in the above decay to have a continuous distribution of energy. However, if an additional particle were present, the available energy can be shared by the electron and the additional particle. This simple logic was among the several arguments which led Pauli to postulate the existence of the third particle unobserved till then in the phenomenon of β-decay. The correct equation for β-decay is, therefore

 ${}_{0}n^{1} \longrightarrow\ {}_{1}H^{1} +\ {}_{-1}e^{0} + \bar{\nu}_{e}$

 where the symbol $\bar{\nu}_{e}$ represents the new particle, called the (electron) antineutrino. It is a neutral particle of negligibly small rest mass and intrinsic spin = $\frac{1}{2}(h/2\pi)$. It was extremely difficult to detect a neutrino because of its weak interaction with matter.

b. A free neutron has rest mass greater than that of a proton. Thus β-decay is energetically allowed. But the β^+ decay of a free proton is not allowed energetically i.e.

$${}_1H^1 \longrightarrow {}_0n^1 + {}_1e^0 + \nu_e$$

is not allowed in case of a free proton. But in a nucleus, individual neutrons and protons are not free. That is why β^+ decay of proton occurs side by side. The energy needed for this decay comes from the appropriate difference in binding energies of a proton and a neutron in the nucleus. In a stable nucleus with Z protons and (A - Z) neutrons, the two reciprocal processes (neutron decay and proton decay) are in dynamic equilibrium.

19. a. A chemical reaction simply changes the original combination of atoms. A chemical equation is balanced in the sense that the number of atoms of each element is the same on both sides of the equation. A chemical reaction merely alters the original combinations of atoms. In a nuclear reaction, elements may be transmuted. Thus, the number of atoms of each element is not necessarily conserved in a nuclear reaction. However, the number of protons and the number of neutrons are both separately conserved in a nuclear reaction. In nuclear reactions, the number of protons and the number of neutrons are the same on the two sides of the equation.

b. We know that the binding energy of a nucleus gives a negative contribution to the mass of the nucleus . Now, since the proton number and neutron number are conserved in a nuclear reaction, the total rest mass of neutrons and protons is the same on either side of a reaction. But the total binding energy of nuclei on the left side need not be the same as that on the right-hand side. The difference in these binding energies appears as the energy released or absorbed in a nuclear reaction. Since binding energy contributes to mass, we say that the difference in the total mass of nuclei on the two sides gets converted into energy or vice-versa. It is in this sense that a nuclear reaction is an example of mass-energy interconversion.

c. From the point of view of mass-energy interconversion, a chemical reaction is similar to a nuclear reaction in principle. The energy released or absorbed in a chemical reaction can be traced to the difference in chemical binding energies of atoms and molecules on the two sides of a reaction. Since, strictly speaking, chemical binding energy also gives a negative contribution (mass defect) to the total mass of an atom or molecule, we can equally well say that the difference in the total mass of atoms or molecules, on the two sides of the chemical reaction gets converted into energy or vice-versa. However, the mass defects involved in a chemical reaction are almost a million times smaller than those in a nuclear reaction. That is why we have the impression, that mass-energy interconversion does not take place in a chemical reaction , though the impression is incorrect.