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Nucleus

A nucleus of an element is represented as $_{Z}X^{A}$, where X is the chemical symbol of the element. Z represents the atomic number which is equal to the number of protons and A, the mass number which is equal to the total number of protons and neutrons. The number of neutrons is represented as N which is equal to A–Z.

For example, the chlorine nucleus is represented as $_{17}Cl^{35}$.
It contains 17 protons and 18 neutrons.

Classification of nuclei

***(i) Isotopes*:** Isotopes are atoms of the same element having the same atomic number Z but different mass number A.

The nuclei $_{1}H^{1}$, $_{1}H^{2}$ and $_{1}H^{3}$ are the isotopes of hydrogen.

***(ii) Isobars*.** Isobars are atoms of different elements having the same mass number A, but different atomic number Z.
The nuclei $_{8}O^{16}$ and $_{7}N^{16}$ represent two isobars.

***(iii) Isotones*:** Isotones are atoms of different elements having the same number of neutrons. $_{6}C^{14}$ and $_{8}O^{16}$ are some examples of isotones.

***Nuclear size*:** The radius of the nucleus R and its mass number A.
It is given by $R \propto A^{1/3}$

$R = r_o A^{1/3}$ where r_o is the constant of proportionality and is equal to 1.3 F (1 Fermi, $F = 10^{-15}$ m)

Nuclear density The nuclear density ρ_N can be calculated from the mass and size of the nucleus. $\rho_N = \dfrac{Nuclear\ mass}{Nuclear\ volume}$

Nuclear mass = Am_N where, A = mass number
and m_N = mass of one nucleon and is equal to 1.67×10^{-27} kg

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

$$\therefore \quad \rho_N = \frac{A\ m_N}{\frac{4}{3}\pi (r_o A^{1/3})^3} = \frac{m_N}{\frac{4}{3}\pi r_o^3}$$

Substituting the known values, the nuclear density is calculated as 1.816×10^{17} kg m^{-3} which is almost a constant for all the nuclei

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Atomic mass unit : One atomic mass unit is considered as one twelfth of the mass of carbon atom $_6C^{12}$.

$$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

The energy equivalence of one amu can be calculated in electron-volt

Einstein's mass energy relation is, $E = mc^2$

Here, $m = 1 \text{ amu} = 1.66 \times 10^{-27}$ kg $c = 3 \times 10^8 \text{ ms}^{-1}$

$\therefore \quad E = 1.66 \times 10^{-27} \times (3 \times 10^8)^2$ J

$$\text{Hence, } E = \frac{1.66 \times 10^{-27} \times (3 \times 10^8)^2}{1.6 \times 10^{-19}} \text{ eV} = 931 \times 10^6 \text{ eV}$$

= 931 million electronvolt = 931 MeV

Thus, energy equivalent of 1 amu = 931 MeV

> One electron-volt (eV) is defined as the energy of an electron when it is accelerated through a potential difference of 1 volt.
> $1 \text{ eV} = 1.6 \times 10^{-19} \text{ coulomb} \times 1 \text{ volt} = 1.6 \times 10^{-19}$ joule

Nuclear mass and mass defect

As the nucleus contains protons and neutrons, the mass of the nucleus is assumed to be the mass of its constituents.

Assumed nuclear mass = $Zm_p + Nm_n$,

where m_p and m_n are the mass of a proton and a neutron respectively. However, from the measurement of mass by mass spectrometers, it is found that the mass of a stable nucleus (m) is less than the total mass of the nucleons.

i.e mass of a nucleus, $m < (Zm_p + Nm_n)$

$Zm_p + Nm_N - m = \Delta m$

where Δm is the mass defect

Thus, the difference in the total mass of the nucleons and the actual mass of the nucleus is known as the mass defect.

Binding energy

When the protons and neutrons combine to form a nucleus, the mass that disappears (mass defect, Δm) is converted into an equivalent amount of energy (Δmc^2). This energy is called the binding energy of the nucleus.

$$\therefore \quad \text{Binding energy} = [Zm_p + Nm_n - m]\, c^2 = \Delta m\, c^2$$

The binding energy per nucleon is

$$\frac{BE}{A} = \frac{\text{Binding energy of the nucleus}}{\text{Total number of nucleons}}$$

Nuclear force The nucleons inside the nucleus are held together by strong attractive forces called nuclear forces.

(i) Nuclear force is charge independent.

(ii) Nuclear force is the strongest known force in nature.

(iii) Nuclear force is a short range force.

Radioactivity

The phenomenon of spontaneous emission of highly penetrating radiations such as α, β and γ rays by heavy elements having atomic number greater than 82 is called radioactivity and the substances which emit these radiations are called radioactive elements.

Radioactive law of disintegration

The rate of disintegration at any instant is directly proportional to the number of atoms of the element present at that instant. This is known as radioactive law of disintegration.

DECAY EQUATION

Let N_0 be the number of radioactive atoms present initially and N, the number of atoms at a given instant t. Let dN be the number of atoms undergoing disintegration in a small interval of time dt. Then the rate of disintegration is

$$-\frac{dN}{dt} \propto N$$ [The negative sign indicates that N decreases with increase in time.]

$$\frac{dN}{dt} = -\lambda N$$, where λ is a constant known as decay constant or disintegration constant.

$$\frac{dN}{N} = -\lambda\, dt \quad ...(1)$$

Integrating equation (1) within propor limit

$$\int_{N_0}^{N} \frac{dN}{N} = \int_{0}^{t} -\lambda\, dt = -\lambda \int_{0}^{t} dt$$

$$\Rightarrow \left[\log_e N\right]_{N_0}^{N} = -\lambda \left[t\right]_{0}^{t}$$

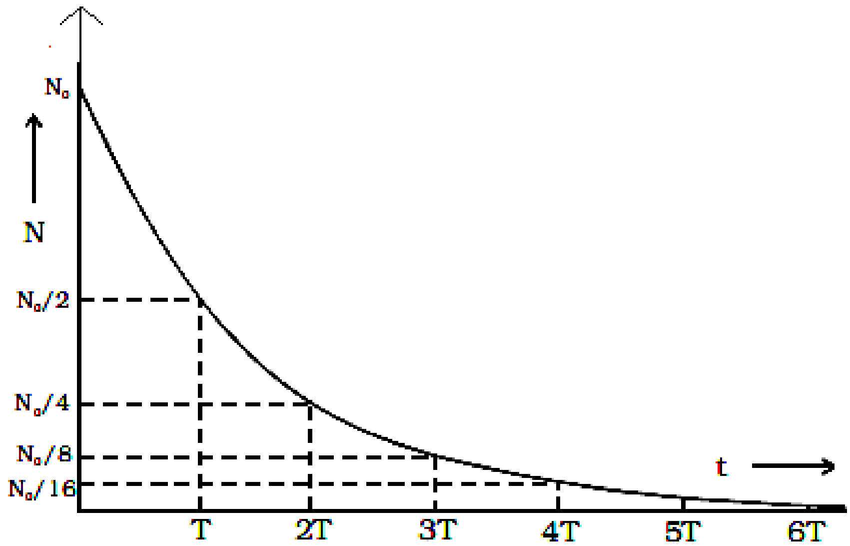
$$\Rightarrow \log_e N - \log_e N_0 = -\lambda\left[t - 0\right]$$

$$\Rightarrow \log_e\left(\frac{N}{N_0}\right) = -\lambda . t$$

$$\Rightarrow \frac{N}{N_0} = e^{-\lambda t}$$

$$\Rightarrow \boxed{N = N_0\, e^{-\lambda t}} \quad ...(2)$$

Equation (2) shows that the number of atoms of a radioactive substance decreases exponentially with increase in time.



Initially the disintegration takes place at a faster rate. As time increases, N gradually decreases exponentially. Theoretically, an infinite time is required for the complete disintegration of all the atoms.

Half life period:-

The half life period of a radioactive element is defined as the time taken for one half of the radioactive element to undergo disintegration

From the law of disintegration, $N = N_0 e^{-\lambda t}$

Let $T_{½}$ be the half life period. Then, at $t = T_{½}$, $N = \frac{N_0}{2}$

$$\therefore \quad \frac{N_0}{2} = N_0 e^{-\lambda T_{½}} \Rightarrow \log_e 2 = \lambda T_{½}$$

$$T_{½} = \frac{\log_e 2}{\lambda} = \frac{\log_{10} 2 \times 2.3026}{\lambda} = \frac{0.6931}{\lambda}$$

Mean life :-

The mean life of a radioactive substance is defined as the ratio of total life time of all the radioactive atoms to the total number of atoms in it.

Mean life = Sum of life time of all the atoms / Total number of atoms

The mean life is calculated from the law of disintegration and it can be shown that the mean life is the reciprocal of the decay constant.

$$\tau = 1/\lambda$$

The half life and mean life are related as $T_{½} = 0.693 / \lambda = 0.693\, \tau$

The unit of Radioactivity :-

The unit of radioactivity is becquerel

1 becquerel = 1 disintegration per second

Activity of a radioactive substance is generally expressed in curie.

Curie is defined as the quantity of a radioactive substance which gives 3.7×10^{10} disintegrations per second or 3.7×10^{10} becquerel.

This is equal to the activity of one gram of radium.

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Origin of alpha decay

When a nucleus undergoes alpha-decay , it transforms to a different nucleus by emitting an alpha-particle (a helium nucleus, $_2He^4$). In alpha decay of $_Z X^A$, the mass number and the atomic number of the daughter nucleus decreases by four and two, as $_2 He^4$ contains two protons and two neutrons, respectively.

Thus, we can write $^A_ZX \rightarrow ^{A-4}_{Z-2}Y + ^4_2He$

where $_ZX^A$ is the parent nucleus and $_{Z-2}Y^{A-4}$ is the daughter nucleus

For example, during alpha-decay of $_{92}U^{238}$

$\mathbf{_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_2He^4}$

Q value of alpha-decay or the disintegration energy of alpha-decay The difference between the initial mass energy and the final mass energy of the decay products is called the Q value or the disintegration energy. Thus, the Q value of an alpha decay can be expressed as $\mathbf{Q = (m_X - m_Y - mHe)\,c^2}$

This energy is shared by the daughter nucleus $_{Z-2}Y^{A-4}$ and the alpha-particle, $_2 He^4$ in the form of kinetic energy.

Origin of beta decay

A nucleus that decays spontaneously by emitting an electron or a positron is said to undergo beta decay.

It is a spontaneous process, with a definite disintegration energy & half-life .

It is two types :-

(1) In beta-minus decay, a neutron transforms into a proton within the nucleus according to $n \rightarrow p + e^- + \bar{\nu}$

In the decay of $_{15} P^{32}$ → $^{32}_{15}P \rightarrow ^{32}_{16}S + e^- + \bar{\nu} \qquad (T_{1/2} = 14.3\text{ d})$

(2) In beta-plus decay, a proton transforms into neutron (inside the nucleus) according to $p \rightarrow n + e^+ + \nu$

In the decay of $_{11}Na^{22}$ → $^{22}_{11}Na \rightarrow ^{22}_{10}Ne + e^+ + \nu \quad (T_{1/2} = 2.6\text{ y})$

The symbols $\bar{\nu}$ and ν represent antineutrino and neutrino, respectively; both are neutral particles, with no mass. Neutrinos interact only very weakly with matter and they can even penetrate the earth without being absorbed.

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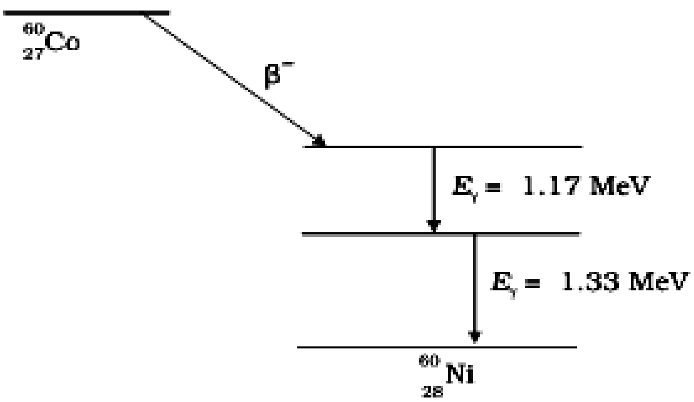
Origin of Gamma decay

Just like in an atom , there are energy levels in a nucleus, When a nucleus is in an excited state, it can make a transition to a lower energy state by the emission of electromagnetic radiation. As the energy differences between levels in a nucleus are of the order of MeV, the photons emitted by the nuclei have MeV energies and are called gamma rays. Most radio nuclides after an alpha decay or a beta decay leave the daughter nucleus in an excited state.The daughter nucleus reaches the ground state by a single transition or sometimes by successive transitions by emitting one or more gamma rays.

Gamma decay from $_{27}Co^{60}$.



By beta emission, the $_{27}Co^{60}$ nucleus transforms into $_{28}Ni^{60}$ nucleus in its excited state. The excited $_{28}Ni^{60}$ nucleus so formed then de-excites to its ground state by successive emission of 1.17 MeV and 1.33 MeV gamma rays.

NUCLEAR FISSION:

The process of breaking up of the nucleus of a heavier atom into two fragments with the release of large amount of energy is called nuclear fission. The fission is accompanied of the release of neutrons.

The fission reactions with $_{92}U^{235}$ are represented as

$$_{92}U^{235} + {}_0n^1 \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_0n^1 + Q$$

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Enrico Fermi found that a neutron was bombarded on a uranium target, the uranium nucleus broke into two nearly equal fragments releasing great amount of energy and with additional neutrons Such reaction is called nuclear fission reaction . An example of such a reaction is

$$ {}_0^1n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U \rightarrow {}_{56}^{144}Ba + {}_{36}^{89}Kr + 3\,{}_0^1n $$

The other possible pairs of equations with U ^{235} are

$$ {}_0^1n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U \rightarrow {}_{51}^{133}Sb + {}_{41}^{99}Nb + 4\,{}_0^1n $$

Still another example is

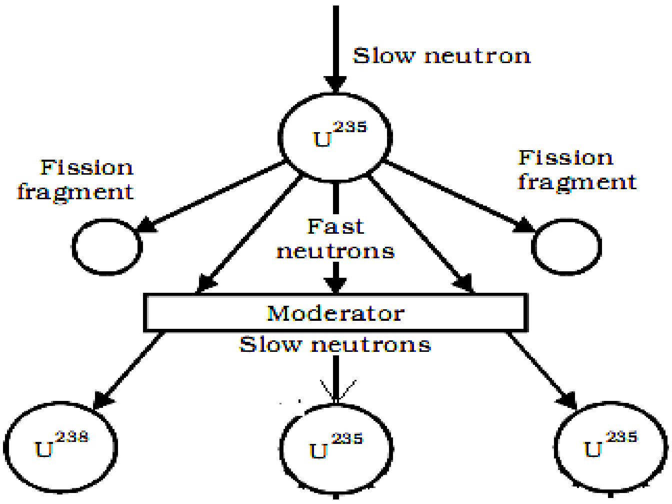
$$ {}_0^1n + {}_{92}^{235}U \rightarrow {}_{54}^{140}Xe + {}_{38}^{94}Sr + 2\,{}_0^1n $$

Products of fission are highly neutron-rich and unstable. They are radioactive and emit beta particles in succession until each reaches a stable end product.

The disintegration energy of fission , first appears as the kinetic energy of the fragments and neutrons . Eventually it is transferred to the surrounding matter appearing as heat.

The source of energy in nuclear reactors, which produce electricity, is nuclear fission. The atom bomb with enormous energy is uncontrolled nuclear fission.

Chain reaction



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Consider a neutron causing fission in a uranium nucleus producing three neutrons. The three neutrons in turn may cause The fission in three uranium nuclei producing nine neutrons. These nine neutrons in turn may produce twenty seven neutrons and so on. A chain reaction is a self propagating process in which the number of neutrons goes on multiplying rapidly almost in a geometrical progression .

Two types of chain reactions are possible.

(i) In the uncontrolled chain reaction, the number of neutrons multiply indefinitely and the entire amount of energy is released within a fraction of a second. This type of chain reaction takes place in atom bombs.

(ii) In the controlled chain reaction the number of fission producing neutron is kept constant and is always equal to one. The reaction is sustained in a controlled manner . Controlled chain reaction is taking place in a nuclear reactor. The chain reaction is possible, only when the loss of neutrons is less than the neutrons produced.

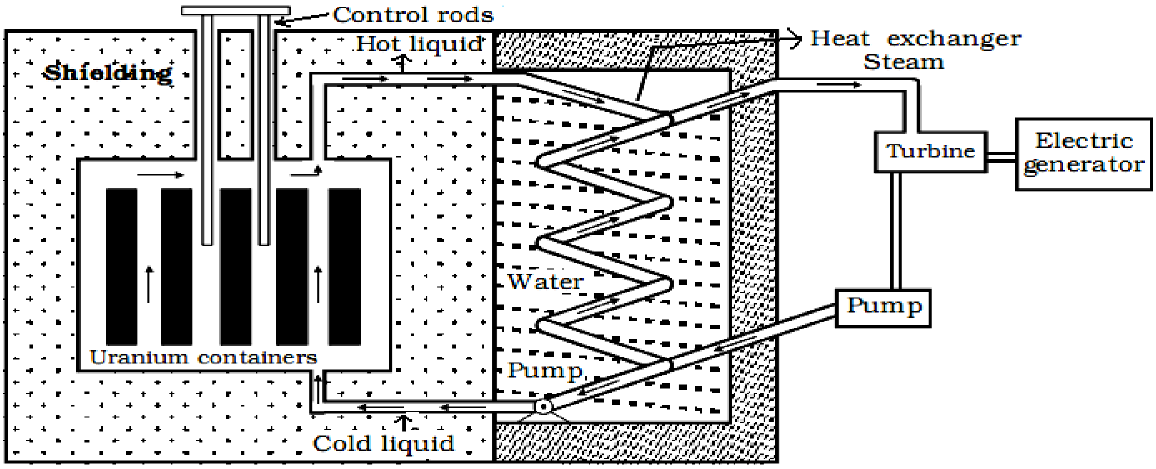
Nuclear reactor :-

A nuclear reactor is a device in which the nuclear fission reaction takes place in a self sustained and controlled manner.

Components of a nuclear reactor are shown above.

(i) Fissile material or fuel:-The fissile material or nuclear fuel generally used is $_{92}U^{235}$,which exist in a small amount (0.7%) in natural uranium. Natural uranium which is enriched with more number of $_{92}U^{235}$ (2 –4%), is used as fuel in some reactors. U^{233} and Pu^{239} are also used as fuel in some of the reactors. It is taken in the form of some fuel rods .

(ii) Moderator:- The function of a good moderator is to slow down fast neutrons produced in the fission process by elastic collisions and it does not remove them by absorption. Ordinary water and heavy water , Graphite are the commonly used moderators. The moderator is present in the space between the fuel rods in a channel.



(iii) Control rods:-The control rods are used to control the chain reaction. They are very good absorbers of neutrons. They are made up of boron or cadmium. The control rods are inserted into the core and they pass through the space in between the fuel tubes and through the moderator. By pushing them in or pulling out, the reaction rate can be controlled. In our country, all the power reactors use boron carbide (B_4C), a ceramic material as control rod.

(iv) The cooling system:-The cooling system removes the heat generated in the reactor core. Ordinary water, heavy water and liquid sodium are the commonly used coolants. A good coolant must possess large specific heat capacity and high boiling point.

The coolant passes through the tubes containing the fuel bundle and carries the heat from the fuel rods to the steam generator through heat exchanger. The steam runs the turbines to produce electricity in power reactors.

(v) Shielding:-

As a protection against the harmful radiations, the reactor is surrounded by a concrete wall of thickness about 2 to 2.5 m.

Uses of reactors

(1) Nuclear reactors are mostly aimed at power production, because of the large amount of energy evolved with fission.

(2) Nuclear reactors are useful to produce radio-isotopes.

(3) Nuclear reactor acts as a source of neutrons, hence used in the scientific research.

Q: Why moderators are used in reactors ?

The average energy of a neutron produced in fission of $_{92}U^{235}$ is 2 MeV.

These neutrons unless slowed down will escape from the reactor without interacting with the uranium nuclei .So a very large amount of fissionable material is used for sustaining the chain reaction. To slow down the fast neutrons in reactors, light nuclei called moderators are provided along with the fissionable nuclei . Moderators commonly used are water, heavy water (D_2O) & graphite.

Using of moderator, it is possible to make the multiplication factor < 1.

Q: What is multiplication factor (K) of a reactor?

It is the ratio of number of fission produced by a given generation of neutrons to the number of fission of the preceeding generation .

It is the measure of the growth rate of the neutrons in the reactor.

For K = 1, the operation of the reactor is said to be critical, which is required for steady power operation.

If K > 1, the reaction rate and the reactor power increases exponentially. Unless the factor K is brought down very close to unity, the reactor will become supercritical and can even explode.

Q:What are the role of control rods and safety rods ?

The reaction rate is controlled through control-rods made out of neutron-absorbing material such as cadmium. In addition to control rods, reactors are provided with safety rods which, when required, can be inserted into the reactor and K can be reduced rapidly to less than unity.

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Q: Although not fissionable, why U^{238} is used as nuclear fuel?

The abundant $_{92}U^{238}$ isotope is not fissionable , on capturing a neutron leads to the formation of plutonium. The series of reactions involved is

$$^{238}_{92}U + n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np + e^- + \bar{\nu}$$

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + e^- + \bar{\nu}$$

Plutonium is highly radioactive and can also undergo fission under bombardment by slow neutrons.

Q: What is pressurised-water reactor ?

In such a reactor, water is used both as the moderator and as the heat transfer medium. In the primary-loop, water is circulated through the reactor vessel and transfers energy at high temperature and pressure (at about 600 K and 150 atm) to the steam generator, which is part of the secondary-loop. In the steam generator, evaporation provides high-pressure steam to operate the turbine that drives the electric generator. The low-pressure steam from the turbine is cooled and condensed to water and forced back into the steam generator.

Q: What is a chemical reactor ?

Chemical reactors are those reactors in which energy is produced by burning coal, wood, gas and petroleum products .

Q: What is the energy released in nuclear fission of 1 kg of $_{92}U^{235}$?

about3 × 10^4 MW.

Q: What are the radioactive waste ?

The fission products and heavy transuranic elements such as plutonium and americium.

Q: What are the safety measures taken by of the Indian Atomic Energy programme

An appropriate plan is being evolved to study the possibility of converting radioactive waste into less active and short-lived material.

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Nuclear fusion

Nuclear fusion is a process in which two or more lighter nuclei combine to form a heavier nucleus.

1: The mass of the product nucleus is always less than the sum of the masses of the individual lighter nuclei. The difference in mass is converted into energy.

2: The fusion process can be carried out only at a extremely high temperature of the order of 10^7 K because, only at these very high temperatures the nuclei are able to overcome their mutual repulsion.

3: Therefore before fusion, the lighter nuclei must have their temperature raised by several million degrees. The nuclear fusion reactions are known as thermo-nuclear reactions.

Nuclear fission	Nuclear fusion
1.The process of breaking up of the nucleus of a heavier atom into two fragments	1.The process in which two or more lighter nuclei combine to form a heavier nucleus.
2. $_{92}U^{235} + {}_0n^1 \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\ {}_0n^1 + Q$	2. $_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1$ + energy
3.It takes place at room temperature	3. It takes place at the temperature of the sun
4. Neutron is the connecting particle	4.Proton is the connecting particle.
5.Atom bomb is the example	5.Hydrogen bomb is the example.

Hydrogen bomb

The principle of nuclear fusion is used in hydrogen bomb.

It is an explosive device to release a very large amount of energy by the fusion of light nuclei. The temperature required for the purpose of fusion is produced by fission reactions. Deuteron and triton are fussed together at the sight of the explosion of the atom bomb as a temperature of about of 50 million ^oC is produced in fission. Favourable temperature initiates the fusion of light nuclei in an uncontrolled manner releasing enormous amount of heat energy. The fusion reaction in hydrogen bomb is $_1H^3 + _1H^2 \rightarrow _2He^4 + _0n^1$ **+ energy**

1.Q: If the barrier height for protons is about 400 keV, then what is the temperature at which protons will have enough energy to overcome the coulomb's barrier ? How it can be achieved ?

Ans: We know , kinetic energy , K = (3/2)k T = 400 keV

Then T = 3×10^9 K.

Such a high temperature is needed so that the particles have enough energy , due to their thermal motions , to penetrate the coulomb barrier. The process required for this is called thermonuclear fusion .

It is the process by which energy is produced in sun.

2.Q: How energy is produced in sun or in a star?

The proton-proton (p, p) cycle by which this occurs is represented by the following sets of reactions:

$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu + 0.42\text{ MeV} \quad \text{(i)}$$

$$e^+ + e^- \rightarrow \gamma + \gamma + 1.02\text{ MeV} \quad \text{(ii)}$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma + 5.49\text{ MeV} \quad \text{(iii)}$$

$$^3_2H + ^3_2H \rightarrow ^4_2He + ^1_1H + ^1_1H + 12.86\text{ MeV} \quad \text{(iv)}$$

2(i) + 2(ii) + 2(iii) +(iv), the net effect is

$$4\,^1_1H + 2e^- \rightarrow ^4_2He + 2\nu + 6\gamma + 26.7\text{ MeV}$$

$$\text{or } (4\,^1_1H + 4e^-) \rightarrow (^4_2He + 2e^-) + 2\nu + 6\gamma + 26.7\text{ MeV} \quad ,$$

Thus, four hydrogen atoms combine to form an $_2He^4$ atom with a release of 26.7 MeV of energy.

3.Q: What is red giant ?

Ans- Sun is going on for about 5×10^9 y, and there is enough hydrogen to keep the sun going for about the same time into the future.

In about 5 billion years, the sun's core will be largely helium, will begin to cool and the sun will start to collapse under its own gravity. This will raise the core temperature and cause the outer envelope to expand, turning the sun into what is called a red giant.

If the core temperature increases to 10^8 K again, energy can be produced through fusion once more , but this time by burning helium to make carbon. However, elements more massive than those near the peak of the binding energy curve cannot be produced by further fusion. The energy generation in stars takes place via thermonuclear fusion.

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