Nuclear energy is the energy released when nuclei undergo a ***nuclear reaction,*** i.e., when one nucleus or a pair of nuclei, due to their interaction, undergo a change in their structure resulting in new nuclei and generating energy in the process. While the energy generated in chemical reactions is of the order of few eV per reaction, the amount of energy released in a nuclear reaction is of the order of a few MeV. Thus, for the same weight of fuel, the nuclear energy released is about a million times that released through chemical reactions. However, nuclear energy generation is a very complex and expensive process and it can also be extremely harmful.

We have seen that the mass of a nucleus is smaller than the sum of masses of its constituents. The difference in these two masses is the binding energy of the nucleus. It would be the energy released if the nucleus is formed by bringing together its constituents from infinity. This energy is large (in MeV), and this process can be a good source of energy. In practice, we never form nuclei starting from individual nucleons. However, we can obtain nuclear energy by two other processes (i) **nuclear fission** in which a heavy nucleus is broken into two nuclei of smaller masses and (ii) **nuclear fusion** in which two light nuclei undergo nuclear reaction and fuse together to form a heavier nucleus. Both fission and fusion are nuclear reactions. Let us understand how nuclear energy is released in the two processes.

Nuclear Fission:

We have seen in graph that the binding energy per nucleon (E_B/A) depends on the mass number of the nuclei. This quantity is a measure of the stability of the nucleus. As seen from the graph, the middle weight nuclei (mass number ranging from 50 to 80) have highest binding energy per nucleon and are most stable, while nuclei with higher and lower atomic masses have smaller values of E_B/A**.** The value of E_B/A goes on decreasing till A~238 which is the mass number of the heaviest naturally occurring element which is uranium. Many of the heavy nuclei are unstable and decay into two smaller mass nuclei.

Let us consider a case when a heavy nucleus, say with A ~230, breaks into two nuclei having A between 50 and 150. The E_B/A of the product nuclei will be higher than that of the parent nucleus. This means that the combined masses of the two product nuclei will be smaller than the mass of the parent nucleus. The difference in the mass of the parent nucleus and that of the product nuclei taken together will be released in the form of energy in the process. This process in which a heavy nucleus breaks into two lighter nuclei with the release of energy is called ***nuclear fission*** and is a source of nuclear energy.

One of the nuclei used in nuclear energy generation by fusion is ${}^{236}_{92}U$ .This has a half-life of 2.3×10^7 years and an activity of 6.5×10^{-5}Ci/g. However, it being fissionable, most of its nuclei have already decayed and it is not found in nature. More than 99% of natural uranium is in the form of ${}^{238}_{92}U$ and less than 1% is in the form of ${}^{235}_{92}U$. ${}^{238}_{92}U$ also decays, but its half-life is about 10^3 times higher than that of ${}^{236}_{92}U$ and is therefore not very useful for energy generation. The species needed for nuclear energy generation, i.e., ${}^{236}_{92}U$ can be obtained from the naturally occurring ${}^{235}_{92}U$ by bombarding it with slow neutrons. ${}^{235}_{92}U$ absorbs a neutron and yields ${}^{236}_{92}U$. This reaction can be written as ${}^{235}_{92}U + n \rightarrow {}^{236}_{92}U$. ${}^{236}_{92}U$ can undergo fission in servral ways producing different pairs of daughter nuclei and generating different amounts of energy in the process. Some of its decays are

$${}^{236}_{92}U \rightarrow {}^{137}_{53}I + {}^{97}_{39}Y + 2n \qquad 184.558.\text{Mev}$$

$${}^{236}_{92}U \rightarrow {}^{140}_{56}Ba + {}^{94}_{36}Kr + 2n \qquad 171.485.\text{Mev}$$

$${}^{236}_{92}U \rightarrow {}^{133}_{51}Sb + {}^{99}_{41}Nb + 4n \qquad \text{Home Work}$$

Some of the daughter nuclei produced are not stable and they further decay to produce more stable nuclei. The energy produced in the fission is in the form of kinetic energy of the products, i.e., in the form of heat which can be collected and converted to other forms of energy as needed.

Uranium Nuclear Reactor :

A nuclear reactor is an apparatus or a device in which nuclear fission is carried out in a controlled manner to produce energy in the form heat which is then converted to electricity. In a uranium reactor, $^{235}_{92}U$ is used as the fuel. It is bombarded by slow neutrons to produce $^{236}_{92}U$ which undergoes fission.

Chain Reaction:

Neutrons are produced in the fission reaction shown in above reactions produce 2 neutrons while others produce 3 or 4 neutrons. The average number of neutrons per reaction can be shown. These neutrons are in turn absorbs by other $^{235}_{92}U$ nucclei to produce $^{236}_{92}U$ which undergo fission. This can have a cascading effect and the number of neutrons produced and therefore the number of $^{236}_{92}U$ nuclei produced can increase quickly. This is called a ***chain reaction.*** Such a reaction will lead to a fast increase in the number of fissions and thereby in a rapid increase in the amount of energy produced. This will lead to an explosion. In a nuclear reactor, methods are employed to stop a chain reaction from occurring in fission and energy generation is allowed to occur in a controlled fashion. The energy generated, which is in the form of heat, is carried away and converted to electricity by using turbines etc.

More than 15 countries have nuclear reactors and use nuclear power. India is one of them. There are 22 nuclear reactors in India,the largest one being at Kudankulam, Tamil Nadu. Maximum nuclear power is generated by the USA.

Nuclear Fusion:

We have seen that light nuclei (A < 40) have lower E_B/A as compared to heavier ones. If any two of the lighter nuclei come sufficiently close, within about one fm (10^{-15}m) of each other, then they can undergo nuclear reaction and form a heavier nucleus. The heavier nucleus will have higher E_B/A than the reactants. The mass of the product nucleus will therefore be lower than the total mass of the reactants, and energy of the order of MeV will be released in the process. This process wherein two nuclei fuse together to form a heavier nucleus accompanied by a release of nuclear energy is called ***nuclear fusion.***

For a nuclear reaction to take place, it is necessary for two nuclei to come to within about 1 fm (10^{-15}m) of each other so that they can experience the nuclear forces. It is very difficult for two atoms to come that close to each other due to the electrostatic repulsion between the electrons of the two atoms. This problem can be solved by stripping the atoms of their electrons and producing bare nuclei. It is possible to do so by giving the electrons energies larger than the ionization potentials of the atoms by heating a gas of atoms. But even after this, the two bare nuclei find it very difficult to go near each other due to the repulsive force between their positive charges. For nuclear fusion to occur, we have to heat the gas to very high temperature thereby providing the nuclei with very high kinetic energies. These high energies can help them to overcome the electrostatic repulsion and come close to one another. As the positive charge of a nucleus goes on increasing with increase in its atomic number, the kinetic energies of the nuclei, i.e., the temperature of the gas necessary for nuclear fusion to occur goes on increasing with increase in ***Z.***

Nuclear fusion is taking place all the time in the universe. It mostly takes place at the centres of stars where the temperatures are high enough for nuclear reactions to take place. There, light nuclei fuse into heavier nuclei generating energy in the process. Nuclear fusion is in fact the source of energy for stars. Most of the elements heavier than boron till iron, that we see around us today have been produced through nuclear fusion inside stars.

The temperature at the centre of the Sun is about 10^7 K. The nuclear reactions taking place at the centre of the Sun are the fusion of four hydrogen nuclei, i.e., protons to form a helium nucleus. Of course, because of the electrostatic repulsion and the values of densities at the centre of the Sun, it is extremely unlikely that four protons will come sufficiently close to one another at a given time so that they can combine to form helium. Instead, the fusion proceeds in several steps. The effective reaction can be written as

$$4p \rightarrow \alpha + 2e^{+} + \text{neutrinos} + 26.7 \text{ MeV}.$$

These reactions have been going on inside the Sun since past 4.5 billion years and are expected to continue for similar time period in the future. At the centres of other stars where temperatures are higher, nuclei heavier than hydrogen can fuse generating energy.

The discussion on nuclear energy will not be complete without mentioning its harmful effects. If an uncontrolled chain reaction sets up in a nuclear fuel, an extremely large amount of energy can be generated in a very short time. This fact has been used to produce what are called atom bombs or nuclear devices. Either fission alone or both fission and fusion are used in these bombs. The first such devices were made towards the end of the second world war by America. By now, several countries including India have successfully made and tested such nuclear devices. America remains the only country to have actually used two atom bombs which completely destroyed the cities of Hiroshima and Nagasaki in Japan in early August 1945.

1. Choose the correct option. **HOME WORK**

i) In which of the following systems will the radius of the first orbit of the electron be smallest?
(A) hydrogen (B) singly ionized helium (C) deuteron (D) tritium

ii) The radius of the 4^{th} orbit of the electron will be smaller than its 8^{th} orbit by a factor of
(A) 2 (B) 4 (C) 8 (D) 16

iii) In the spectrum of hydrogen atom which transition will yield longest wavelength?
(A) n = 2 to n = 1 (B) n = 5 to n = 4 (C) n = 7 to n = 6 (D) n = 8 to n = 7

iv) Which of the following properties of a nucleus does not depend on its mass number?
(A) radius (B) mass (C) volume (D) density

v) If the number of nuclei in a radioactive sample at a given time is ***N*,** what will be the number at the end of two half-lives?
(A) N/2 (B) ***N/4*** (C) ***3 N/4*** (D) ***N/8***