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NUCLEAR FISSION AND FUSION

We all know that the sun supports life on the earth by continuously providing energy. It has been doing so for the last several billion years and will continue to do so for billions of years to come. What is the source of this huge amount of energy emitted by the sun? This question fascinated human mind always. But now we reliably know that the energy in the core of sun is produced by fusion of hydrogen nucli into helium at very high temperatures. This is also true of other stars. Imitation of these conditions in a fusion reactor is being highlighted as the ultimate source of all our energy requirements in coming years.

Similarly, you most have read about energy security and the role of nuclear energy to produce electricity in our nuclear reactors at Tarapore, Kota, Kaiga, Narora, Kalpakkam and Kakrapara. Similarly, you may have read in newspapers that on August 6, 1945, an atom bomb dropped over Hiroshima, a large city of Japan, destroyed the entire city almost completely in a span of a few seconds and lacs of lives were lost. It released an energy equivalent to that released by the explosion of a 20,000 ton TNT (tri-nitro toluene) bomb and was completely new in human history. Since then, more powerful (atomic, hydrogen and neutron) bombs have been made whose destructive power is equivalent to several Mega tons of TNT. The super powers are said to have stockpiled a large number of such bombs. The destructive power of their stock is so enormous that they can destroy the entire earth several times over. The physical process responsible for such colossal amount of energy is nuclear fission. You will now learn about these processes.

OBJECTIVES

After studying this lesson, you should be able to

- *state conservation laws for nuclear reactions;*

- *explain the terms nuclear chain reaction, controlled and uncontrolled fission chain reactions;*
- *describe working of a nuclear reactor; and*
- *explain the mechanism of production of energy in stars.*

27.1 CHEMICAL AND NUCLEAR REACTIONS

27.1.1 Chemical Reaction

We know that all substances are made up of atoms. In lesson 26, you learnt that electrons in the outermost orbit govern the chemical properties of an element. That is, atoms combine with other atoms or molecules (a group of atoms) and rearrange their valence electrons This is accompanied by reduction in their potential energy.

The formation of a new compound molecule due to rearrangement of valence electrons in interacting atoms and molecules with the release or absorption of energy is called a chemical reaction. In this process, the nucleus is not affected at all. Even the electrons in the inner orbits remain unaffected.

An example of a chemical reaction is the interaction of carbon atoms with oxygen molecules to produce carbon dioxide :

$$C + O_2 \rightarrow CO_2 + 4.08 \text{ eV} \qquad (27.1)$$

In this chemical reaction, 4.08* eV *energy is released for each reacting* carbon *atom. It is called the binding energy (B.E) of* CO_2 *molecule. Reactions which result in release of energy are said to be *exothermic*. Chemical reactions which require energy to be supplied to be initiated are *endothermic*. For example, if 4.08 eV of energy is given to a CO_2 molecule under suitable conditions, it will break up into its constituents:

$$CO_2 + 4.08 \text{ eV} \rightarrow C + O_2 \qquad (27.2)$$

As shown in Eq. (27.1), 4.08 eV energy leaves the system to form CO_2 gas. Therefore, the mass of CO_2 molecule will be less than the total mass of C and O_2 by a mass equivalent of 4.08 eV. The loss of mass Δm can be calculated using the relation $E = mc^2$:

$$\Delta m = \frac{4.08 \times 1.602 \times 10^{-19}}{9 \times 10^{16}} = 7.26 \times 10^{-36} \text{ kg} \qquad (27.3)$$

Such a small change in mass cannot be detected and we say that the mass is conserved in chemical reactions, though slight change of mass does occur.

The important points to be noted in chemical reactions are

- Energies of the order of 10 eV are involved.
- Change of mass is of the order of 10^{-35} kg, which is extremely small and we say that the mass is conserved.
- The total number of atoms of each type on the right hand side of the chemical equation is always equal to the total number of atoms of each type on the left hand side.

27.1.2 Nuclear Reactions

In nuclear reactions, the nuclei, not electrons, of the reactants interact with each other. They result in the formation of new elements. This process is also called transmutation of nuclei. From the previous lesson, you may recall that in nuclear reactions energies of the order of MeV are involved.

We know that the entire positive charge of an atom is concentrated in its nucleus, whose size is of the order of 10^{-15} m. The nucleus is surrounded by electrons revolving in certain specified orbits. These create a strong electrostatic potential barrier (also called the Coulomb barrier) as shown in Fig. 27.1. The Coulomb barrier is about 3 MeV for carbon nuclei and 20 MeV for lead nuclei. It means that a charged projectile aimed at a nucleus will experience strong repulsion by the Coulomb barrier of the target nucleus. If the kinetic energy of projectile is not large enough to penetrate the barrier, it will come back without producing any nuclear reaction. For a proton to enter a carbon nucleus and produce transmutation, its energy should be more than 3MeV or so. It is because of the large amounts of energy involved in nuclear reactions that we do not observe these reactions in everyday life at ordinary temperatures and pressures.

The phenomenon of nuclear ***transmutation*** or nuclear reaction was discovered by Lord Rutherford in the year 1919. He bombarded nitrogen gas with high energy α-particles of energy 7.7 M eV obtained from a polonium source. He observed

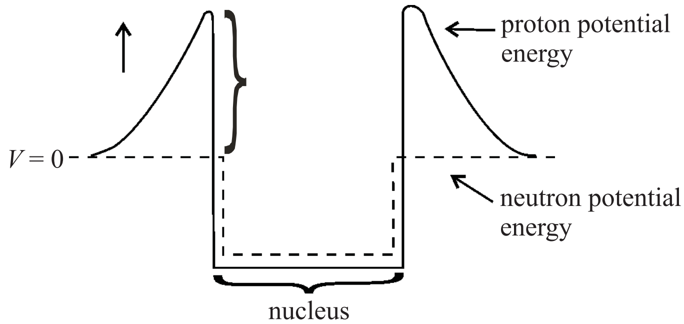


Fig. 27.1 : Proton and neutron potential energies near a nucleus

Notes

that nitrogen transformed into oxygen. This change was accomponied by high energy protons :

$$ {}^{4}_{2}\text{He} + {}^{14}_{17}\text{N} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H} \qquad (27.5)$$

The oxygen nuclei and protons carry away 6.5 MeV. Clearly this reaction can occur if 1.2 MeV energy is supplied from outside. Therefore, it is an endothermic nuclear reaction. When aluminium is bombarded by 7.7 M eV alpha particles from polonium, the following nuclear reaction takes place and 10.7 MeV energy is released:

$$ {}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow {}^{30}_{14}\text{Si} + {}^{1}_{1}\text{H} \qquad (27.6)$$

Here we see that more energy is released than the input energy; it is an exothermic reaction. Note that there is a gain of nearly 3 MeV energy per reaction, which is approximately 700,000 times the energy released in burning of one carbon atom. *But this reaction can't be used for production of energy because out of 125,000 incident alpha particles only one succeeds in producing the reaction.* Hence on the whole, there is much more energy spent than produced.

Nuclear reactions can also be produced by protons, deuterons, neutrons and other light nuclei. Of these, *neutrons are the best projectiles for producing nuclear reactions; being neutral particles, they do not experience Coulomb repulsion..* Thus even thermal neutrons (i.e. neutrons having energy 0.0253 eV) can penetrate the target nucleus and produce a nuclear reaction.

Some typical examples of nuclear reactions produced by protons, deutrons and neutrons are:

$$ {}^{6}_{3}\text{Li} + {}^{1}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{4}_{2}\text{He} \qquad (27.7)$$

$$ {}^{10}_{5}\text{B} + {}^{2}_{1}\text{H} \rightarrow 3\,{}^{4}_{2}\text{He} \qquad (27.8)$$

$$ {}^{10}_{5}\text{B} + \text{n} \rightarrow {}^{7}_{3}\text{Li} + {}^{4}_{2}\text{He} \qquad (27.9)$$

Like chemical reactions, nuclear reactions also follow conservation laws.We state these now.

27.1.3 Conservation Laws for Nuclear Reactions

- *The sum of the mass numbers of the reactants is equal to the sum of mass numbers of the products. In Eqn.* (27.7), *mass number* $7 = 3 + 4 = 6 + 1$ *is conserved.*

- *The sum of atomic numbers of the reactants is equal to the sum of atomic numbers of the products. In Eqn.* (27.7), *atomic number* 4 = 3 + 1 = 2 + 2 *is conserved.*
- *Nuclear reactions follow the law of conservation of energy. We know that mass is concentrated form of energy. Therefore the sum of input kinetic energy plus the mass of the reactants is equal to the output kinetic energy plus the mass of the products.*
- *Nuclear reactions follow the law of conservation of momentum, which results in distribution of kinetic energy among various product nuclei.*

Now, answer the following questions.

INTEXT QUESTIONS 27.1

1. Complete the following equations of nuclear reaction.

   (a) ${}^{19}_{9}F + {}^{1}_{1}H \rightarrow {}^{16}_{8}O + ?$

   (b) ${}^{27}_{13}Al + {}^{1}_{0}n \rightarrow ? + {}^{4}_{2}He$

   (c) ${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + ?$

   (d) ${}^{63}_{29}Cu + {}^{2}_{1}D \rightarrow {}^{64}_{30}Zn + ?$

2. Calculate the energy released in the nuclear reaction given below

   ${}^{10}_{5}B + {}^{2}_{1}D \rightarrow 3\,{}^{4}_{2}He + Q$

   Given that $m({}^{10}B)$ = 10.01294 u; $m\left({}^{2}_{1}D\right)$ = 2.014103 u, and $m({}^{4}_{2}He)$ = 4.002604 u.

3. ${}^{14}_{7}N$ nucleus, on bombarding with alpha particles, produces ${}^{17}_{8}O$. Write down the reaction equation and calculate the energy released.

   Given that: $m\left({}^{14}_{7}N\right)$ = 14.003014 u; $m\left({}^{17}_{8}O\right)$ = 16.999138 u; $m\left({}^{4}_{2}He\right)$ = 4.002604 u; $m\left({}^{1}_{1}H\right)$ = 1.007825 u and energy of α particle = 7.7MeV.

27.2 NUCLEAR FISSION

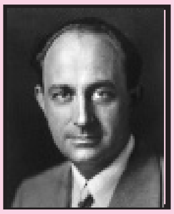
The story of discovery of fision is very fascinating. In the year 1938, Enrico Fermi, Otto Hahn and others irradiated uranium nuclei with slow neutrons to produce transuranic elements (having Z greater than 92), which do not occur in nature. When incident neutrons were captured by the uranium nuclei, the neutron-proton ratio increased. In reducing this ratio, it was expected that uranium would become β–active. That is a neutron would essentially behave as if it has changed into a proton resulting in the release of a β-particle and some energy according to the equation:

$$ {}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e} + \text{Q} \qquad (27.10)$$

In this process, a new transuranic element having atomic number 93 was expected to be produced. In fact, Fermi and his co-researchers observed β–activities with half-lives different from any of the known values for heavy elements in the vicinity of uranium. From those observations, they concluded that transuranic elements had been produced. And to identify the element, they carried out chemical analysis but failed.

In the same year, Otto Hahn and Fritz Strausmann carried out a series of experiments and established that barium, an element of intermediate mass number, rather than a transuranic element, was one of the products of the reaction and it was accomponied by release of nearly 200 MeV of energy. This result – the product of slow neutron bombardment of uranium was barium – was completely unexpected and defied all knowledge of nuclear physics of that time. These findings were reported in *Nature* in Dec. 1938.

Initially, Lise Meitner and Otto Frisch explained these results on the basis of liquid drop model of nucleus and named this process *nuclear fission* using the analogy with biological cell division. Later on, Bohr and Wheeler calculated the amount of energy released in the process, confirming the physical basis of this model.



Enrico Fermi
(1901 – 1954)

Enrico Fermi, the Italy born physicist, was responsible for peaceful uses of nuclear energy for mankind. He demonstrated that nuclear transformations may occur in any element exposed to stream of neutrons. He achieved self-sustained nuclear fission chain reaction in 1942.

Fermi was only 25 years old when he formulated the Fermi–Dirac statistics, applicable to particles having half integral spin values (called fermions). At the time of his premature death, he was engrossed in theoretical studies of cosmic radiations.

27.2.1 Mechanism of Nuclear Fission

In the year 1939, Bohr and Wheeler developed the theory of fission using the analogy between nuclear forces and the forces which bind molecules in a liquid. They predicted that ${}^{235}_{92}U$ was more fissile than ${}^{235}_{92}U$. Refer to Fig. 27.2. If shows the schematics of nuclear fission of ${}^{235}_{92}U$ by thermal neutrons according to the equation.

$$ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{36}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + Q \qquad (27.11)$$

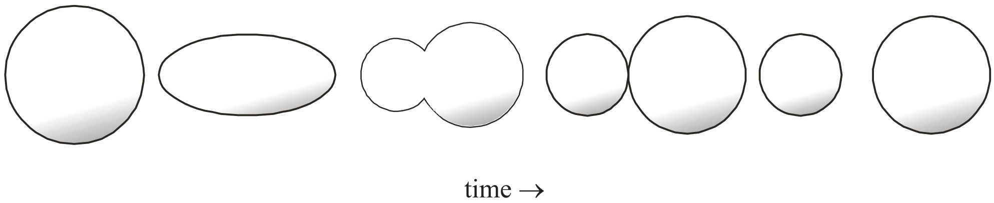


Fig. 27.2 : Nuclear-fission of a nucleus according to the liquid drop model

The emitted neutrons have energy of the order of a few MeV, and $Q \simeq 200 MeV$.

Note that a fission event occurs within 10^{-17} s of neutron capture and fission neutrons are emitted within about 10^{-14} s of the event. Moreover, the fission fragments are of unequal mass; one being 1.5 to 2 times heavier than the other. Also, Eqn. (27.11) gives only one of the more than 40 different modes in which a ${}^{235}_{92}U$ nucleus can fission. It means that about 80 different nuclei of intermediate masses are produced in the fission of ${}^{235}_{92}U$. The heavier fragments lie in the mass range 125–150 with the a maximum around 140, whereas the lighter fragments lie in the range 80 – 110 with a maximum around 95. The number of neutrons emitted is either two or three and the average number of neutrons produced per fission of ${}^{235}U$ is 2.54

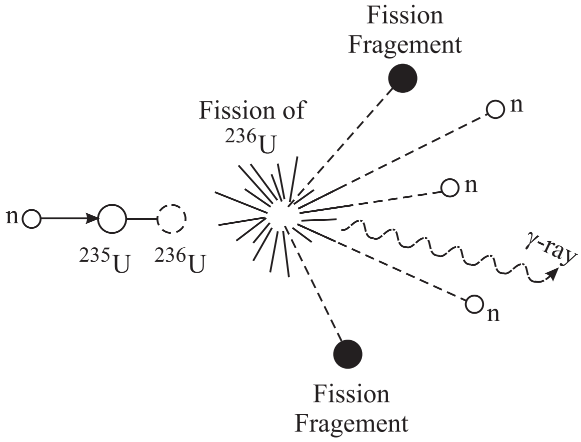


Fig. 27.3 : Nuclear fission

Bohr and Wheeler treated the nucleus as a charged spherically symmetric liquid drop in its equilibrium (lowest energy) state. According to them, when a nucleus captures a thermal neutron, the binding energy (BE) of this neutron, which is 6.8 MeV per atomic mass unit for ^{235}U, is released. This energy excites the nucleus and distorts its shape. While the force of surface tension tries to restore the original shape, the Coulomb force tends to distort it further. As a result, it oscillates between spherical and dumb bell shapes, as shown in Fig.27.2, depending on the energy of excitation. When the energy gained by the nucleus is large, the amplitude of these oscillatious pushes the nuclens into dumb bell shape. When the distance between the two charge centres exceeds a critical value, electrostatic repulsion between them overcomes nuclear surface tension and pushes the nucleus into two parts resulting in fission.

A substance like $^{235}_{92}U$ which undergoes fission by thermal neutrons is called a fissile material. Other fissile materials are $^{233}_{90}Th$, $^{233}_{92}U$ and $^{239}_{93}Pu$. You may note that all these nuclei have odd mass number and even atomic number.

We can estimate the amount of energy released in the fission of $^{235}_{92}U$ by calculating the mass defect as follows:

Table 27.1 Energy Generated in a Nuclear Reaction

Reactants	Mass	Products	Mass
^{235}U	235.0439 u	$^{141}_{56}Ba$	140.9139 u
^{1}n	1.008665 u	$^{92}_{36}Kr$	91.8973 u
		$3 \times Vn$	3.025995 u
Total mass	236.052565 u	**Total mass**	235.837195 u
Mass defect	0.21537u		
Energy released	$0.21537 \times 931 \simeq 200$ MeV		

27.2.2 Nuclear Chain Reaction

You have now learnt that when a neutron is captured by $^{235}_{92}U$, it splits into two fragments and 2-3 neutrons are emitted. These are capable of causing further fissions. This immediately presented the exciting possibility of maintaining a fission chain reaction in which each fission event removes one neutron and replaces that by more than two. When

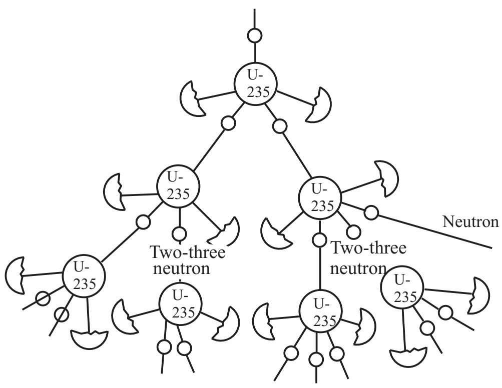


Fig. 27.4 : Nuclear Chain reaction

the rate of production of neutrons equals the rate of loss of neutrons, the reaction is said to be *self-sustained*. The device designed to maintain a self-sustained and controlled chain reaction is called a *nuclear reactor*.

Nuclear reactors are usually classified according to the purpose for which they are used. So a nuclear power reactor is used to produce electricity and a research reactor is used to produce radioisotopes for medical purposes, carrying out experiments for refinements or applied research. We also categorise nuclear reactors as fast and thermal, depending on the energy of neutrons causing fission. In India, we have thermal power reactors at Tarapore, Narora, Kota, Kaiga, etc. At Kalpakkam, we are developing a fast breeder research reactor.

You will now learn about a nuclear reactor in brief.

27.3 NUCLEAR REACTOR

Ever since the first nuclear reactor was constructed by Fermi and his co-workers at the university of Chicago USA, a large number of reactors have been built the world over primarily to meet demand for energy. Some countries generate as much as 70% of their total energy from nuclear reactors. In India, the contributions of nuclear energy is only about 2%, but efforts are on to increase this share. In absolute terms, we are generating about 20,000 MWe from nuclear reactors.

Nuclear reactors have huge complex structures and great care has to be exercised in designing them. The basic principle of a nuclear power plant is very simple and analogous to any power plant. The heat liberated in fission is used to produce steam at high pressure and high temperature by circulating a coolant, say water, around the fuel. (In a coal fired station, coal is burnt to produce steam. Since one fission event generates about 7×10^5 times more energy than that produced in burning one atom of carbon, we can cut down on emission of greenhouse gases substantially by switching over to nuclear energy. However, there are some complex social and political issues with global dimensions that will ultimately decide our ultimate nuclear energy options.)

The steam runs a turbine–generator system to produce electricity. (In research reactors, the heat is discharged into a river or sea. You many have heard about Bhahha Atomic Research Centre at Trombay, Mumbai or Indira Gandhi Atomic Research Centre at Kalpakkam. The heat generated by the research reactors at these centres is discharged into the Arabian sea and the Bay of Bengal, respectively.)

The general features of a reactor are illustrated in Fig. 27.5. All nuclear reactors consist of:

- A *reactor core,* where fission takes place resulting in release of energy. It has fuel rods (embedded in a modertor in a thermal reactors), and *control rods* to maintain the chain reaction at the desired level. *Coolant* is circulated to remove the heat generated in fission. Usually, heavy water or ordinary water are used as coolants and cadmium or boron are used for control rods.

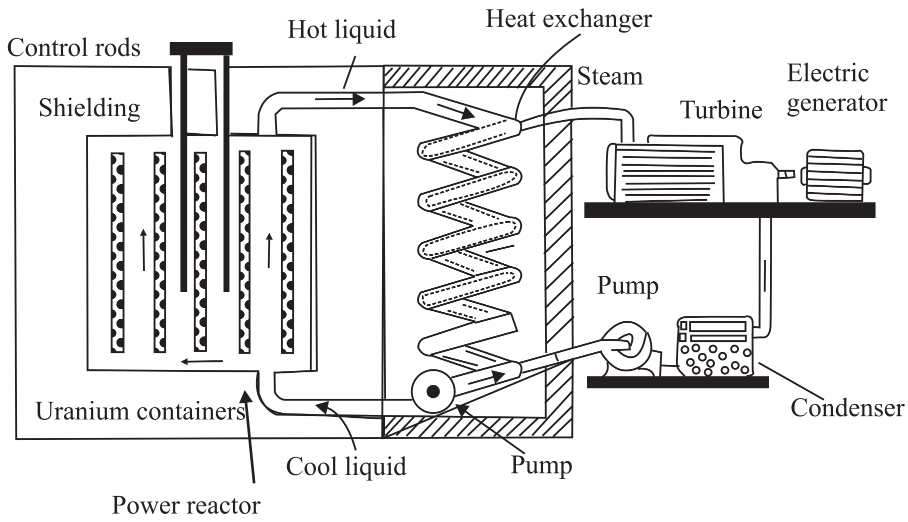


Fig. 27.5 : Schematic diagram of a nuclear reactor

- A *reflector is* put next to the core to stop neutron leakage from the core.
- The whole assembly is placed inside a vessel, called *pressure vessel*. Usually, a few inches thick stainless steel is used for this purpose.
- A thick *shield* is provided to protect the scientists and other personnel working around the reactor from radiations coming from the reactor core. It is usually in the form of a thick concrete wall.
- The entire structure is placed inside a *reactor building*. It is air tight and is maintained at a pressure slightly less than the atomospheric pressure so that no air leaks out of the building.

The heat generated inside the reactor core of a reactor due to fission is removed by circulating a *coolant*. The heated coolant is made to give up its heat to a secondary fluid, usually water in a heat exchanger. This generates steam, which is used to drive turbine-generator system to produce electricity in a power plant and discharged into a river/lake/sea in a research reactor.

INTEXT QUESTIONS 27.2

1. Why does a ${}^{238}_{92}U$ nucleus become β–active after absorbing a neutron?

2. Out of ${}^{238}_{92}U$, ${}^{141}Ba$, ${}^{239}Pu$, and ${}^{12}_{6}C$, which nucleus is fissile?

3. How much energy is released when ${}^{235}_{92}U$ undergoes nuclear fission?

27.4 NUCLEAR FUSION

You now know that uranium nucleus can be made to split into lighter nuclei resulting in release of huge amount of energy. You may now ask: Can we combine lighter nuclei to produce energy? To discover answer to this question, refer to the binding energy per nucleon (BE/A) curve (Fig.26.2). You will note that binding energy per nucleon increases as we go from hydrogen to helium . It means that helium is more stable than hydrogen. Consider the following reaction:

$$_1D^2 + {}_1D^2 \rightarrow {}_2He^4 + Q$$

You can easily calculate the B.E of reactants and products:

$$\text{Total B.E of reactants, } BE_1 = 2 \times 2.22 = 4.44 \text{ MeV}$$

$$\text{Total B.E of products, } BE_2 = 28.295 \text{ MeV}$$

$$Q = (BE_2 - BE_1) \simeq 24 \text{ MeV}$$

∴ Note that the energy released per nucleon in this reaction is 24/4=6 MeV, which is nearly seven times the energy released per nucleon (200/238 = 0.83 MeV) in a nuclear fission event.

The process in which two light nuclei combine to form a heavier nucleus is called nuclear fusion.

Table 27.2 : Binding Energy per nucleon (BE/A) of some light nuclei

Nucleon	*BE/A*(in MeV)
^{2}D	1.11
^{3}T	2.827
^{3}He	2.573
^{4}He	7.074
^{6}Li	5.332
^{7}Li	6.541

Fusion process presents itself as a more viable energy option. However, the process of fusion is more difficult to achieve than nuclear fission because both the deuterons are positively charged. When we try to bring them together to fuse into one nucleus, they repel each other very strongly and the reaction is ordinarily impossible.

To achieve this reaction, the deuterons have to be heated to nearly 10 million kelvin so that they acquire sufficient kinetic energy to overcome repulsion before they collide to fuse into helium nucleus. But the problems associated with maintaining such high temperatures continuously and containing the reactants together has not yet been solved fully. The controlled thermonuclear reaction necessary for harnessing this source of energy is however not far now.

Almost inexhaustible amount of deuterium (heavy hydrogen) is present in the ocean. Once we begin to harness this source, our energy problem should be solved for ever. We will get an endless supply of cheap electricity without any pollution. This is because one gram of deuterium (heavy hydrogen) yields about 100,000 kW h of energy.

27.4.1 Energy in the Sun and Stars

The stars like our sun are very massive objects. They have been continuously emitting tremendous amount of energy for the last billions of years.

Such a huge amount of energy cannot be obtained by burning conventional fuels like coal. Nuclear fission can also not be the source of this energy, because heavy elements do not exist in the sun in large quantity. The sun mainly consists of hydrogen and helium gases. Then you may like to know: What is the source of energy in the sun? This question has engaged human intellect for long. As a child, you must have gazed the sky when you learnt the rhyme: Twinkle twinkle litter star, How I wonder what you are!

You may know that the huge mass of the sun produces extremely strong gravitational field, which compresses its constituent gases by enormous pressure resulting in the rise of temperature to millions of kelvin at its centre. It has been estimated that the temperature at the centre of the sun is 20 million kelvin. At such high temperatures and pressures, gas molecules travel at high speeds and collide setting in thermonuclear reaction and resulting in the release of large amount of energy.

Bethe proposed that fusion of hydrogen into helium is responsible for the energy produced in stars:

$$4\,{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,{}^{0}_{+1}\text{e} + \text{Q}$$

The overall result here is: four hydrogen nuclei fuse into a helium nucleus with the release of two positrons (electron-like microscope particles of the same mass but positive charge) and 26.8 MeV energy. ***The tremendous amount of energy released in a thermo-nuclear reaction is the source of energy in stars.*** The quantity of hydrogen in the sun is sufficient to keep it shining for nearly 8 billion years more.

INTEXT QUESTIONS 27.3

1. 200 MeV energy is released in fission of one ${}^{235}_{92}\text{U}^5$ nucleus and 26.8 MeV energy is released in fusion of 4 protons. Which process releases more energy per unit mass?
2. Consider the following reactions:

   (*a*) ${}^{1}_{1}\text{H} + {}^{7}_{3}\text{Li} \rightarrow {}^{4}_{2}\text{He} + Q$.

   (b) ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + {}^{1}_{1}\text{H} + 4\text{MeV}.$

   Calculate Q in the first reaction and mass of tritium in the second reaction.

   Given $m\left({}^{2}_{1}\text{H}\right) = 2.014103\text{u}$, $m\left({}^{4}_{2}\text{H}\right) = 4.002604\text{u}$, $m\left({}^{1}_{1}\text{H}\right) = 1.007825\text{u}$ and

   $m\left({}^{7}_{3}\text{Li}\right) = 7.015982\text{u}.$

27.5 NUCLEAR ENERGY

We need energy for all economic activities in life. The amount of energy consumed per capita is a measure of advancement of a nation. According to a recent UNESCO report (2007), we are consuming about 40% more than what mother earth can generate in the form of food, water and energy. In fact, the human society has been continuously striving for energy security and looking for newer sources of energy. Due to over use, conventional sources of energy are depleting very fast and may exhaust completely in the next one hundred years. The nuclear energy is perhaps an important option for meeting our future energy needs through peaceful applications. Let us discuss these now.

27.5.1 Peaceful Applications

The most important peaceful application of nuclear energy is in the *generation of electricity.* One of the main advantages of nuclear power plant is that the fuel is not required to be fed into it continuously like the gas or coal in a thermal power plant. Further, it does not *pollute the environment to the extent discharge of smoke or ash from fossil fuel/power plants do.* The fuel once loaded in a reactor runs for nearly 6 months at a stretch. Because of this nuclear power plants have been used to power huge ships and submarines.

However, spent fuel of a reactor is highly radioactive because a large number of radio-isotopes are present in it. India has developed its own facility to treat spent fuel and extract it from those *radio-isotopes which find uses in agriculture, medicine, industry and research.* To avoid the spread of radioactive radiations from the radioactive wastes, the radioactive wastes are generally embedded deep inside salt mines in heavy steel cases. Yet, it has evoked considerable controversy due to its destructive potential which was displayed on August 6, 1945, when an atom bomb was dropped on Hiroshima (Japan) killed hundred thousand people in a very short time. Subsequently, even more powerful hydrogen and nitrogen bombs have been developed. These can destroy this beautiful planet many times over.

Nuclear Power in India

The possibility of harnessing nuclear power for civil use was recognised by Dr H.J. Bhabha soon after India got independence. He outlined a three stage development plan for meeting country's nuclear power needs. These are :

- Employ pressurised Heavy Water Reaction (PHWR) fuelled by natural uranium to generate electricity and produce plutonium as a by-product.
- Set up fast breeder reactors burning the plutonium to breed U-233 from thorium.
- Develop the second stage and produce a surplus of fissile material.

Notes

Nuclear power has been produced in India through 14 small and one mid-sized nuclear power reactors in commercial operation, eight under construction and more planned. As of now, nuclear power contributes nearly 2×10^{10} kW h of electricity – 3% of total power capacity available.

Government policy is to have 20 GWe of nuclear capacity operating by 2020 and 25% nuclear contribution is foreseen by 2050.

INTEXT QUESTIONS 27.4

1. What type of reactors are used in India for power generation?
2. How much $^{235}_{92}U$ undergoes fission in an atomic bomb which releases energy equivalent to 20,000 tons of TNT. (Given that 1 g of TNT gives out 1000 calorie of heat).

27.5.2 Hazards of Nuclear Radiations and Safety Measures

The living and non-living things around us constitute our environment. In this environment, a delicate balance has existed for millions of years between the flora, fauna, acquatic and human life. This balance is now being threatened. One of the factors disturbing this balance is the ever increasing pollution in our environment. Out of the various types of pollutants present in our environment, the one which has very serious long term biological effects are the 'nuclear radiations'. Earlier these were present only because of natural sources like the radioactive minerals and cosmic rays, but now their presence is increasing day by day due to man-made sources. The major present day man-made sources of nuclear radiations are the nuclear tests, nuclear installations like the nuclear research facilities, nuclear reactors, and radio isotopes in treating diseases.

Nuclear radiations dissociate complex molecules of living tissues through ionisation and kill the cells. They induce cancerous growth, cause sterility, severe skin burns, and lower the body resistance against diseases. They disrupt the genetic process, mainly in the unborn child, and show their effects even upto five generations. Nuclear radiations affect us not only directly, but also indirectly by affecting the flora, fauna and the acquatic life around us. They kill vegetation, fishes and animals.

The damage caused by nuclear radiations depends on the exposed part of the body, as well as on the energy, intensity and the nature of the radiation. Different parts of human body show different sensitivities to radiation. The α-particles are, as a rule, quite harmful because of their high ionising power. The damaging effects of different radiations are generally compared in terms of their 'relative biological effectiveness', called the RBE factors. These factors for different particles/rays are given in Table 27.3.

Table 27.3: RBE factors of different radiations

Particles/rays	RBE factors
X-rays, γ -rays, β-particles	1
Thermal neutrons	2 to 5
Fast neutrons	10
α-particles, high energy ions of O, N, etc.	10 to 20

There is no control on natural sources of radiation. However, efforts can certainly be made to lower down radiation from man-made sources. Some of these are to:

- Avoid nuclear explosions.
- Minimise production of radio-isotopes.
- Extreme care should be exercised in the disposal of industrial wastes containing traces of radio-nuclides.
- Nuclear medicines and radiation therapy should be used only when absolutely necessary, and with well considered doses.

WHAT YOU HAVE LEARNT

- Valence electrons take part in chemical reactions and the energy involved in such reactions is of the order of 1eV.
- In a nuclear reaction, the atomic nuclei interact to form a new element.
- Energy involved in nuclear reaction is of the order of MeV.
- In a nuclear reaction, atomic number, mass number and charge are conserved.
- When a heavy nucleus like uranium is bombarded by slow neutrons, it splits into two fragment with release of 2-3 neutrons and 200 MeV energy. This process is known as nuclear fission.
- Substances that undergo fission are called fissile substances. ^{233}Th, ^{233}U, ^{235}U, and ^{239}Pu are fissile materials.
- Chain reaction occurs when more than one emitted neutron induce further fission for each primary fission.
- Nuclear reactor is a device to sustain controlled chain reaction.
- In nuclear fusion two light nuclei are fused into one.
- For producing nuclear fusion, the reacting nuclei must be heated to nearly 20 million kelvin to gain sufficient kinetic energy to overcome the Coulombian potential barrier.
- In stars energy is produced by nuclear fusion reaction.
- Amount of hydrogen consumed in the sun is nearly 400×10^6 ton per second.
- Radio-isotopes find diverse applications in agriculture, medicine and industry.

TERMINAL EXERCISE

1. How does a nuclear reaction differ from a chemical reaction?
2. What is the use of moderator and absorber in a fission reactor?

3. On the basis of B.E per nucleon versus mass number curve, explain nuclear fusion.

4. What is a nuclear reaction? State the conservation laws obeyed in nuclear reactions. Give threes examples of nuclear reactions.

5. What is nuclear fission? Give an example to illustrate your answer.

6. Calculate the mass of ^{235}U consumed to generate 100 mega watts of power for 30 days.

7. Heavy hydrogen undergoes the following fusion reaction

$$ {}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{4}_{2}He + 24\text{ MeV} $$

Calculate the amount of heavy hydrogen used in producing the same energy as above. Compare the two results.

8. What is nuclear fusion? Write an equation of nuclear fusion to support your answer.

9. What is the source of energy in the sun? How is it generated? Illustrate with an example.

10. Describe the construction of an atomic reactor.

11. Calculate the energy released in a fusion reaction

$$ 3\,({}^{4}_{2}He) \rightarrow {}^{12}_{6}C $$

Given, the mass of on α-particle = 4.00263u.

ANSWERS TO INTEXT QUESTIONS

27.1

1. a. ${}^{19}_{9}F + {}^{1}_{1}H \rightarrow {}^{16}_{8}O + {}^{4}_{2}He$;

   b. ${}^{27}_{13}Al + {}^{1}_{0}n \rightarrow {}^{24}_{11}Na + {}^{4}_{2}He$;

   c. ${}^{234}_{90}Th \rightarrow {}^{234}_{90}Pa + {}^{0}_{-1}e$;

   d. ${}^{63}_{29}Cu + {}^{2}_{1}D \rightarrow {}^{64}_{30}Zn + {}^{1}_{0}n$

2. 17.9MeV

3. ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + 6.5\text{MeV}.$

27.2

1. Due to increase of *n*/*p* ratio above the natural ratio, its stability decreases. To decrease the ratio to attain more stability, it emits a β-particle.

2. 239Pu

3. 200 MeV.

27.3

1. (1) In fission the energy released is 0.84 MeV/u where as in fusion. It is 6.7 MeV/u. Thus energy released per unit mass is more in the later case.

2. (*a*) 17.3 MeV, (b) 2.69 MeV.

27.4

1. Pressurized Heavy Water Reactor   2. nearly 1 kg.

Answers to Problems in Terminal Exercise

6. 30.6 kg   7. 146.6 g

11. 7.35 MeV