UNIT:4 NUCLEAR CHEMISTRY(9HRS)

Radioactivity - rate of radioactive disintegration –half life- Nature of radiation from radioactive elements – stability of nucleus-binding energy-magic numbers-packing fractions-n/p ratio. Detection and measurement of radioactivity - Gieger-Muller counter - Wilson cloud chamber. Radioactive tracers - Rock dating, Carbon dating - Artificial radio activity - Artificial transmutations of elements - cyclotrons - Induced radio activity - Q values of nuclear reactions - Nuclear reactors Nuclear fission and nuclear fusion - Classification of reactors - Breeder reactor - India'snuclear energy programme.

Nuclear Chemistry

The emission of radiations from a radioactive material comes from the fact that a radioactive isotope is unstable and it converts to a stable isotope by emitting radiations like α, β, positron, γ -rays, etc. In order to understand the nature of these radiations, it would be pertinent to recall atomic and nuclear structures in brief.

When atomic nuclei have a greater or lesser number of protons or neutrons than what is required for a stable nucleus, they rearrange their nucleons in order to achieve a more stable neutron/proton ratio; this rearrangement is independent of the chemical or physical state of the element. Sometimes, the nucleus may undergo a series of changes before it ultimately attains stability. The unstable nuclides are known as “radioactive isotopes” and the phenomenon of radiation emission is called “radioactivity”. The method of rearrangement is called a “decay process”, and is independent of past life or method used for the production of nuclei.

If mass defect is positive, then the process is said to be exoergic decay and if negative, then we call it endoergic decay. The example for the exoergic

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + Energy$$

Emission of α particles

Radioactive atoms possess an excess of either protons or neutrons than required to be a stable isotope. The easiest way to remove excess neutrons or protons would seem to be by ejecting them directly from the nucleus. But in reality, such processes are very rare. Neutron or proton emission is not possible unless energy equivalent to the binding energy of the ejected proton or neutron is put into the nucleus. However if two protons together with two neutrons emits

from the nucleus as alpha particles, the energy required would be lesser than the binding energy of the alpha particles and so the reaction is exoergic. Thus, the ejection of an α-particle (He^{2+}) from the nucleus of a heavy element is exoergic and spontaneous, and α-decay is able to take place rather than decay by the emission of either protons or neutrons.

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + Energy$$

Emission of β particles

An unstable nucleus that has excess neutron, but not enough to combine with proton in pairs and emit α-particles and become stable; are made stable by converting a neutron into a proton. Nuclear electron known as a β-particle (to maintain conservation of electric charge) along with electromagnetic radiation known as a neutrino is emitted. When a neutron is converted into a proton, some excess mass (i.e., the mass difference between the parent and daughter + β-particle) may still be left. Therefore, this un-utilized excess mass is converted into electromagnetic radiation. This type of electromagnetic radiation is called a neutrino. In other words, β-particles together with a neutrino are emitted to conserve excess mass left in the nucleus after one neutron has been converted into a proton.

Electron capture

Like the conversion of an excess neutron to a proton, a nucleus with an excess proton (i.e., excess than needed for its stability) can approach stability by converting a proton into a neutron by capturing one of the nearest orbital electrons. This type of decay is known as electron capture (E.C.).

$$p + e^{-} \rightarrow n + \mu$$

Positron emission

If for some reasons, electron capture is not possible, the proton can be converted into a neutron by the emission of a positron (β^{+}); this type of decay is known as positron decay. In this type of decay also the neutrino is ejected for the same reason as expressed earlier. This decay can be expressed as follows:

$$p \rightarrow n + \beta^{+} + \mu$$

A positron is a positively charged electron designated by β^{+}.

Natural radioactive series

There are some radioactive isotopes which decay to another radioactive isotope which decays further to another radioactive isotope. This type of decay continues till it comes to a stable isotope. During this series of decays, the radioactive isotopes decay by α-particles or β-particles. Moreover, the half-life of decays varies from a few seconds to a few years. It is interesting to note that the Mass number of all series is divisible by digit 4.

• (4n) as the Thorium series starting with Thorium-232;
• (4n + 1) is Neptunium-237;
• (4n + 2) is the Uranium series with Uranium-238
• (4n + 3) is the Actinium series with Actinium-235.

However, the natural form of (4n + 1) has not been found, though it has been synthesized artificially. The reason could be the very short-lived half-lives of some of the isotopes of the (4n + 1) series.

Rate of radioactive decay

Unstable nuclides can approach stability by a suitable mode of decay, but none of these decay processes are instantaneous. The unstable nuclei may require a millionth of a second or millions of years to decay to a more stable one. The rate of decay can be expressed using the differential form:

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

in which "N" is the number of radioactive atoms dN is the change in the number of atoms and dt is the change in time. By introducing a proportionality constant λ, and indicating a decrease in activity with a negative sign, this equation becomes equal to the product of λN. In other words, radioactive decay follows the law of first-order kinetics.

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

$$[lnN]_{N_0}^{N} = [-\lambda t]_0^t$$

$$ln\frac{N}{N_0} = -\lambda t$$

On taking power of e on both sides

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

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

which N_0 is the number of radioactive atoms at time t = 0, "N" the number of radioactive atoms at time "t", and λ is the decay constant. λ is a fundamental constant for each nucleus and has the dimension of reciprocal time. It is a measure of the probability that a given single nucleus will decay within unit time.

It may not always be possible to measure absolute values of N or N_0. However, each atom of the radioactive isotope emits one radiation per decay of the atom. If the radiations emitted by atoms could be measured for some period and the value is converted to a unit "number of radiations recorded per unit time", i.e., activity.

$$A = A_0 e^{-\lambda t}$$

in which "A" is the activity at time "t" (i.e., counts per unit time) and A_0 is activity at some reference time (i.e., counts per unit time). This relationship can be used to determine the half-life of the radioactive isotope.

Half life

The radioactive nuclides are generally described by the term half-life, i.e., time required by a radioactive nuclei to disintegrate to half of its initial activity. Half-life is a characteristic of a radioactive species, and it is very unlikely that any two nuclides will have exactly the same value. The half-life is given by substituting the value of A = A_0/2 in the following equation

$$ln\frac{A}{A_0} = -\lambda t$$

$$\ln 2 = -\lambda t_{1/2}$$

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

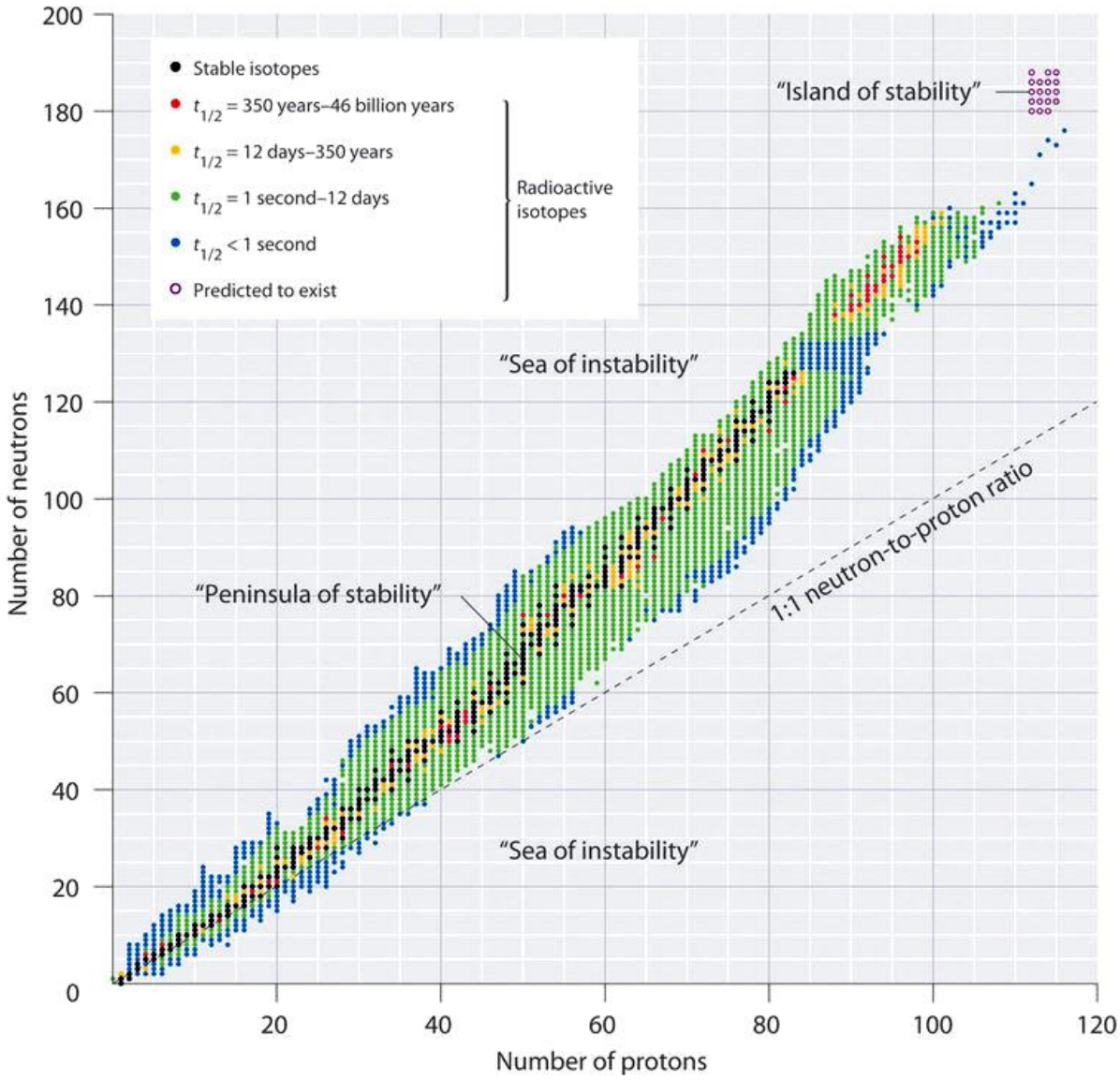
where $t_{1/2}$ is the half-life of the radioactive material.

Nuclear Stability

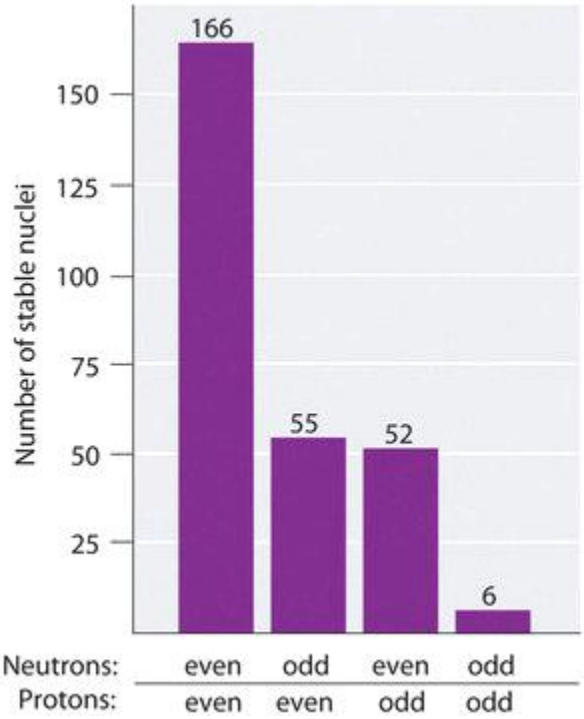
(1) n/p ratio

The stability of the nucleus can be explained by n/p ratio. The nuclei with n/p ratio is in the range 1 to 1.52 are stable.

The nucleus of an atom occupies a tiny fraction of the volume of an atom and contains the number of protons and neutrons that is characteristic of a given isotope. Electrostatic repulsions would normally cause the positively charged protons to repel each other, but the nucleus does not fly apart because of the strong nuclear force, an extremely powerful but very short-range attractive force between nucleons. All stable nuclei except the hydrogen-1 nucleus (^{1}H) contain at least one neutron to overcome the electrostatic repulsion between protons. As the number of protons in the nucleus increases, the number of neutrons needed for a stable nucleus increases even more rapidly. Too many protons (or too few neutrons) in the nucleus result in an imbalance between forces, which leads to nuclear instability. The relationship between the number of protons and the number of neutrons in stable nuclei, arbitrarily defined as having a half-life longer than 10 times the age of Earth, is shown graphically in Figure



The stable isotopes form a "peninsula of stability" in a "sea of instability." Only two stable isotopes, ^{1}H and ^{3}He, have a neutron-to-proton ratio less than 1. Several stable isotopes of light atoms have a neutron-to-proton ratio equal to 1 (e.g., ${}_{2}^{4}He$, ${}_{5}^{10}B$, and ${}_{10}^{20}Ca$). All other stable nuclei have a higher neutron-to-proton ratio, which increases steadily to about 1.5 for the heaviest nuclei. Regardless of the number of neutrons, however, all elements with Z > 83 are unstable and radioactive.



As shown in the above Figure , more than half of the stable nuclei (166 out of 279) have even numbers of both neutrons and protons; only 6 of the 279 stable nuclei do not have odd numbers of both. Moreover, certain numbers of neutrons or protons result in especially stable nuclei; these are the so-called magic numbers 2, 8, 20, 50, 82, and 126. For example, tin (Z = 50) has 10 stable isotopes, but the elements on either side of tin in the periodic table, indium (Z = 49) and antimony (Z = 51), have only 2 stable isotopes each. Nuclei with magic numbers of both protons and neutrons are said to be "doubly magic" and are even more stable. Examples of elements with doubly magic nuclei are $^{4}_{2}He$, with 2 protons and 2 neutrons, and $^{208}_{82}Pb$, with 82 protons and 126 neutrons, which is the heaviest known stable isotope of any element. The pattern of stability suggested by the magic numbers of nucleons is reminiscent of the stability associated with the closed-shell electron configurations of the noble gases in group 18 and has led to the hypothesis that the nucleus contains shells of nucleons that are in some ways analogous to the shells occupied by electrons in an atom.

(2) Packing fraction

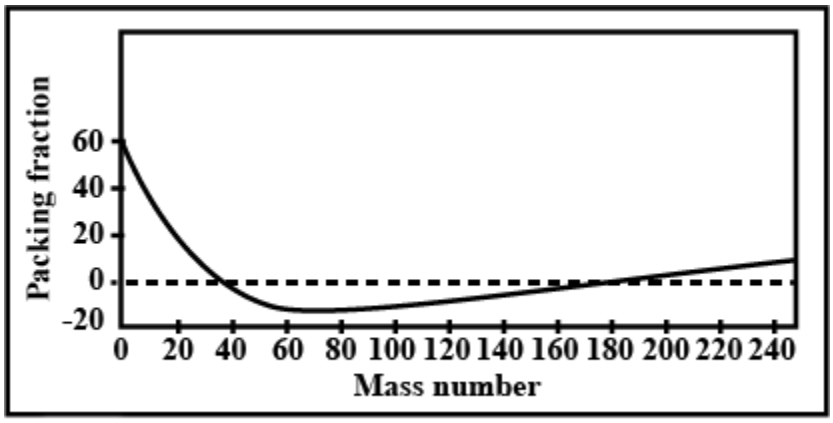
Mass number of an element is the sum of the protons and neutrons present within the neucleus of an atom. ' Aston' noticed that the actual atomic mass of an atom is slightly different from the mass number of the atom. This deviation varies from nucleus to nucleus is expressed as the term of "Packing fraction" which may be defined as-

$$\text{Packing fraction(f)} = \frac{\text{Nuclear mass} - \text{mass number(A)}}{\text{Mass number}} 10^4$$

The nuclear mass is equal to the atomic mass by ignoring the mass of the electrons and the mass number is generally the nearest whole no of the atomic mass. The factor 10^4 is arbitrarily chosen to make the figure reasonable.

Significance of the packing fraction:

Packing fraction does not have precise theoretical significance. But it gives an indicator for the stability of the nucleus. It is observed from the plot of packing fraction vs mass number that packing fraction may be negative, positive and zero. A negative packing fraction indicates that the nuclear mass is actually less than the nearest whole number i.e; mass number. This suggests that the small fraction of the mass is converted into the energy to bind the nucleons. Thus to split the nucleons from the nucleus the same amount of energy would have to be supplied. Thus a negative packing fraction stabilizes a nucleus. More negative the packing fraction , more stable will be the nucleus.



Variation of packing fraction with mass number

On the other hand a positive or zero packing fractions indicates that the concern nucleus should not be stable. But, there are some lighter nuclides whose packing fractions are positive but they are known to be stable. Thus apparent contradiction arises due to considering of mass number instead of the actual mass of the nucleus. However, the observation from the packing fraction viz mass number curves summarizes the following points:-

a) The packing fraction of the stable nuclei lies more or less on a smooth curve.

b) The curve passes through a minima in a mass number range 50-60 implying maximum stability their nucleus and they have high abundant in nature.

c) After, the minima the packing fraction tends to move toward positive quantity with increasing the mass number. This is consistent with the observed radioactivity, i.e, inherent instability of these element.

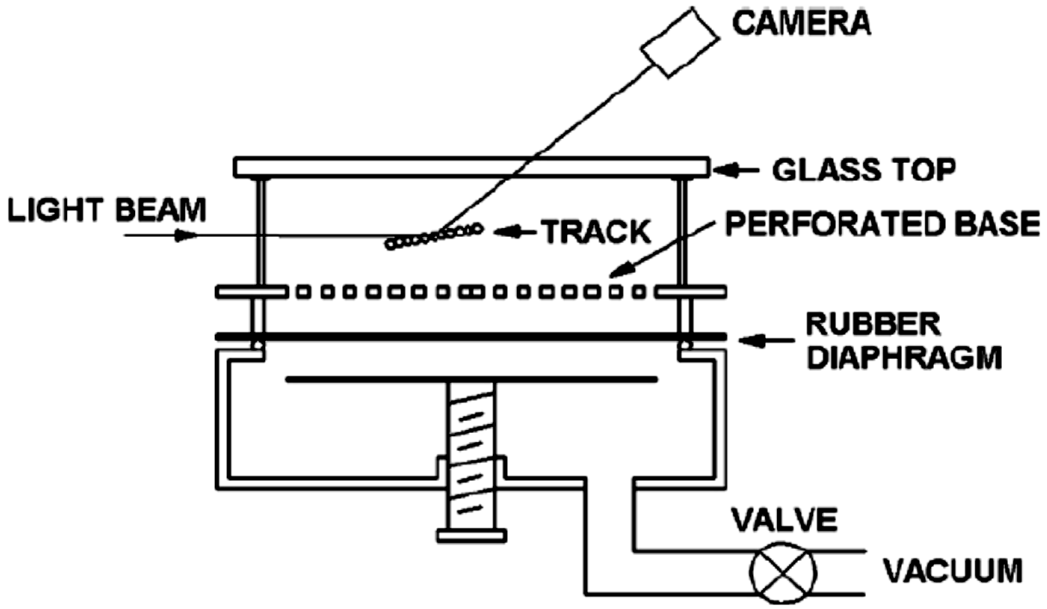
d) Generally, the nuclides having higher packing fraction tend to move there region where the packing fraction is minimum. This may be attained through fusion by the lighter elements and through fission by the heavier elements.

Detection and measurement of radioactivity

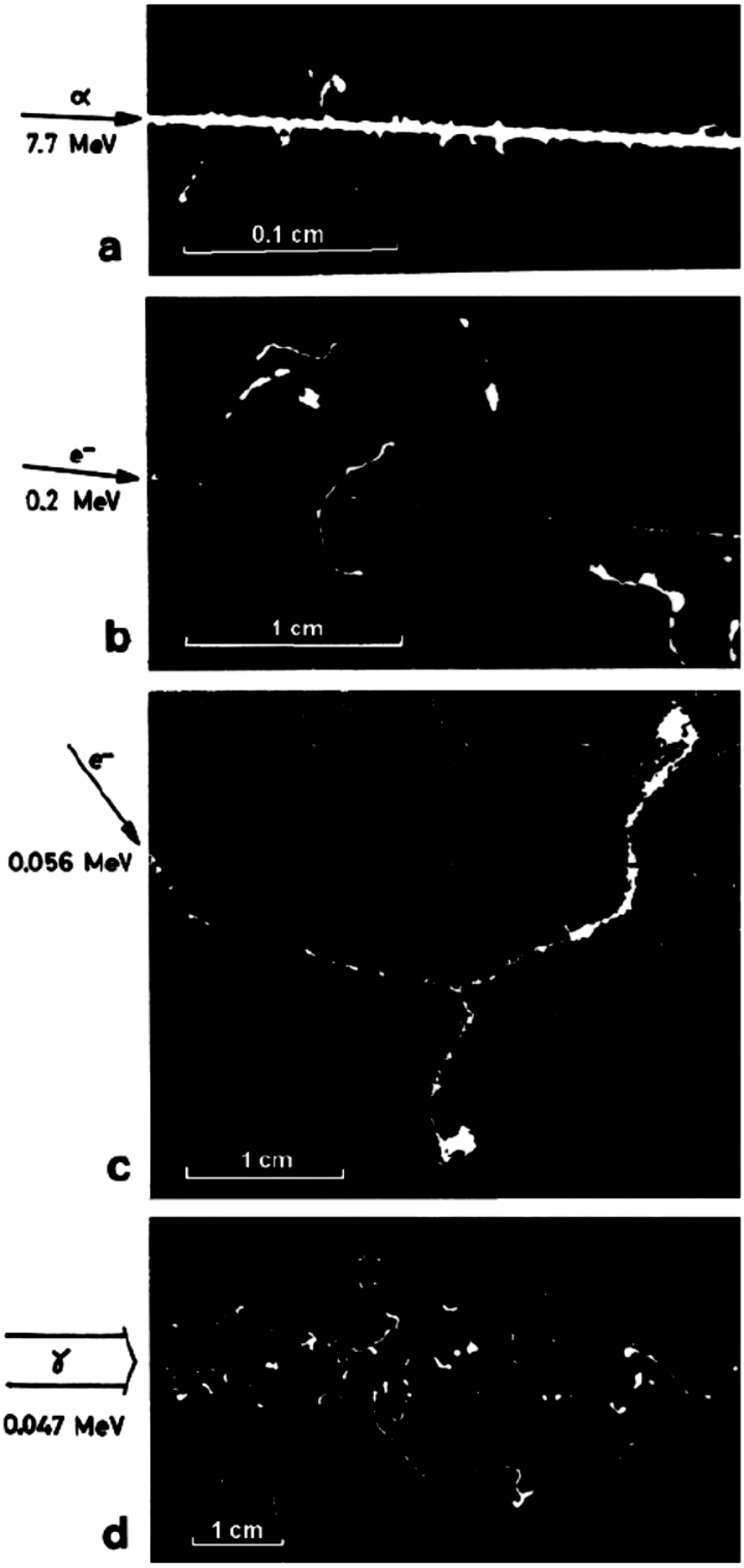
The ionization and/or excitation of atoms and molecules when the energies of nuclear particles are absorbed in matter is the basis for the detection of individual particles. Macroscopic collective effects, such as chemical changes and heat evolution, can also be used.

Cloud and bubble chambers (Wilson cloud chamber)

The principle of a cloud chamber is shown in Figure. A volume of saturated vapour contained in a vessel is made supersaturated through a sudden adiabatic expansion. When ionizing radiation passes through such a supersaturated vapour the ionization produced in the vapour serves as condensation nuclei.



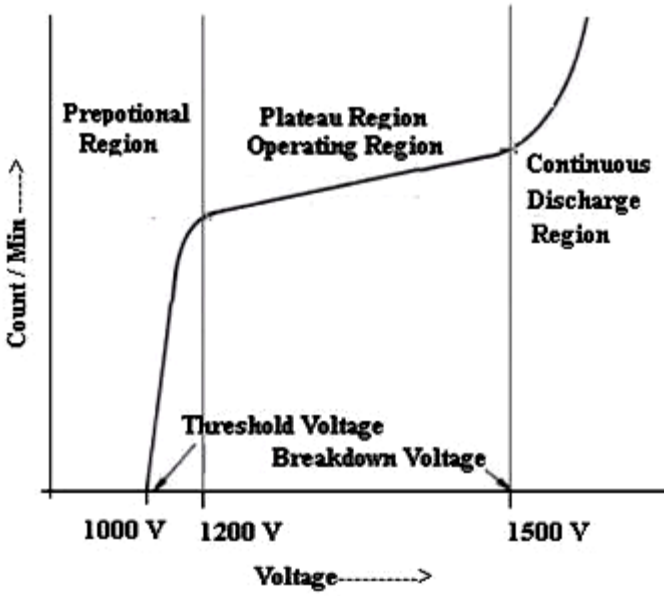
As a result small droplets of liquid can be observed along the path of the radiation. These condensation tracks have a lifetime of less than a second and can be photographed through the chamber window. The density of the condensation depends on the ionization power of the projectile as well as on the nature of the vapour, which is often an alcohol or water. Cloud chamber photographs are shown in Figure


α
7.7 MeV
0.1 cm
a
e⁻
0.2 MeV
1 cm
b
e⁻
0.056 MeV
1 cm
c
γ
0.047 MeV
1 cm
d

A Geiger counter (Geiger-Muller tube) is a device used for the detection and measurement of all types of radiation: alpha, beta and gamma radiation. Basically it consists of a pair of electrodes surrounded by a gas. The electrodes have a high voltage across them. The gas used is usually Helium or Argon. When radiation enters the tube it can ionize the gas. The ions (and electrons) are attracted to the electrodes and an electric current is produced. A scaler counts the current pulses, and one obtains a ”count” whenever radiation ionizes the gas. The apparatus consists of two parts, the tube and the (counter + power supply). The Geiger-Mueller tube is usually cylindrical, with a wire down the center. The (counter + power supply) have voltage controls and timer options. A high voltage is established across the cylinder and the wire as shown in the figure.

When ionizing radiation such as an alpha, beta or gamma particle enters the tube, it can ionize some of the gas molecules in the tube. From these ionized atoms, an electron is knocked out of the atom, and the remaining atom is positively charged. The high voltage in the tube produces an electric field inside the tube. The electrons that were knocked out of the atom are attracted to the positive electrode, and the positively charged ions are attracted to the negative electrode. This produces a pulse of current in the wires connecting the electrodes, and this pulse is counted. After the pulse is counted, the charged ions become neutralized, and the Geiger counter is ready to record another pulse. In order for the Geiger counter tube to restore itself quickly to its original state after radiation has entered, a gas is added to the tube. For proper use of the Geiger counter, one must have the appropriate voltage across the electrodes. If the voltage is too low, the electric field in the tube is too weak to cause a current pulse. If the voltage is too high, the tube will undergo continuous discharge, and the tube can be damaged. Usually the manufacture recommends the correct voltage to use for the

tube. Larger tubes require larger voltages to produce the necessary electric fields inside the tube.



Radioactive dating

Radiometric dating, radioactive dating or radioisotope dating is a technique which is used to date materials such as rocks or carbon, in which trace radioactive impurities were selectively incorporated when they were formed. The method compares the abundance of a naturally occurring radioactive isotope within the material to the abundance of its decay products, which form at a known constant rate of decay. The use of radiometric dating was first published in 1907 by Bertram Boltwood and is now the principal source of information about the absolute age of rocks and the age of fossilized life forms or the age of the Earth itself, and can also be used to date a wide range of natural and man-made materials. Among the best-known techniques are radiocarbon dating, potassium–argon dating and uranium–lead dating.

Uranium–lead dating

The uranium lead sample contains two clocks, one based on uranium-235's decay to lead-207 with a half-life of about 700 million years, and one based on uranium-238's decay to lead-206 with a half-life of about 4.5 billion years, providing a built-in crosscheck that allows accurate determination of the age of the sample even if some of the lead has been lost.

Potassium–argon dating

This involves electron capture or positron decay of potassium-40 to argon-40. Potassium-40 has a half-life of 1.3 billion years, so this method is applicable to the oldest rocks. Radioactive potassium-40 is common in micas, feldspars, and hornblendes.

$$D^* = D_0 + N(t)\left(e^{\lambda t} - 1\right)$$

where t is age of the sample, D* is number of atoms of the radiogenic daughter isotope in the sample, D_0 is number of atoms of the daughter isotope in the original or initial composition, N(t) is number of atoms of the parent isotope in the sample at time t (the present), given by $N(t) = N_0 e^{-\lambda t}$, and λ is the decay constant of the parent isotope, equal to the inverse of the radioactive half-life of the parent isotope times the natural logarithm of 2. The equation is most conveniently expressed in terms of the measured quantity N(t) rather than the constant initial value N_0. To calculate the age, it is assumed that the system is closed (neither parent nor daughter isotopes have been lost from system), D_0 must be either negligible or can be accurately estimated, λ is known to a high precision, and one has accurate and precise measurements of D* and N(t).

Carbon dating

The method was developed by Willard Libby in the late 1940s and soon became a standard tool for archaeologists. Libby received the Nobel Prize in Chemistry for his work in 1960. The radiocarbon dating method is based on the fact that radiocarbon is constantly being created in the atmosphere by the interaction of cosmic rays with atmospheric nitrogen. The resulting radiocarbon combines with atmospheric oxygen to form radioactive carbon dioxide, which is incorporated into plants by photosynthesis; animals then acquire ^{14}C by eating the plants. When the animal or plant dies, it stops exchanging carbon with its environment, and from that point onwards the amount of ^{14}C it contains begins to decrease as the ^{14}C undergoes radioactive decay. Measuring the amount of ^{14}C in a sample from a dead plant or animal such as a piece of wood or a fragment of bone provides information that can be used to calculate when the animal or plant died. The older a sample is, the less ^{14}C there is to be detected, and because the half-life of ^{14}C (the period of time after which half of a given sample will have decayed) is about 5,730 years, the oldest dates that can be reliably measured by this process date to around 50,000 years ago, although special preparation methods occasionally permit accurate analysis of older samples.

In nature, carbon exists as two stable, nonradioactive isotopes: carbon-12 (^{12}C), and carbon-13 (^{13}C), and a radioactive isotope, carbon-14 (^{14}C), also known as "radiocarbon". The half-life of ^{14}C (the time it takes for half of a given amount of ^{14}C to decay) is about 5,730 years, so its concentration in the atmosphere might be expected to reduce over thousands of years, but ^{14}C is constantly being produced in the lower stratosphere and upper troposphere by cosmic rays, which generate neutrons that in turn create ^{14}C when they strike nitrogen-14 (^{14}N) atoms. The following nuclear reaction creates ^{14}C:

$$n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p$$

When n represents neuron and p represents protons

Once produced, the ^{14}C quickly combines with the oxygen in the atmosphere to form carbon dioxide (CO_2). Carbon dioxide produced in this way diffuses in the atmosphere, is dissolved in the ocean, and is taken up by plants via photosynthesis. Animals eat the plants, and ultimately the radiocarbon is distributed throughout the biosphere. The ratio of ^{14}C to ^{12}C is approximately 1.5 parts of ^{14}C to 10^{12} parts of ^{12}C. In addition, about 1% of the carbon atoms are of the stable isotope ^{13}C.

The equation for radioactive decay is

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} \ (\beta \ particle) + \bar{\gamma}_e \ (electron \ antineutrino)$$

one of the neutrons in the ^{14}C nucleus changes to a proton and the ^{14}C nucleus reverts to the stable (non-radioactive) isotope ^{14}N

During its life, a plant or animal is exchanging carbon with its surroundings, so the carbon it contains will have the same proportion of ^{14}C as the atmosphere. Once it dies, it ceases to acquire ^{14}C, but the ^{14}C within its biological material at that time will continue to decay, and so the ratio of ^{14}C to ^{12}C in its remains will gradually decrease. Because ^{14}C decays at a known rate, the proportion of radiocarbon can be used to determine how long it has been since a given sample stopped exchanging carbon – the older the sample, the less ^{14}C will be left. The equation governing the decay of a radioactive isotope is

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

where N0 is the number of atoms of the isotope in the original sample (at time t = 0, when the organism from which the sample was taken died), and N is the number of atoms left after

time t. λ is a constant that depends on the particular isotope; for a given isotope it is equal to the reciprocal of the mean-life i.e. the average or expected time a given atom will survive before undergoing radioactive decay. The mean-life, denoted by τ, of ^{14}C is 8,267 years, so the equation above can be rewritten as

$$t = 8267\ ln\left({}^{N_0}/_{N}\right) \text{ years}$$

The sample is assumed to have originally had the same $^{14}C/^{12}C$ ratio as the ratio in the atmosphere, and since the size of the sample is known, the total number of atoms in the sample can be calculated, yielding N_0, the number of ^{14}C atoms in the original sample. Measurement of N, the number of ^{14}C atoms currently in the sample, allows the calculation of t, the age of the sample, using the equation above.

Artificial radioactivity

The transmutation of one element into another as a result of natural disintegration of radioactive element lead the discovery of artificial transmutation of elements. It all started in 1919 when Rutherford bombarded nucleus of nitrogen with alpha particle and obtained traces of oxygen. It was first time in history that one element had been obtained from another.

$$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

Thus nitrogen was changed into an isotope of oxygen by alpha particle bombardment. Since then numerous transmutations have been studied and several new radioactive isotops have been produced by bombardment of different elements by alpha particles. How ever it may be noted that above reaction take place only when alpha particle makes a head on collision with a nitrogen nucleus. This may occur only in the case of one alpha particle out of a million therefore take place only in traces.

In 1932 Chadwick discovered the subatomic particle neutron by bombardment of beryllium with alpha particle.

$$^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

The neutron has proved far more useful than alpha particle for artificial transmutation neutron being neutral will not be repelled by the nucleus like positively charged alpha particle. Thus certain transmutations which were impossible previously have been achieved since the

discovery of neutron. James Chadwick was awarded the 1935 Nobel prize for the discovery of neutron.

Alpha particle (^4_2He), protons (^1_1H), deuterons (^2_1H) and neutrons (^1_0n)re some of the important fundamental particles which have been used for the bombardment of different elements. Protons and deuterons which carry single positive charge are much better projectiles than the alpha particles which carry double positive charge. However they are not as good as neutron which carries no charge at all.

Induced radio activity

In 1934 Frederic Joliot and Irene Curie found that certain light elements such as aluminium, boron, and magnesium when bombarded with alpha particles change into radioactive isotopes of other elements. These isotopes disintegrate in the same way as naturally occurring radioactive elements uranium radium etc. Thus induced or artificial radioactivity is a process by which a new radioactive isotope of known element can be prepared.

$$^{24}_{12}Mg + {}^4_2He \rightarrow {}^{27}_{14}Si + {}^1_0n$$

The silicon produced is radioactive and disintegrates as

$$^{27}_{14}Si \rightarrow {}^{27}_{13}Al + {}^0_{+1}e$$

This was how positron, a counter part of electron having a unit positive charge but negligible mass was first discovered.

The bombardment of boron with alpha particles yields a radioactive isotope of nitrogen with mass number 13. It has a short half life period and disintegrates as represented below.

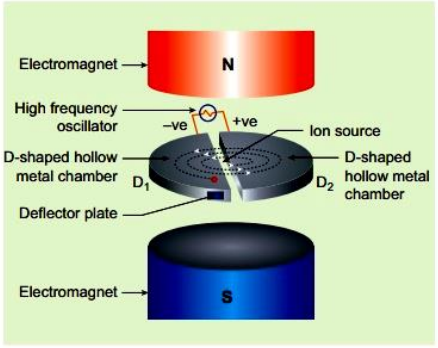
$$^{10}_5B + {}^4_2He \rightarrow {}^{13}_7N + {}^1_0n$$

$$^{13}_7N \rightarrow {}^{13}_6C + {}^0_{+1}e$$

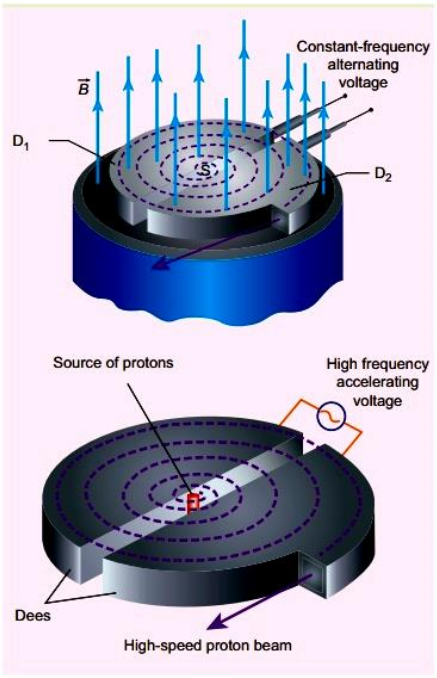
Frederic Joliot and Irene Curie were jointly awarded chemistry Nobel prize for the synthesis of radioactive elements in 1935.

Cyclotron

Alpha particles, protons and deuterons can be made much more effective projectile if they are imparted with high velocity so that they can easily overcome the coulombic energy barrier. The apparatus developed by E. O Lawrence is known as cyclotron. In its common form it consists of two flat semicircular boxes called dees (because of their D-like shapes) marked as D_1 and D_2. These are surrounded by a vessel containing hydrogen, helium or deuterium gas at low pressure. This vessel is placed between the poles of an electromagnet as shown in figure. High frequency alternating potential of several millions per second is applied across D_1 and D_2.



construction and working of cyclotron



Dees are enclosed in an evacuated chamber and it is kept in a region with uniform magnetic field controlled by an electromagnet. The direction of magnetic field is normal to the plane of the Dees. The two Dees are kept separated with a gap and the source S (which ejects the particle to be accelerated) is placed at the center in the gap between the Dees. Dees are connected to high frequency alternating potential difference. Suppose at a particular instant the direction of the applied potential is such that D_1 is negative and D_2 is positive. A positive ion from the centre would move to D_1 following semicircular path due its deflection caused by the magnetic field. When the ion reaches the gap between D_1 and D_2 its get exposed to the influence of the applied potential. If the oscillation frequency is such that during the time the positive ion passes though the D1 then the sign of the potential get reversed ie D2 become negative and the ion get accelerated through the D2. The ion moves faster therefore radius of its path increases. However the time taken by the ion to transverse the dee domain remains same because the increased path is compensated by increased speed of the ion. Consequently each time the ion crosses the gap, the radius of

the spiral path of the ion steadily increases and so does its energy. Finally the ion possessing energy as high as several hundred million electron volt and velocity as high as 40,000 kms^{-1} emerge out of the exit of the instrument.

$$\frac{mv^2}{r} = qvB$$

$$mv = qBr$$

$$KE = \frac{mv^2}{2} = \frac{q^2B^2r^2}{2m}$$

$\frac{mv}{qB} = \ r$, where r is the radius of the circular path

Let T be the time taken by the particle to finish one complete circular motion, then

$$T = \frac{2\pi r}{v}$$

On substituting for r

$$T = \frac{2\pi mv}{qBv} = \frac{2\pi m}{qB}$$

This is called cyclotron period. The reciprocal of time period is the frequency *f*, which is

$$\frac{1}{T} = \frac{qB}{2\pi m} = f$$

Limitations of cyclotron

a) The speed of the ion is limited

b) Electron cannot be accelerated

c) Uncharged particles cannot be accelerated

Suppose a cyclotron is operated to accelerate protons with a magnetic field of strength 1 T. Calculate the frequency in which the electric field between two Dees could be reversed.

Solution

Magnetic field B = 1 T

Mass of the proton, mp = 1.67×10^{-27} kg

Charge of the proton, q = 1.60 ×10^{-19} C

$$f = \frac{qB}{2\pi m_p} = \frac{\left(1.60\times10^{-19}\right)(1)}{2(3.14)(1.67\times10^{-27})}$$
$$= 15.3\times10^{6}\,Hz = 15.3\,MHz$$

Q values

The complete equation for a nuclear change should include the energy as well. This energy change is usually denoted by Q. Thus the complete equation for nuclear reaction representing bombardment of nitrogen by alpha particle to give an isotope of oxygen should be represented as

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} + \mathrm{Q}$$

Q is called the nuclear reaction energy. The value of Q may be positive when the reaction is said to be exoergic and negative when reaction is said to be endoergic.

Sum of the masses of reactants = 14.0031 u + 4.0026 u = 18.0057 u

Sum of masses of products = 16.9991 u + 1.0078 u = 18.0069

$$\Delta\mathrm{m} = \text{Sum of the masses of products} - \text{sSum of the masses of reactants} = 0.0012\ \mathrm{u}$$

The reaction is evidently involves increase of mass by 0.0012 u. An equivalent amount of energy is therefore absorbed.

Nuclear fusion

The world is getting warmer because of rising earth surface temperature mainly due to greenhouse gases emitted by fossil fuel burning. The nuclear energy is considered as clean energy as it is not emitting any greenhouse gases. Nuclear fusion is the nuclear reaction that produces huge energy in sun. It is expected that fusion energy can play a significant role in mitigating greenhouse gases in decades to come by its use in energy production. The nuclear fusion and fission were considered as potential processes from the mid of 20th century as energy sources. The International Atomic Energy Agency (IAEA) has been the leader in nuclear fusion research since the 1950s and focused on facilitating the coordination of international fusion undertakings and enhancing the interaction among member countries for meeting the global energy demand. The depletion of fossil fuel reserves and imbalances arisen from its consumption lead to

unsustainability in energy sector. India with rich thorium reserves was thinking of utilizing nuclear reactions for energy production to address this issue. A challenge prevails in production of energy by nuclear fusion on the earth.

Fusion is the opposite of nuclear fission. Nuclear fusion is the phenomenon in which two lightweight atomic nuclei joined into a single, heavier nucleus along with production and release of high energy. Here two fusing atoms overcome their natural repulsion and fuse forwarding a reaction producing large amount of energy. The fusion reaction mainly occurs between two hydrogen isotopes. The reactions are as follows:

$$_1^1H + \ _1^2H \rightarrow \ _2^3He + \ \gamma + \ 5.49 \text{ MeV}$$

One protium fuses with deuterium atom to form one atom of helium (^{3}He) with gamma rays and 5.49 MeV of energy.

$$_1^2H + \ _1^2H \rightarrow \ _2^4He + \gamma + \ 23.85 \text{ MeV}$$

Two Deuterium atoms fused together to form one atom of helium (^{4}He), gamma rays and 23.85 MeV of energy.

$$_1^2H + \ _1^2H \rightarrow \ _2^3He + n + \ 3.27 \text{ MeV}$$

Two deuterium atoms fused together to form one atom of helium (^{3}He) along with gamma rays and 3.27 MeV of energy.

$$_1^2H + \ _1^2H \rightarrow \ _1^3H + \ _1^1H + \ 4.03 \text{ MeV}$$

Two deuterium atoms fused together to form one atom of tritium and one atom of protium and 4.03 MeV of energy

$$_1^2H + \ _2^3He \rightarrow \ _2^4He + \ _1^1H + \ 18.35 \text{ MeV}$$

One deuterium fused with one atom of tritium to form one atom of helium (^{4}He), one atom of protium and 18.35 MeV of energy.

$$_1^2H + \ _1^3H \rightarrow \ _2^4He + \ _0^1n + \ 17.6 \text{ MeV}$$

One deuterium fuses with one atom of tritium to form one atom of helium (^{4}He), one neutron and 17.6 MeV of energy.

The conditions required for nuclear fusion reactions are

Optimum and very high temperature: This will help to separate the electron from the nucleus and overcome electrostatic repulsion forces. This is possible by highly ionized plasma, a gaseous mass consisting of electrons and free atoms.

Confinement time: In addition to providing a sufficiently high temperature to enable the particles to overcome the Coulomb barrier, that temperature must be maintained for a sufficient confinement time and with a sufficient ion density in order to obtain a net yield of energy from a

fusion reaction. The overall conditions which must be met for a yield of more energy than is required for the heating of the plasma are usually stated in terms of the product of ion density and confinement time, a condition called Lawson's criterion. Once a critical ignition temperature for nuclear fusion has been achieved, it must be maintained at that temperature for a long enough confinement time at a high enough ion density to obtain a net yield of energy. In 1957, J. D. Lawson showed that the product of ion density and confinement time determined the minimum conditions for productive fusion, and that product is commonly called Lawson's criterion. Commonly quoted figures for this criterion are

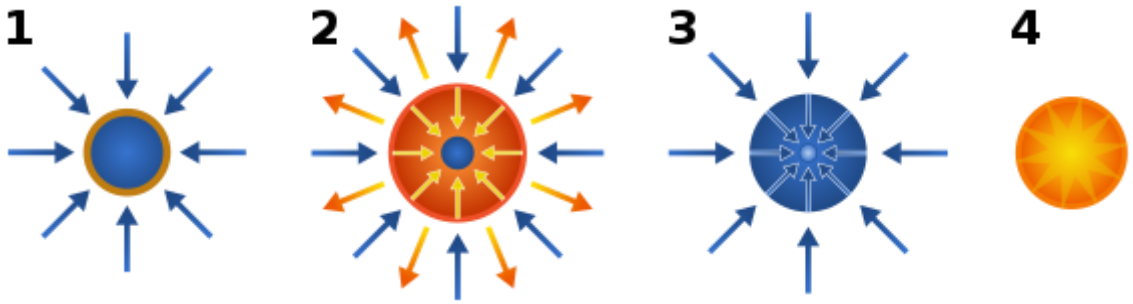
Lawson's criterion for fusion	$n\tau \geq 10^{14}$ s/cm^3	deuterium-tritium fusion
	$n\tau \geq 10^{16}$ s/cm^3	deuterium-deuterium fusion

Adequate plasma density – for nuclear fusion reaction between nuclei.

Confinement nuclear fusion reactions

The two important methods of confinement are

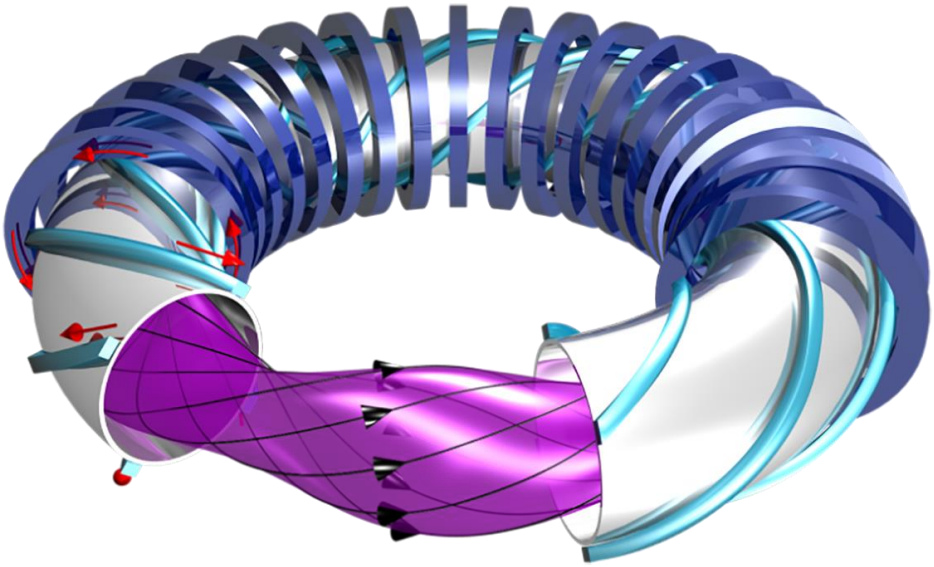
Inertial confinement fusion (ICF): In this radiation of laser beam is used to implode a small pellet of fusible fuel (deuterium and tritium) by confining high temperature. The energy is directed from different directions on the fuel till the fusion occurs. Usually one mg of Deuterium- Tritium makes a pellet and it generate 350 MJ and 10 micro explosions per second produce 3.5 GW.



Schematic of the stages of inertial confinement fusion using lasers. The blue arrows represent radiation; orange is blowoff; yellow is inwardly transported thermal energy.

1. Laser beams or laser-produced X-rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.
2. Fuel is compressed by the rocket-like blow off of the hot surface material.
3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 ˚C.
4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Magnetic confinement fusion (MCF): The charged plasma particles are trapped and confined by applying a specially configured magnetic field space. The confinement with magnetic field by using a magnetic mirror or a closed geometry (toroidal field)



Fuel used for nuclear fusion reactions

Usually light nuclei mainly deuterium and tritium are used for nuclear fusion.

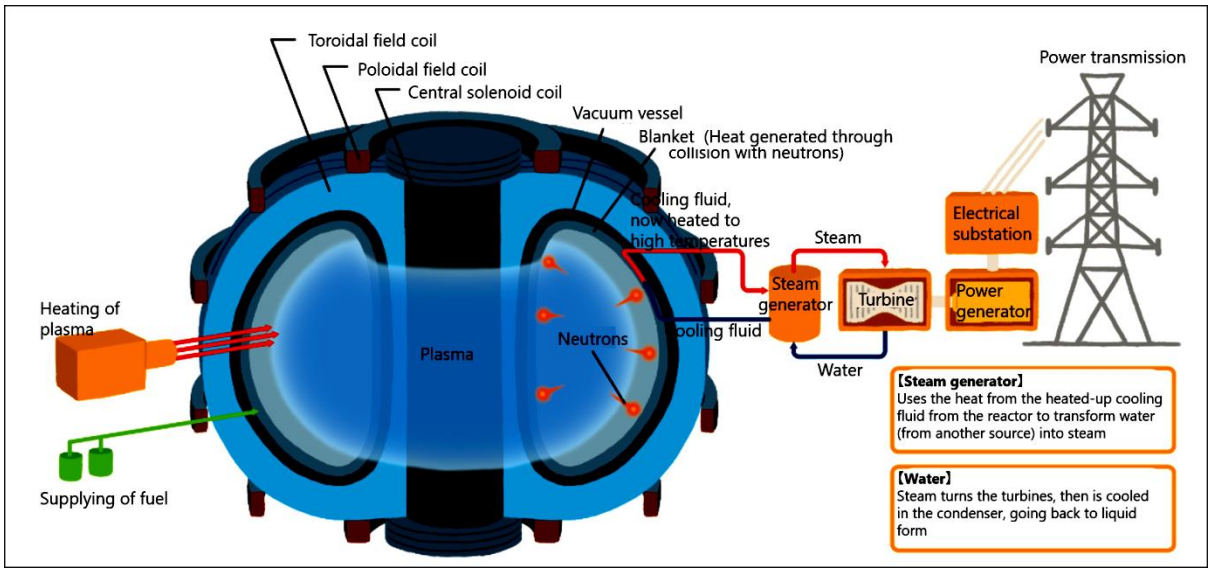
Deuterium ($_1^2H$): is stable isotope consisting of a proton and neutron. It is present in sea water (1 atom per 6500 atoms of hydrogen). 34 grams of deuterium is present in every cubic meter of sea water. Hence, nuclear fusion is an inexhaustible source of energy because on earth three fourth (71%) part is covered by water.

Tritium ($_1^3H$): composed of a proton and two neutrons by beta emission decay. The neutron capture reactions with the isotopes of lithium produce tritium. Lithium is an abundant material in the earth's crust and in seawater. But tritium is limited in nature.

Fusion reactors

For example, to produce fusion, first you have to turn the hydrogen fuel into a plasma by separating the electrons from the nuclei. This plasma needs to be created in a vacuum and be heated to temperatures of over 100 million degrees Celsius. The plasma must also be contained and controlled inside the reactor by using powerful magnetic fields. Generating these magnetic fields stably requires the use of superconducting coils**.** The energy is produced by plasma in the form of particles and radiation. Afterwards the energy is lost in the first wall after absorption of charged particles and radiation. The kinetic energy is converted to heat in the blanket. By using the heat the generated steam is used to turn turbine and alternator for

electricity production. Fig below shows the schematic diagram of a fusion tokamak-based nuclear fusion reactor.



There is a worldwide project now underway to make fusion a reality, called **ITER ("The Way" in Latin)**—the Avengers of the energy world, if you will, with **seven member entities (Japan, the EU, Russia, the U.S., Korea, China, and India) working together** to build an experimental reactor in Saint-Paul-lez-Durance in southern France.

Advantages of nuclear fusion process

- Production of high amount of energy from a small mass of nuclei
- It is a clean energy
- Fusion reactions are not radio-active like nuclear fission. Lithium and deuterium are not radioactive. Tritium is radioactive but with a short half-life of 12.6 years. As tritium is generated and used inside the reactor, no transport of radioactive fuel is required. The radiotoxicity in the reactor chamber and additional structural and waste substances will decay quickly within life of fusion reactor.
- No greenhouse gases are emitted by this process.
- Availability of abundant fusile fuel (deuterium from sea water and tritium from lithium).
- It is easy to control or stop the reaction in comparison to nuclear fission due to absence of chain reaction
- No nuclear wastes are produced

Constraints in nuclear fusion

- Commercial production of energy by nuclear fusion is not completely proved yet. \
- Highly expensive
- The fusion process requires extremely high temperatures.
- It requires energy to start the fusion reaction
- Building full-scale fusion-generating facilities will need engineering advancements like better superconducting magnets and advanced vacuum systems.

Nuclear fission

N**uclear fission** is the splitting of a heavy nucleus into two lighter ones. Fission was discovered in 1938 by the German scientists Otto Hahn, Lise Meitner, and Fritz Strassmann, who bombarded a sample of uranium with neutrons in an attempt to produce new elements with Z > 92. They observed that lighter elements such as barium (Z = 56) were formed during the reaction, and they realized that such products had to originate from the neutron-induced fission of uranium-235:

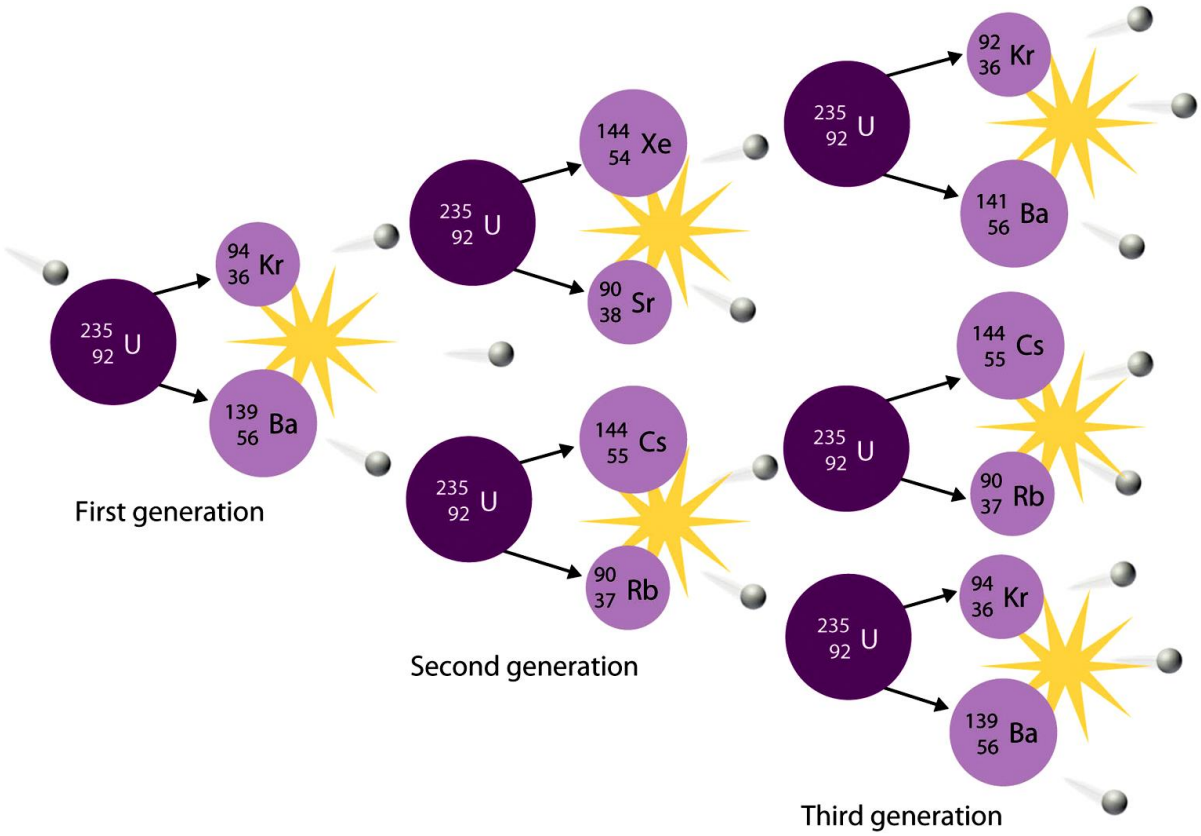
$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n$$

This hypothesis was confirmed by detecting the krypton-92 fission product. Usually the nucleus divides asymmetrically rather than into two equal parts, and the fission of a given nuclide does not give the same products every time.

In a typical nuclear fission reaction, more than one neutron is released by each dividing nucleus. When these neutrons collide with and induce fission in other neighboring nuclei, a self-sustaining series of nuclear fission reactions known as a **nuclear chain reaction** can result (Figure). For example, the fission of ^{235}U releases two to three neutrons per fission event. If absorbed by other ^{235}U nuclei, those neutrons induce additional fission events, and the rate of the fission reaction increases geometrically. Each series of events is called a generation. Experimentally, it is found that some minimum mass of a fissile isotope is required to sustain a nuclear chain reaction; if the mass is too low, too many neutrons are able to escape without being captured and inducing a fission reaction. The minimum mass capable of supporting sustained fission is called the **critical mass**. This amount depends on the purity of the material and the shape of the mass, which corresponds to the amount of surface area available from which neutrons can escape, and on the identity of the isotope. If the mass of the fissile isotope is greater than the critical mass, then under the right conditions, the resulting **supercritical mass** can release energy explosively.

If mass of the fissionable material is less than its critical mass, nuclear fission will not occur. The system is said to be **sub critical**. The enormous energy released from nuclear chain reactions is responsible for the massive destruction caused by the detonation of nuclear weapons such as

fission bombs, but it also forms the basis of the nuclear power industry. An impression may be formed from the nuclear fission reactions that only specific fission fragments which decay by beta ray or neutron emission to give stable end products. This is not actually so. Nearly 50 modes of fission reactions of ^{235}U are known.



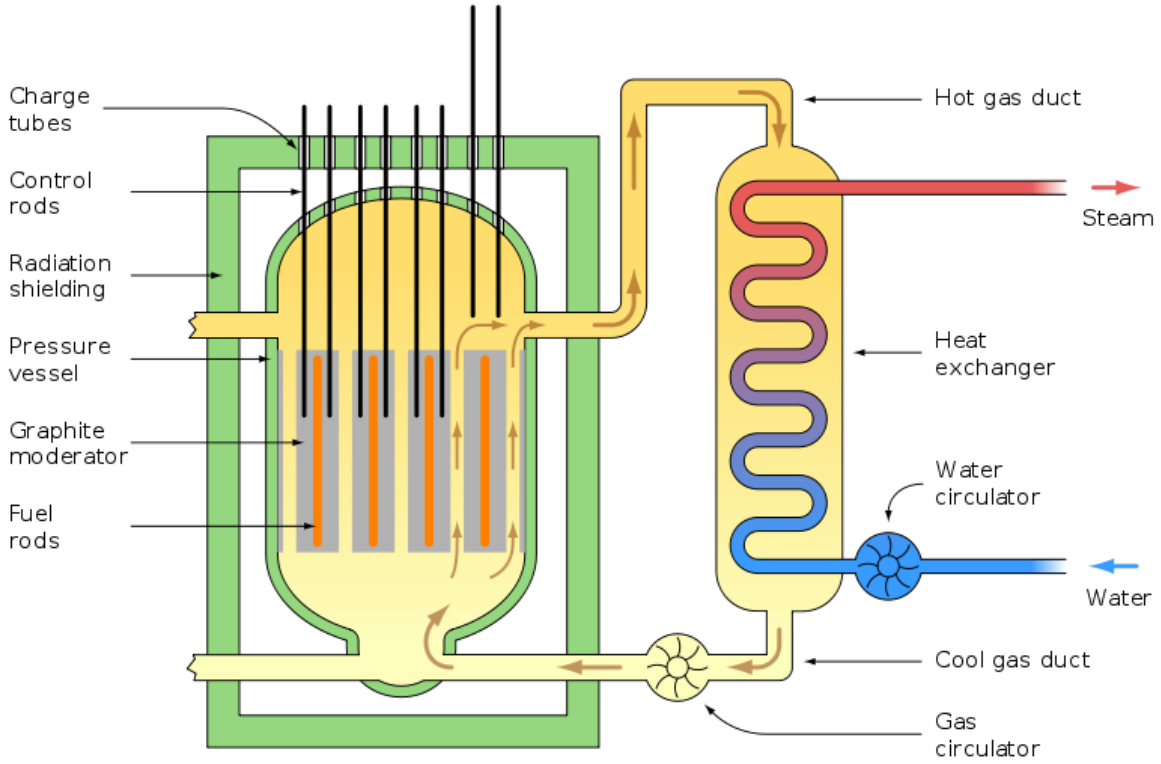
The energy released in one fission reactions is different from the energy released in another fission reaction. The number of neutrons released also varies from 1 to 4. On an average approximately 200 MeV energy, corresponding to average mass defect of 0.22 u, is released in the fission of ^{235}U. It is noted that fast moving neutrons are not captured by the nuclei of ^{235}U and hence no fission occurs no matter how large is the size of the materials. The neutrons have to be slowed down to render them catchable by the nuclei of ^{235}U. This is done by using moderators. The moderator of a nuclear reactor is **a substance that slows neutrons down**. In traditional nuclear reactors, the moderator is the same thing as the coolant: it's heavy water! When fast neutrons strike the hydrogen atoms in heavy water, they slow down a lot.

Types of reactors

(1) **Thermal reactors**

In these reactors the neutrons released during the fission of ^{235}U are made to collide with the light nuclei so as to lower their speed. They are called moderatos. Heavy water and graphite are the most commonly used moderators. Most thermal reactors use oxides of ^{235}U as fuel taken in the form of aluminium plated rods. There is a provision to insert cadmium rods into the reactor in the

case the rate of the fission reactions become very high. The heat generated in the reactor is removed by circulating a liquid called coolant around the reactor. The coolant is generally an alloy of sodium and potassium. The coolant pipes are lead to a heat exchange where they are immersed in the water which gets converted into steam by the heat of the coolant. The steam is used to run the turbines for the generation of electricity. A sufficiently thick special concrete structure is built around the reactor to protect the workers from the damaging gamma radiation.



(2) **Fast breeder reactors (FBR)**

In these reactors the moderators are not used. The non fissionable $^{238}_{92}U$ is used as a fuel. The fast neutrons produced in the fission of ^{235}U are used to convert the non-fissionable $^{238}_{92}U$ into fissionable ^{239}Pu. These ^{239}Pu produced undergoes fission even by slow neutrons. More plutonium is produced than is used in fission hence the name fast breeder reactors. The non fissionable $^{232}_{90}Th$ can also be used as fuel.

$$^{232}_{90}Th + {}^{1}_{0}n \rightarrow {}^{233}_{91}Pa + {}^{0}_{-1}e$$

$$^{233}_{91}Pa \rightarrow {}^{233}_{92}U + {}^{0}_{-1}e$$

$^{233}_{92}U$ produced above can be fissionable as usual by slow neutrons. In this type of reactors the coolant is the same as used in thermal reactors.

India's Nuclear Energy Program

India has only 2% of World's Uranium reserves, on the other hand, India has 25% of the World's Thorium reserves. India has approximately 400 thousand tonnes of thorium reserves, close to 25% of Global Thorium reserves. Thorium is not a fissile material, but it can be converted into Uranium – 233, which can then undergo fission to produce energy.

India's three stage nuclear power program

Stages	Process
Stage 1	1. Use natural Uranium to fuel a Pressurized Heavy Water Reactor (PHWR). 2. The byproduct, Plutonium (Pu) – 239 is used in Stage 2.
Stage 2	1. Develop Fast Breeder Reactor (FBR) to produce excess, Pu-239, which will then lead to the conversion of Thorium (Th – 232) to fissile Uranium U-233.
Stage 3	1. Develop Breeder Reactors, these are Thorium-based Nuclear reactors.

- India has consciously proceeded to explore the possibility of tapping nuclear energy for the purpose of power generation. In this direction **three-stage nuclear power programme** was formulated by **Homi Bhabha** in the 1950s.
- **Atomic Energy Act, 1962** was framed and implemented with the set objectives of using two naturally occurring elements Uranium and Thorium having good potential to be utilized as nuclear fuel in Indian Nuclear Power Reactors.
- The estimated natural deposits of Uranium are about 70,000 tonnes and Thorium are about 3, 60,000 tonnes in the country.

Three Stage programme

- **Stage one – Pressurised Heavy Water Reactor** uses
  - Natural UO_2 as fuel matrix,
  - Heavy water as moderator and coolant.
- In the reactor, the first two plants were of boiling water reactors based on imported technology. Subsequent plants are of PHWR type through indigenous R&D efforts. India

achieved complete self- reliance in this technology and this stage of the programme is in the industrial domain.

- The future plan includes the setting up of **VVER type** i.e. **Russian version of the Pressurized Water Reactor (PWR)** is under progress to augment power generation.
- **MOX fuel (Mixed oxide)** is developed and introduced at Tarapur to conserve fuel and to develop new fuel technology.
- **Second stage** of nuclear power generation envisages the **use of Pu-239** obtained from the first stage reactor operation, as the fuel core in **fast breeder reactors (FBR)**.
- **Third phase** of India's Nuclear Power Generation programme is, **breeder reactors** using **U-233 fuel**.
- India's vast thorium deposits permit design and operation of **U-233 fuelled breeder reactors**.

The Fast Breeder reactor at Kalpakkam

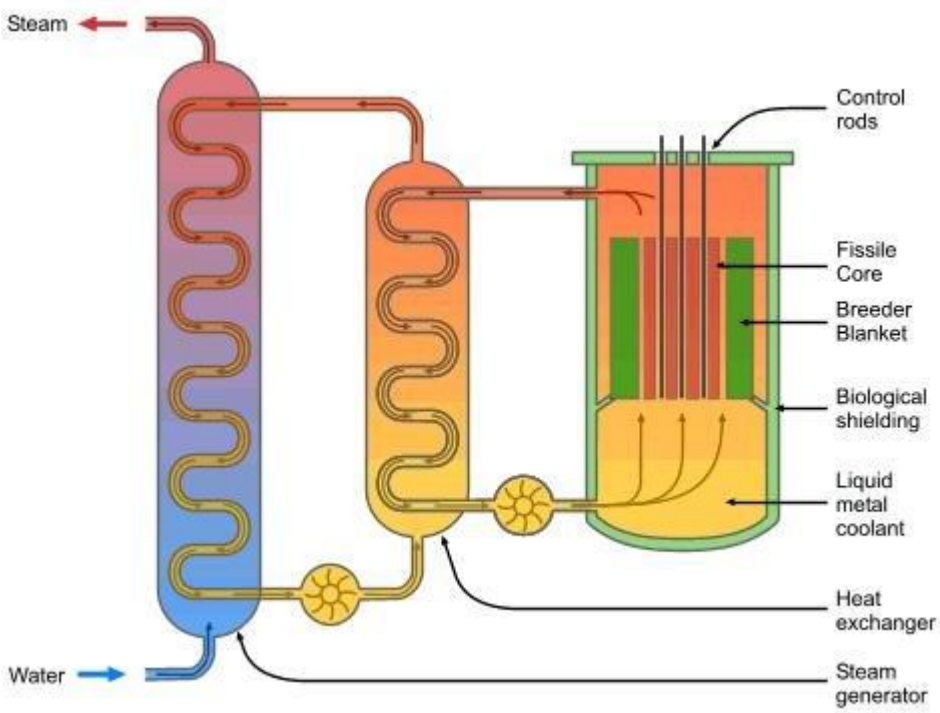
This is a totally Indian designed and fabricated Fast Breeder Test Reactor (FBTR) at the Indira Gandhi Centre for Atomic Research functioning since December 1985.

(a) Fuel

Because of the absence of moderator, the fast neutron reactor requires fuel of much higher fissile content, in the range of 15-20 per cent, as against 3-5 per cent enrichment adequate for thermal reactors moderated by light water. Unlike the breeder reactors of other countries, the one at Kalpakkam, is a sodium cooled, plutonium fuelled loop type reactor of 40 MWt . The fuel is in the form of sintered ceramic pellets of plutonium and uranium carbides, 5.1 mm diameter encapsulated in stainless steel tubes. The reactor used six boron carbide control rods of enriched ^{10}B.

(b) Coolant

In the fast neutron reactor there is no moderator. Hence the reactor core is much smaller resulting in a much higher power density than in a thermal reactor of the same power level. A sodium pump drives the liquid metal at 380 $°C$ into the reactor core from below and when the liquid leaves the top at 515 $°C$ much heat would have been extracted for the reactor core and used for generating steam.



Radioactive tracers

Isotopes of a chemical element differ only in the mass number. For example, the isotopes of hydrogen can be written as ^{1}H, ^{2}H and ^{3}H, with the mass number superscripted to the left. When the atomic nucleus of an isotope is unstable, compounds containing this isotope are radioactive. Tritium is an example of a radioactive isotope. The principle behind the use of radioactive tracers is that an atom in a chemical compound is replaced by another atom, of the same chemical element. The substituting atom, however, is a radioactive isotope. This process is often called radioactive labeling. The power of the technique is due to the fact that radioactive decay is much more energetic than chemical reactions. Therefore, the radioactive isotope can be present in low concentration and its presence detected by sensitive radiation detectors such as Geiger counters and scintillation counters. George de Hevesy won the 1943 Nobel Prize for Chemistry "for his work on the use of isotopes as tracers in the study of chemical processes". There are two main ways in which radioactive tracers are used.

(1) When a labeled chemical compound undergoes chemical reactions one or more of the products will contain the radioactive label. Analysis of what happens to the radioactive isotope provides detailed information on the mechanism of the chemical reaction.

(2) A radioactive compound is introduced into a living organism and the radio-isotope provides a means to construct an image showing the way in which that compound and its reaction products are distributed around the organism.

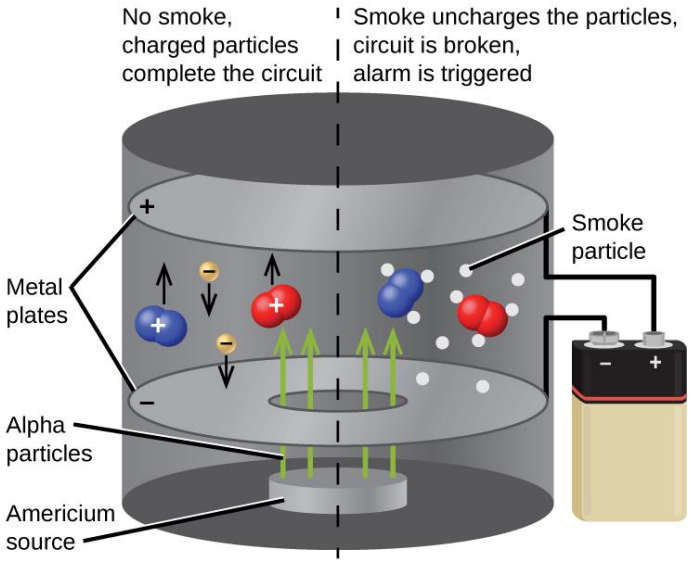
Hydrogen Tritium (^{3}H) is produced by neutron irradiation of ^{6}Li:

$$^{6}Li + n \rightarrow {}^{4}He + {}^{3}H$$

Tritium has a half-life 4500±8 days (approximately 12.32 years) and it decays by beta decay. The electrons produced have an average energy of 5.7 keV. Because the emitted electrons have relatively low energy, the detection efficiency by scintillation counting is rather low. However, hydrogen atoms are present in all organic compounds, so tritium is frequently used as a tracer in biochemical studies.

Fluorine ^{18}F decays predominately by β emission, with a half-life of 109.8 min. It is made by proton bombardment of ^{18}O in a cyclotron or linear particle accelerator. It is an important isotope in the radiopharmaceutical industry. For example, it is used to make labeled fluorodeoxyglucose (FDG) for application in PET scans.

Americium-241 is used in smoke detector. It is an α emitter with a half-life of 458 years, is used in tiny amounts in ionization-type smoke detectors. The α emissions from ^{241}Am ionize the air between two electrode plates in the ionizing chamber. A battery supplies a potential that causes movement of the ions, thus creating a small electric current. When smoke enters the chamber, the movement of the ions is impeded, reducing the conductivity of the air. This causes a marked drop in the current, triggering an alarm.



Four typical examples of radioactive tracers used in medicine are technetium-99 (^{99}Tc) , thallium-201 (^{201}Tl) , iodine-131 (^{131}I) , and sodium-24 (^{24}Na) . Damaged tissues in the heart, liver, and lungs absorb certain compounds of technetium-99 preferentially. After it is injected, the location of the technetium compound, and hence the damaged tissue, can be determined by detecting the γ rays emitted by the Tc-99 isotope. Thallium-201 becomes concentrated in healthy

heart tissue, so the two isotopes, Tc-99 and Tl-201, are used together to study heart tissue. Iodine-131 concentrates in the thyroid gland, the liver, and some parts of the brain. It can therefore be used to monitor goiter and treat thyroid conditions, such as Grave's disease, as well as liver and brain tumors. Salt solutions containing compounds of sodium-24 are injected into the bloodstream to help locate obstructions to the flow of blood.