UNIT 27 NUCLEAR PHYSICS

The atom is the building block of matter; an atom is composed of a positively charged nucleus, with a cloud of negatively charged electrons surrounding it, bound together by electrostatic force. and atomic nucleus is the small, dense region consisting of protons and neutrons at the center of an atom. Almost all of the mass of an atom is located in the nucleus, with a very small contribution from the electron cloud. All properties of a nucleus are determined by the number of protons and neutrons it has. A specific combination of protons and neutrons is called a nuclide and is a unique nucleus. The following notation is used to represent a particular nuclide.

ATOMIC NUMBER

The number of protons in the nucleus of an atom is the atomic number. This is denoted by the letter Z

MASS NUMBER

The mass number, denoted by the symbol "A," represents the total number of protons and neutrons in the nucleus of an atom of a specific element.

$$A = Z + N$$

ISOTOPES:

Two or more forms of the same element contain equal numbers of protons but different numbers of neutrons in their nuclei are called isotopes. They share almost the same chemical properties, but differ in mass and therefore in physical properties.

ISOTOPES ARE OF TWO TYPES:

STABLE ISOTOPES:

They do not show any radioactivity and are stable.

EXAMPLE,

(i) $^{14}_{7}N$ & $^{15}_{7}N$ (ii) $^{32}_{16}S$ & $^{34}_{16}S$

RADIOACTIVE ISOTOPES:

They are unstable and show radioactivity. Some of the radioactive

EXAMPLE,

(i) Carbon-14 is unstable and undergoes radioactive decay with a half-life of about 5,730 years

(ii) Uranium-238 and Uranium-235 are Unstable isotopes.

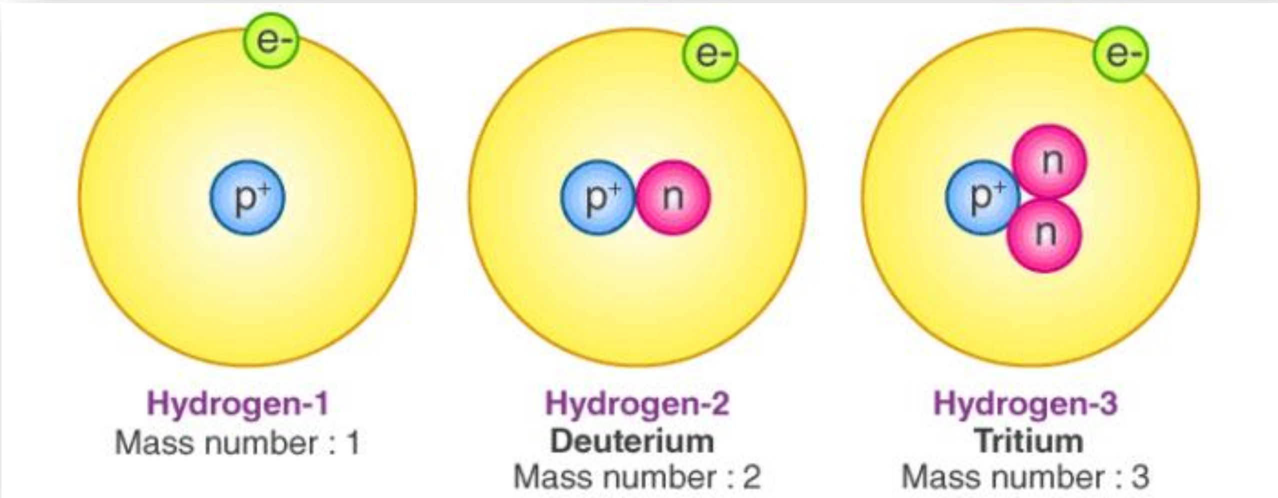
UNIT 27 NUCLEAR PHYSICS

ISOTOPIC VARIATIONS: DIFFERENT NUMBERS OF NEUTRONS:

An element can exist in various isotopic forms, each with a different number of neutrons. Elements with low atomic numbers tend to have fewer isotopes, while elements with high atomic numbers tend to have more isotopes.

Every element on the periodic table naturally occurs in various isotopic forms, although some may be more prevalent than others. For instance:

- **Oxygen:** About 99.76% of oxygen in nature is Oxygen-16 (with 8 neutrons). However, Oxygen-17 and Oxygen-18 are also found in much smaller quantities.
- **Uranium**: The naturally occurring isotopes of uranium are Uranium-238 (99.3%) and Uranium-235 (0.7%). Uranium has 35 known isotopes. The most stable isotope of uranium is uranium-238, which has 146 neutrons.
- **Hydrogen**: Hydrogen has only three isotopes: protium, deuterium, and tritium. Protium has no neutrons, deuterium has one neutron, and tritium has two neutrons.



MASS SPECTROGRAPH

A mass spectrograph is a device that can be used to separate isotopes of an element based on their mass and it works by accelerating charged particles through a magnetic field. The magnetic field then deflects the particles, and the particle's mass determines the deflection amount.

BAINBRIDGE MASS SPECTROGRAPH

Bainbridge mass spectrograph is a type of mass spectrometer that uses a combination of electric and magnetic fields to separate Ions according to their charge-to-mass ratio. It is named after its inventor, Kenneth T. Bainbridge, who developed it in 1933.

PRINCIPLE:

The fundamental principle behind the Bainbridge Mass Spectrograph is the application of magnetic and electric fields to separate and measure the masses of charged particles,

typically Ions. This separation is based on the principles of magnetic deflection and kinetic energy.

CONSTRUCTION

The Bainbridge mass spectrograph consists of three main components: an ion source, a velocity selector, and a magnetic analyzer.

THE ION SOURCE

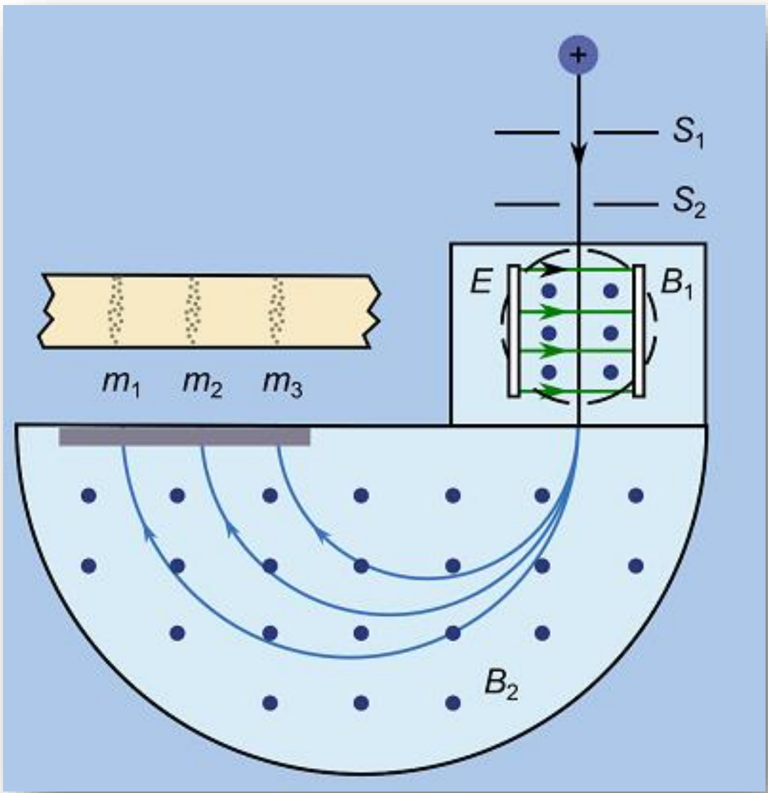
The ion source is where the Ions are produced. The Ions are typically produced by bombarding a sample with electrons, which knocks electrons out of the atoms, creating positively charged Ions.

THE VELOCITY SELECTOR

The velocity selector is used to select Ions of a particular velocity. The Ions are passed through a region of electric and magnetic fields, which are adjusted so that only Ions of a certain velocity can pass through.

THE MAGNETIC ANALYZER

The magnetic analyzer is used to separate the Ions according to their charge-to-mass ratio. The Ions are passed through a region of magnetic field, and the radius of their path is determined by their charge-to-mass ratio.



WORKING

A beam of positive Ions produced in a discharge tube is collimated into a narrow beam by the two slits S_1 and S_2. After emerging from the slit, the positive Ions enter a velocity selector.

The velocity selector consists of two plates E and B_1, between which a steady electric field is maintained in a direction at right angles to the ion beam. The electric field and the magnetic field of the velocity selector are so adjusted that the deflection produced by one is exactly equal and opposite to the deflection produced by the other so that there is no net deflection for Ions having a particular

$$eletric\ field = magnetic\ field$$

$$e E = evB_1$$

$$v = \frac{eE}{eB_1}$$

$$v = \frac{E}{B_1} \quad \ldots\ldots (i)$$

The Ions were accelerated to known kinetic energy, ensuring that all Ions of different masses had the same kinetic energy. Positive ions entering the evacuated chamber are subjected to a perpendicular electromagnetic field of intensity B_2, causing them to follow curved paths. When a charged particle with mass **m** and charge **e** is accelerated through a potential difference **V**, it gains a velocity ***v***, given by

$$kinetic\ energy = work$$

$$\frac{1}{2} m v^2 = e V$$

$$m v^2 = 2 e V$$

$$v^2 = \frac{2 e V}{m}$$

$$v = \sqrt{\frac{2 e V}{m}} \quad \ldots\ldots\ldots\ldots (ii)$$

When this charged particle moves with a velocity v enters a magnetic field **B** in a direction perpendicular to the field, the force acting on it due to the field is **Bev** acting in a direction at right angles to the direction of motion of the charged particle and that of the magnetic field. The particle, therefore, moves along a circular path of radius **r** given by

$$Bev = \frac{m v^2}{r}$$

$$Be = \frac{m v}{r}$$

$$m = \frac{Be\,r}{v}$$

Substituting the expression v from equation (ii) in above equation

$$m = \frac{B\,e\,r}{\sqrt{\frac{2\,e\,V}{m}}}$$

Squaring both sides

$$m^2 = \frac{(B\,e\,r)^2}{\left(\sqrt{\frac{2\,e\,V}{m}}\right)^2}$$

$$m^2 = \frac{B^2\,e^2\,r^2}{\frac{2\,e\,V}{m}}$$

$$m^2 = B^2\,e^2\,r^2 \times \frac{m}{2\,e\,V}$$

$$m = B^2\,e\,r^2 \times \frac{1}{2\,V}$$

$$m = \left(\frac{e\,r^2}{2\,V}\right) \times B^2$$

The mass of each ion reaching the detector depends on the value of B^2. By changing B and keeping other variables constant, ions of different masses can be directed into the detector.

RADIOACTIVE DECAY:

Radioactive decay is the random process in which a nucleus loses energy by emitting radiation. This is usually in the form of alpha particles (Helium nuclei), beta particles (electrons or positrons), or gamma rays (high-energy photons). The nucleus' energy reduces, making it more stable. In all decay processes mass, charge, and lepton number are conserved.

A material containing unstable nuclei is considered a radioactive element.

TYPES

NATURAL RADIOACTIVITY

Nuclear reactions which occur spontaneously are said to be an example of natural radioactivity. There are three naturally occurring radioactive series among the elements in the periodic table. These are known as the uranium series, the actinium series, and the thorium series

ARTIFICIAL RADIOACTIVITY

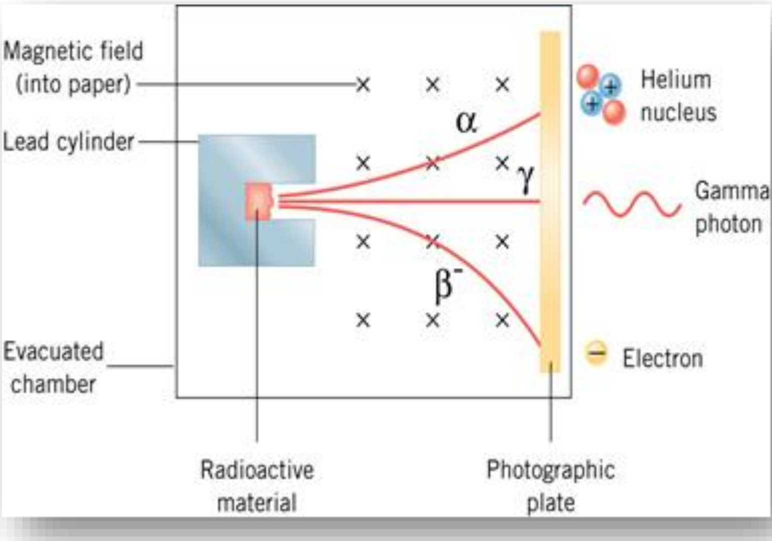
Not all nuclear reactions are spontaneous. These reactions occur when stable isotopes are bombarded with particles such as neutrons. This method of inducing a nuclear reaction to proceed is termed artificial radioactivity.

UNIT 27 NUCLEAR PHYSICS

Radioactivity is a phenomenon, independent of all physical factors like temperature, density, and pressure.

RADIOACTIVE DECAY PROCESS:

A small sample of radioactive substance is placed in a cavity drilled into a block of lead. Radiations given off by the radioactive substance are allowed to pass through the electric or magnetic fields. Three different paths followed by the radiation components show that there are three kinds of radiation.

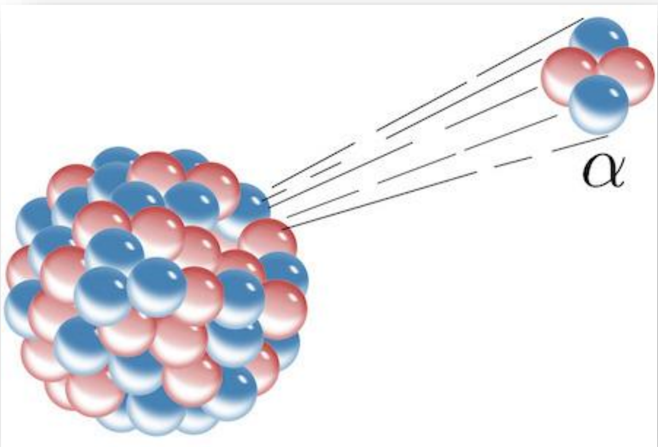


ALPHA DECAY

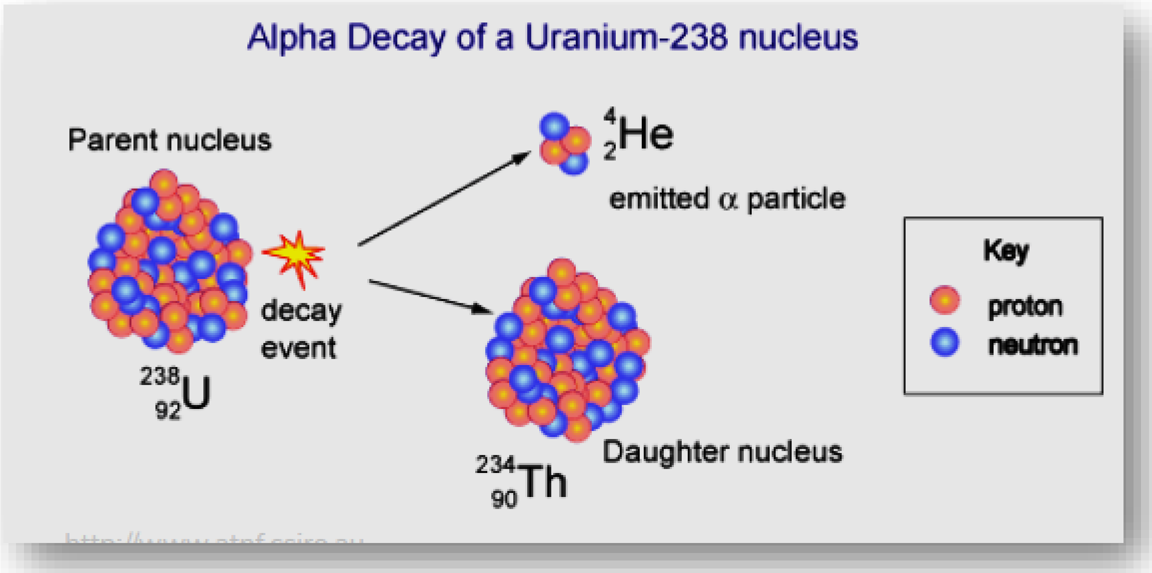
When a nucleus produces α rays it is said to undergo α decay. An α particle consists of two protons and two neutrons which can be described as a Helium-4 nucleus. The symbol for an α particle in nuclear equations is ${}_{2}^{4}\text{He}$.

The emission of alpha particles from an unstable nucleus is given by

$$ {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}\text{He} $$



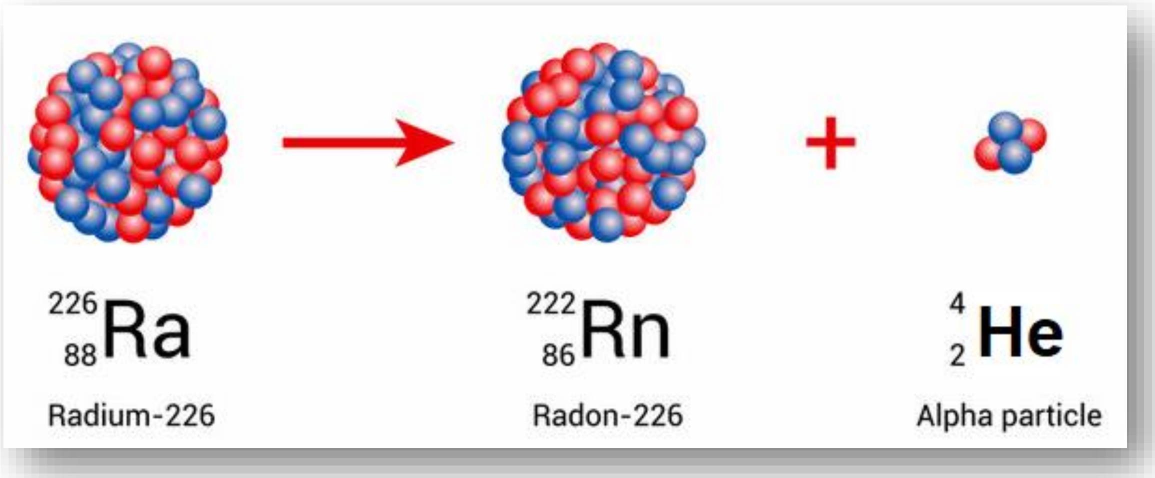
The α decay of U-238 is a good example.



The equation is:

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

Radium-226, for another example, undergoes alpha decay to form radon-222:



The equation is:

$$^{226}_{88}Ra \rightarrow \; ^{222}_{86}Rn + \, ^{4}_{2}\mathrm{He}$$

BETA DECAY:

The beta-decay is a spontaneous process in which the mass number of the nucleus remains unchanged, but the atomic number changes by unity (Z = ±1). The change in atomic number is due to the emission of an electron, the emission of a positron, or by capture of an orbital electron (K-capture).

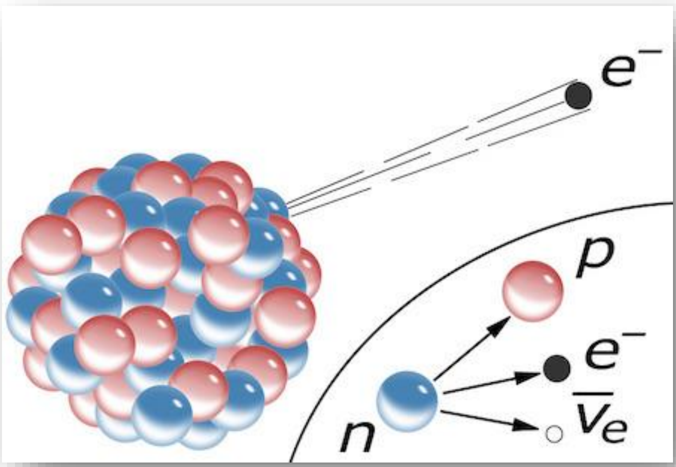
NEGATIVE BETA DECAY

One of the examples of beta decay is the β– decay of the carbon atom. Here, a neutron of carbon is converted into a proton, and the emitted beta particle is an electron

$$ {}_{0}^{1}n \rightarrow {}_{1}^{1}P + {}_{-1}^{0}\beta $$

The emission of an electron (negative beta particle) from a nucleus is given by

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta $$



Here is an example

$$ {}_{6}^{14}C \rightarrow {}_{7}^{14}N + {}_{-1}^{0}\beta $$

POSITIVE BETA DECAY (POSITRON EMISSION):

In beta plus decay, the proton disintegrates to yield a neutron causing a decrease in the atomic number of the radioactive sample. The nucleus experiences a loss of proton but gains a neutron.

$$^{1}_{1}P \rightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta$$

The general equation of positron emission is:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta$$

Here is an example

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}\beta$$

ELECTRON CAPTURE

In this process, an electron from the K-shell of the atom is captured by the nucleus to form a new nucleus, and a photon is emitted:

$$^{1}_{1}P + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n$$

An example of electron capture is the decay of krypton-81 into bromine-81

$$^{81}_{36}K + {}^{0}_{-1}e \rightarrow {}^{81}_{35}Br$$

GAMMA DECAY

The gamma decay is the spontaneous emission of an electromagnetic photon from the nucleus. When the nucleus in an excited state goes to a lower or ground state, then it emits gamma rays. During gamma decay, there is no change in mass number A or atomic number Z. An excited nucleus is denoted by an asterisk (*) after or over its usual symbol. Thus $^{87}_{38}S^*$ refers to $^{87}_{38}S$ in an excited state. The general equation for gamma decay is:
The equation of gamma decay is:

$$^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$$

Here is an example of gamma-decay

$$^{60}_{27}Co^* \rightarrow {}^{60}_{27}Co + \gamma$$

This equation represents the decay of an excited state of cobalt-60 ($^{60}_{27}Co^*$) into the ground state of cobalt-60 ($^{60}_{27}Co$) with the emission of a gamma (γ) photon.

THE LAW OF RADIOACTIVE DECAY

STATEMENT

The law of radioactive decay states that the rate of decay of a radioactive sample at any instant is directly proportional to the number of atoms present.

MATHEMATICAL EXPRESSION

If a radioactive sample contains N radioactive nuclei at some instant, it is found that the number of nuclei, ΔN, is the number of atoms disintegrating in a time Δ t, then the rate of decreases $\frac{\Delta N}{\Delta t}$ is proportional to N

$$\frac{\Delta N}{\Delta t}\ \alpha\ -N$$

$$\frac{\Delta N}{\Delta t} = -\lambda N \quad \ldots\ldots (i)$$

Where λ is a constant called the decay constant. The negative sign is significant that N decreases with time, that is ΔN is negative.

Equation (1) can be written in the form

$$\frac{\Delta \mathrm{N}}{\mathrm{N}} = -\lambda\,\Delta \mathrm{t}$$

By using integration, the law can be written as

$$N = N_0\, e^{-\lambda t} \quad \ldots\ldots\ldots\ldots (ii)$$

Where the constant N_o represents the number of radioactive nuclei at t = 0. The above equation shows that the number of radioactive nuclei in a sample decreases exponentially with time.

THE SPONTANEOUS AND RANDOM NATURE OF RADIOACTIVE DECAY:

Radioactive decay is both spontaneous and random.

SPONTANEOUS PROCESS:

It is a process which cannot be influenced by environmental factors, Such as:

(i) Temperature
(ii) Pressure
(iii) Chemical conditions

RANDOM PROCESS:

It is a process in which the exact time of decay of a nucleus cannot be predicted.

The random nature of radioactive decay can be demonstrated by observing the count rate of a Geiger-Muller (GM) tube.

(i) When a GM tube is placed near a radioactive source, the counts are found to be irregular and cannot be predicted.
(ii) Each count represents a decay of an unstable nucleus.
(iii) These fluctuations in the count rate on the GM tube provide evidence for the randomness of radioactive decay.

UNIT 27 NUCLEAR PHYSICS

ACTIVITY

The decay rate, or activity A of a sample is defined as the number of disintegrations(decay) occurring per unit of time

If a radioactive sample contains N atoms at any time t, then activity at time t is given as a number

$$A\ (\text{ activity })\ =\ -\left(\frac{\Delta N}{\Delta t}\right)$$

Where the negative sign shows that activity decreases with time. According to the law of radioactive decay

$$\frac{\Delta N}{N}\ =\ -\lambda\,\Delta t$$

The above equation can be written as

$$A\ =\ \lambda N$$

Thus, we see that isotopes with a large λ value at a rapid rate and those with a small λ value decay slowly.

UNIT OF ACTIVITY

A frequently used unit of activity is the curie (Ci), defined as

1 Ci = 3.7 x 10 10 decay per second (decay/s)

This value was originally selected because it is the approximate activity of 1 g of radium. The SI unit of activity is the becquerel (Bq):

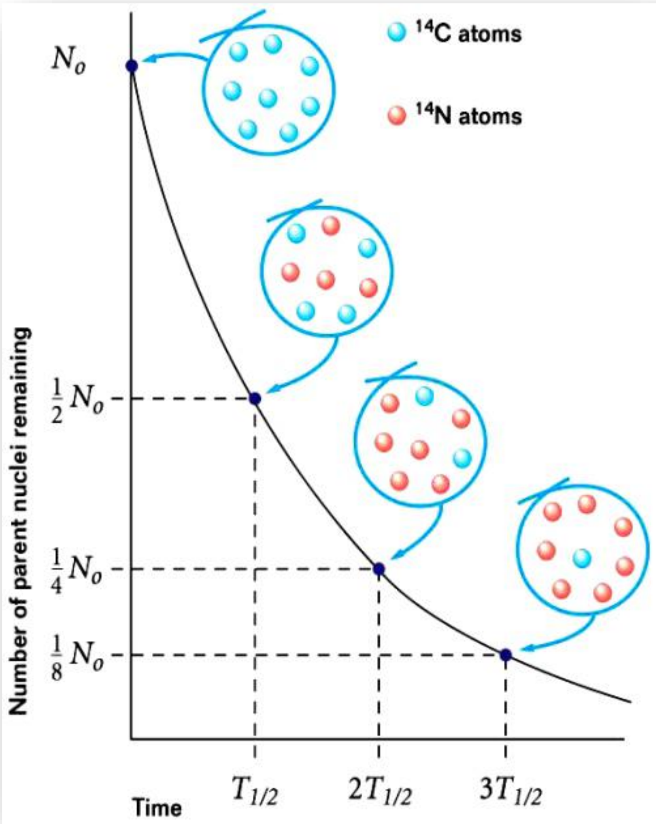
1 Bq = 1 decay/s

Therefore, 1 Ci = 3.7×10^{10} Bq. The curie is a rather large unit and, the more frequently used activity units are millicurie and microcurie.

EXPONENTIAL NATURE OF RADIOACTIVITY

Radioactive decay follows an exponential decay pattern. This means that the rate of decay proportionally decreases with the remaining amount of radioactive material and it can be visualized graphically by the decay curve.

A decay curve is a plot of the number of radioactive parent nuclei remaining in a sample as a function of half-life. A typical decay curve for a radioactive sample is shown in Figure. After each half-life, half of the remaining parent nuclei have decayed. This is represented in the circles to the right of the decay curve. The blue spheres are the parent nuclei (carbon-14), and the red spheres are the daughter nuclei (nitrogen-14). Notice that the total number of nuclei remains constant, while the number of carbon atoms continually decreases over time. For example, the initial sample contains 8 carbon-14 atoms. After one half-life, there are 4 carbon-14 atoms and 4 nitrogen-14 atoms. By the next half-life, the number of carbon-14 atoms is reduced to 2, and the process continues. As the number of carbon-14 atoms decreases, the number of nitrogen-14 atoms increases.



HALF-LIFE

The half-life of a radioactive substance is the time it takes for half of the initial amount of the substance to decay or transform into another element. It's a measure of the stability of an atom and the rate at which it loses its radioactivity.

Now, $N = \frac{N_o}{2}$ and $t = T_{1/2}$ in equation (ii) gives

$$\frac{N_0}{2} = N_0\ e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$2^{-1} = e^{-\lambda T_{1/2}}$$

Taking the natural logarithm of both sides gives

$$ln\,(2^{-1}) = ln\left(e^{-\lambda T_{1/2}}\right)$$

$$(-1) ln\,(2) = (-\lambda T_{1/2})\, ln\,(e)$$

$$-1 ln\,(2) = -\lambda T_{\frac{1}{2}}\, ln\,(e) \qquad \{lne = 1\}$$

$$ln\,(2) = \lambda T_{1/2} \qquad \{ln2 = 0.693\}$$

$$0.693 = \lambda T_{1/2}$$

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

This is a convenient expression relating half-life $T_{1/2}$ to decay constant.

MASS DEFECT AND BINDING ENERGY:

When examining the nucleus of an atom, we find that its mass is actually less than the combined mass of its protons and neutrons. This discrepancy is due to the strong nuclear forces holding the nucleus together. To better understand this phenomenon, we need to learn some important terms.

Mass Defect and Binding Energy or the Hidden Energy within Atoms:

Two fundamental concepts that play a critical role in understanding atomic behavior are Mass Defect and Binding Energy.

MASS DEFECT:

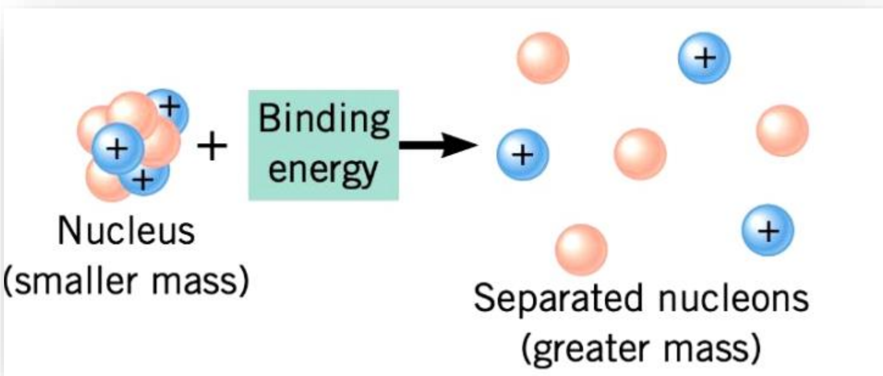
Mass Defect refers to the difference between the total mass of individual protons, neutrons, in an atom and the actual mass of the atom.

The mass defect Δm of a nucleus can be calculated using:

$$\Delta m = [\, Z\,(m_P) + (A - Z) m_n \,] - m_{total}$$

BINDING ENERGY:

Binding Energy is the energy required to break apart the nucleus of an atom into its constituent protons and neutrons. Exploring the Connection: as shown in the figure



UNIT 27 NUCLEAR PHYSICS

FORMULA

Let Δm = mass defect

B.E = binding energy

(i) if 'Δm' is in kilogram:

then,

$$B.E. = (\Delta m)c^2,$$

(ii) if 'Δm' is in a unified atomic mass unit (u)

$$B.E. = (\Delta m)\,u \times 931.5\,MeV.$$

PACKING FRACTION

The binding energy per nucleon is called the packing fraction.

$$paking\ friction = \frac{B.E}{A}$$

UNIFIED ATOMIC MASS UNIT

Atomic and nuclear masses are measured in unified atomic mass units (abbreviation u) chosen so that the atomic mass of ${}_6C^{12}$ is taken exactly equal to 12u. The relation for this unit to the SI mass standard is

$$1\ u = 1.6605 \times 10^{-27}\ kg.$$

For examples:

$$mass\ of\ proton\ m_p = 1.007276\ amu = 1.67865 \times 10^{-27}\ kg$$

$$mass\ of\ neutron\ m_n = 1.008665 amu = 1.67495 \times 10^{-27}\ kg$$

$$mass\ of\ Hydrogen\ atom\ {}_1^1H = 1.00784\ amu$$

$$mass\ of\ Chlorine\ atom = 35.47\ amu$$

The energy equivalent of

The energy equivalent of a.m.u

According to Einstein's mass-energy relation, the energy equivalent to mass m is given by:

$$E = mc^2$$

where

c is the velocity of light. ($c = 3 \times 10^8\ m/s$)

let mass m = 1 a.m.u = 1.680665 x 10^{-27} kg, c = 3 x 10^8 m/s. Then equivalent to 1 a.m.u is given as:

$$E = mc^2$$

$$1\ a.m.u = 1.680665 \text{ x } 10^{-27}\ (3 \times 10^8)^2$$

$$1\ a.m.u = 1.4925 \text{ x } 10^{-10}\ \text{Joules}$$

$$1\ a.m.u = \frac{1.4925 \text{ x } 10^{-10}}{1.6 \times 10^{-19}}$$

UNIT 27 NUCLEAR PHYSICS

$$1\ a.m.u = 931.5 \times 10^6\ eV$$
$$1\ a.m.u = 931.5\ MeV$$

The energy equivalent to the mass of the electron = $0.511\ MeV$

The energy equivalent to the mass of the proton = $938.279\ MeV$

The energy equivalent to the mass of the proton = $939.573\ MeV$

THE BINDING ENERGY PER NUCLEON

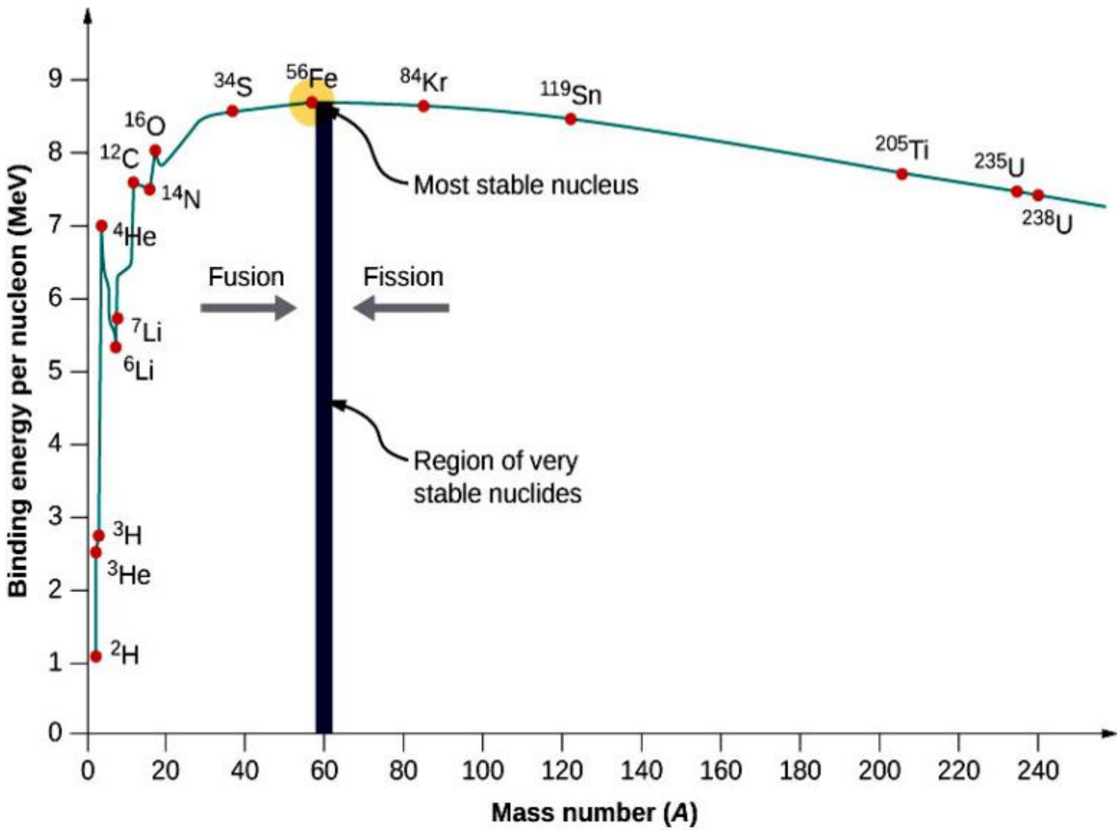
The binding energy per nucleon ($\overrightarrow{E_B}$) is the average energy required to release a nucleon from the nucleus. It is given mathematically as

$$\overrightarrow{E_B} = \frac{E_B}{A}$$

Where **A** is the total number of nucleons in the nucleus.

The binding energy per nucleus ($\overrightarrow{E_B}$) of a nucleus is more important than the total binding energy E_B of the nucleus because it determines the stability of the nucleus. The higher the binding energy value per nucleon, the more stable the nucleus. The nuclei with less binding energy per nucleon are comparatives less stable.

The graph between binding energy per nucleon and the mass number of different nuclei is shown in the figure.



- The binding energy per nucleon for light nuclei (i.e. $^{2}_{a}H$) is very small. The binding energy per nucleon increases rapidly for nuclei up to mass number 20.
- The curve possesses peaks corresponding to nuclei

$$^{4}_{2}He\ ,\ \ ^{8}_{4}Be,\ \ ^{12}_{6}C\ ,\ \ ^{16}_{8}O\ ,\ \ ^{20}_{10}Ne$$

- The peaks indicate that these nuclei are more stable than other nuclei in their neighborhood. After mass number 20 binding energy per nucleon increases gradually.
- The curve has an average binding energy value per nucleon of about 8.6 MeV for a considerable range of mass numbers 10 to 120. In this range, the curve is more or less flat.
- For mass number A = 6(i.e., $^{56}_{26}Fe$), the binding energy per nucleon is maximum and is equal to 8.8 MeV.
- The nuclei of intermediate masses (i.e. A=40 to 120) are most stable and a very high amount of energy has to be supplied to liberate each of their nucleons.
- The binding energy per nucleon has a low value for both very light and very heavy nuclei.
- To attain the higher value of binding energy per nucleon, the lighter nuclei may unite together to form a heavier nucleus (process of nuclear fusion) or a heavier nucleus may split into light nuclei (process of nuclear fission). In both these nuclear processes, the resulting nucleus acquires a greater value of binding energy per nucleon, and large amount of energy is released.

NUCLEAR REACTIONS:

Any process that involves a change in the nucleus of an atom is called a nuclear reaction. Mathematically,

$$\boldsymbol{X + x \ \rightarrow \ Y + y + Q}$$

where **X** is the target, $\boldsymbol{x}$ are the projectiles, **y** is a particle that is emitted during a reaction and **Y** is called the residual(product) nucleus.

27.4.1 Energy Released from Nuclear Reactions:

The energy is either absorbed or emitted which is called Q value and it is equal to the mass defect. The Q value can also be defined as the difference between the rest energies of X and $\boldsymbol{x}$ and the rest of energies of Y and y:

$$Q = \left(m_X + m_x - m_Y - m_y\right) c^2 \ldots\ldots(i)$$

The value of Q is taken as positive when the energy is released, and its corresponding reaction is called exothermic. Similarly, the value of Q is taken as negative when the energy is absorbed, and its corresponding reaction is called endothermic.

CONSERVATION OF ATOMIC AND MASS NUMBERS:

Whenever there is a nuclear decay, there is always some physical quantities need to be conserved or remain constant. The following are rules for any nuclear reaction:

1. The total of the atomic numbers (Z) on the left is the same as the total on the right of the given equation because charge must be conserved.

2. The total of the mass numbers (A) on the left is the same as the total on the right of the equation because nucleon numbers must be conserved.

For example, in the following nuclear reaction, the total atomic number and mass number remain the same on both sides of the equation:

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

In the above reactions, Z=92 on the left side which is equal to 90+2=92 on the right side. Similarly, A=238 on the left side which is equal to 234+4=238 on the right side.

CONSERVATION OF MASS AND ENERGY:

According to Einstein's mass-energy relationship (E = mc2), in all nuclear reactions, the total sum of mass and energy must be conserved. This means the total mass on the left side of the equation (before the decay) is equal to the total mass on the right side (after the decay), plus the Q value. The Q value represents the mass difference before and after the decay, and this difference is converted into energy according to the mass-energy relationship (E=mc2). This released energy is typically in the form of kinetic energy of the decay products, such as alpha particles, beta particles, or gamma rays.
So, the equation that represents the conservation of mass and energy in radioactive decay can be expressed as:

Total mass before decay=Total mass after decay + Q-value

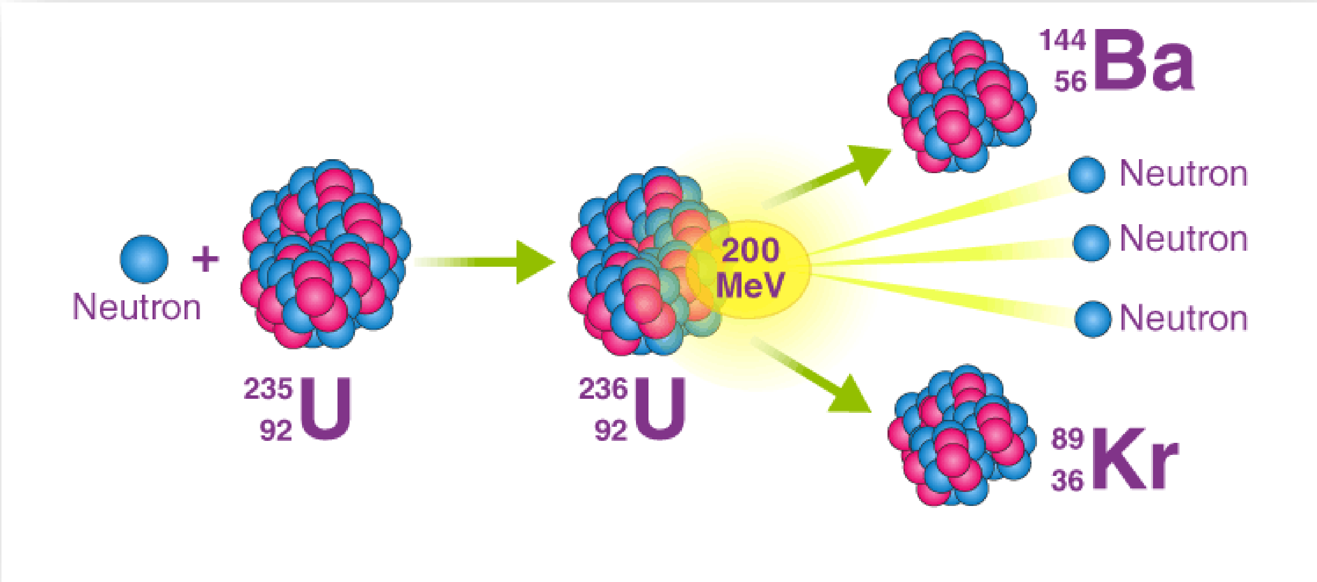
This equation underscores the principle that while mass may appear to decrease due to the emission of particles; the lost mass is accounted for in the form of energy released during the decay process.

NUCLEAR FISSION

The breakup of a heavy nucleus into two intermediate-sized nuclei (called fission fragments) with the release of a tremendous amount of energy is called nuclear fission.

In 1934, Enrico Fermi discovered that binary fission can take place in heavy nuclei (A > 230) with thermal neutrons (-0.02 MeV). In 1938, Otto Hahn and Fritz Strassman discovered that fission can take place in U-235 spontaneously. In 1939, Lise Meitner and O.R. Frisch coined the term fission and suggested that U-235 spontaneously undergoes fission, producing two fragments that release a tremendous amount of energy.

For example, when a uranium nucleus (U-235) is bombarded by a slow-moving neutron (called a thermal neutron), the U-235 nucleus splits into two medium-mass nuclei with the release of a huge amount of energy, as shown in figure



NUCLEAR REACTION:

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}U \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}Kr + 3\left({}^{1}_{0}\mathrm{n}\right) + 200\ \mathrm{MeV} $$

FISSION ENERGY:

When nuclear fission takes place, it is found that the sum of the masses of fission products is very slightly less than the sum of the masses of reactant products. As a result, there occurs a mass defect (m) in nuclear fission. This mass defect is converted into energy according to the relation E = mc^2. The energy released in the above fission can be determined from the mass defect that occurs in the process.

Total mass before fission

Mass of uranium nuclide:235.045733 a.m.u
Mass of one neutron: 1.008665 a.m.u
The total mass of the reactants: 236.044398 a.m.u

Total mass after fission

Mass of two fragments = 232.812000 a.m.u
Mass of three neutrons = 3.025995 a.m.u
Sum of the masses after fission = 235.837995 a.m.u
Mass defect = Δm = 236.052598 – 235. 837995 = 0.214603 a.m.u
Energy released per fission= 0.214603 x 931.5 = 200 MeV.

UNIT 27 NUCLEAR PHYSICS

SALIENT FEATURES ABOUT FISSION:

(i) Fission in U-235 can take place spontaneously.

(ii) About 200 MeV energy is released per fission, and $\frac{200 MeV}{235} = 0.85\ MeV$ per nucleon.

(iii) Three neutrons (on the average) are produced per fission. This tends to make fission chain reaction self-sustaining.

(iv) The division of fission nuclei has asymmetric mode.

(v) The fission fragments are radioactive (They undergo β and γ-decay before stabilizing).

(vi) Three fissionable nuclides U-233, U-235 and Pu – 239 (also called fissile nuclides) are important in the large scale production of nuclear energy.

(vii) The nuclides which are not fissionable by themselves (e.g. U-238 and Th-232 but they can be converted to fissionable nuclides (i.e. Pu –239 and U–233) are known as fertile nuclides.

(viii) Energy released per kg of U-235 is 2.3×10^{7} kWh or 1000 MW for one day.

(ix) Fission can occur spontaneously (in less than 10^{-14} second) or it can be induced.

(x) The fission, has been produced in bismuth, gold, lead and rare earths, too.

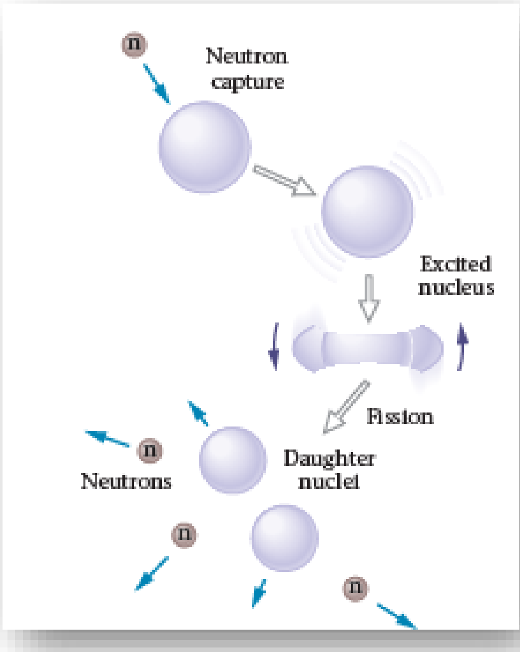
(xi) Super explosion of a fission bomb (called atomic bond) is the self-sustaining fission chain reaction which take place in an uncontrolled manner.

(xii) Nuclear power plants (reactors) produce power when fission chain reaction is performed in a controlled manner.

MECHANISM OF FISSION:

Niels Bohr and J.A. Wheeler explained fission on the basis of Liquid Drop Model of a nucleus in 1939.

The capture of a neutron by a heavy nucleus sets up oscillations within the 'drop'. These oscillations tend to distort the shape, and it becomes ellipsoid in shape. If excitation energy (and hence oscillations) are sufficiently large, it becomes 'dumbell' in shape. The coulomb repulsive forces then push the two 'bells' apart. Consequently, it splits into two drops of nearly equal sizes.

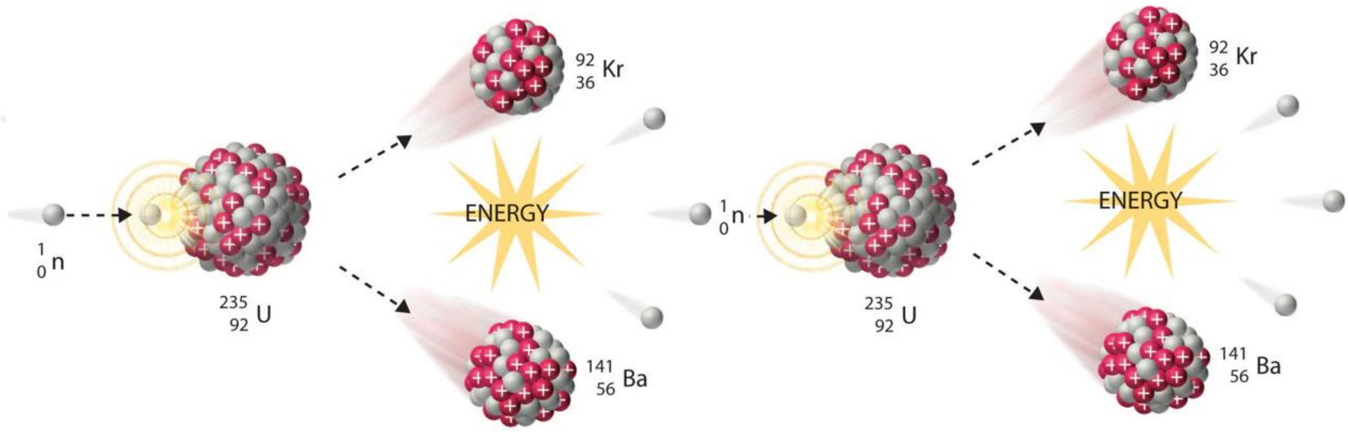


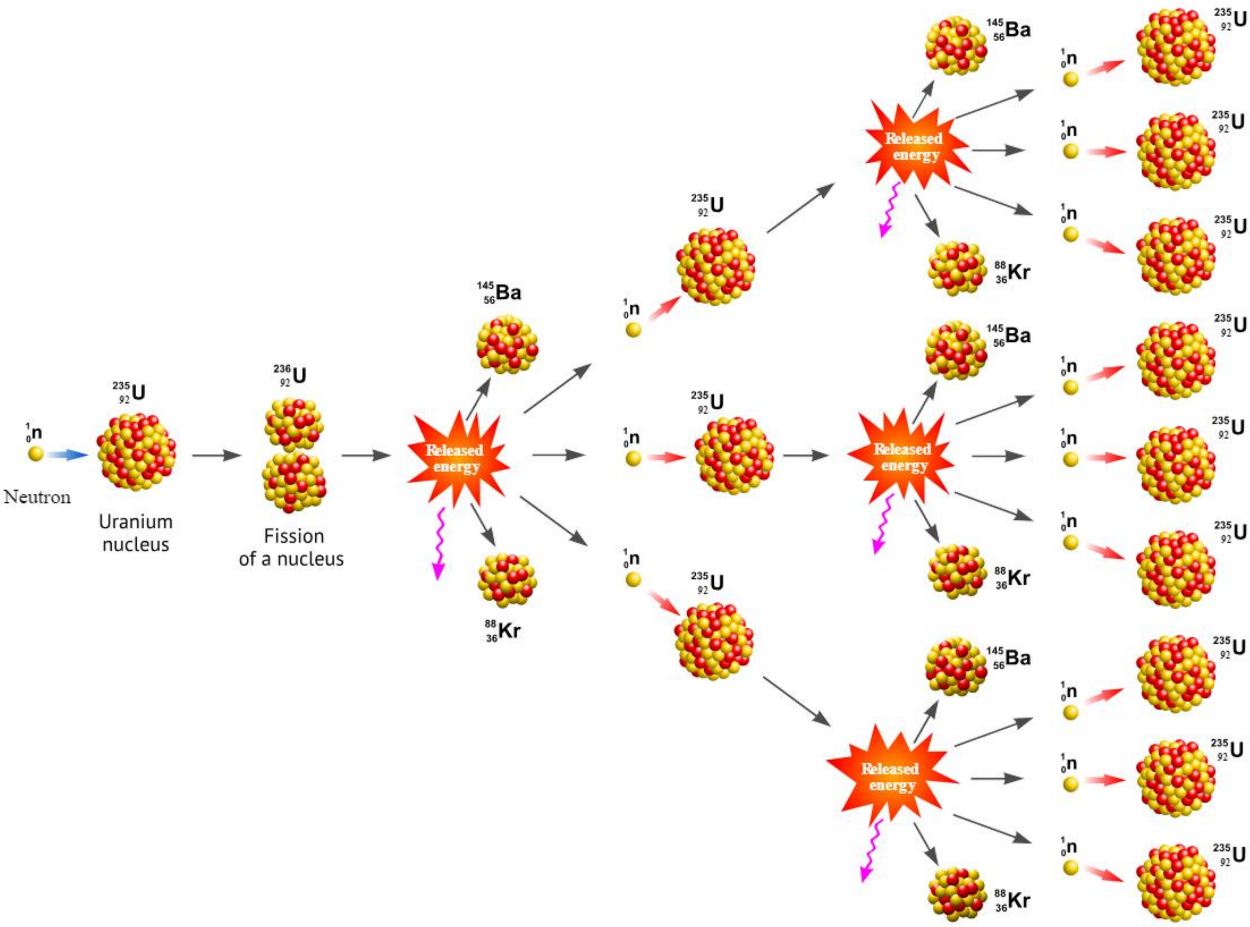
FISSION CHAIN REACTION

On average, the emission of three neutrons in the fission of a U-235 nucleus permits a self-sustaining chain reaction. It is the process in which the number of neutrons multiply rapidly in a geometrical progression till the total fissionable nuclei are fissioned.

Consider some amount of highly enriched uranium i.e., the uranium containing more U-235 atoms (which is only 0.71% in natural uranium). Then any stray neutron will produce fission in one of the atoms of uranium, releasing 2 to 3 neutrons. It is said that the 'multiplication factor' (k) is greater than 1. If conditions are correct, the neutrons will produce fission in other uranium atoms in a rapid geometric progression. Hence a self-maintained chain reaction will build up. It will result in an explosive violence.

The minimum quantity of fissile material that is capable of producing a self-sustaining chain reaction is called "critical mass". A sub-critical amount of U-235 will not produce a chain reaction.





A very common factor is often used in chain reactions; it is represented by K

$$k = \frac{rate\ of\ production\ of\ neutrons}{rate\ of\ loss\ of\ neutrons}$$

For a chain reaction to be self-sustaining, the value of k must be greater than 1. The value of k > 1 means that neutrons increase or multiply with time.

There are two types of fission chain reactions (according to neutron multiplication factor k):

1. CONTROLLED CHAIN REACTION:

A controlled chain reaction is a chain reaction in which the number of neutrons produced can be controlled. This allows for a sustained release of energy, which can be used for beneficial purposes, such as generating electricity. A chain reaction can be controlled by systematically removing some of the fission neutrons from the reaction vessel. The apparatus in which a controlled chain reaction takes place is called a nuclear reactor.

2. UNCONTROLLED CHAIN REACTION:

An uncontrolled chain reaction is a chain reaction in which the number of neutrons produced cannot be controlled. This results in a sudden and rapid release of energy, which can be destructive. For example, the atomic bomb.

FISSION BOMB:

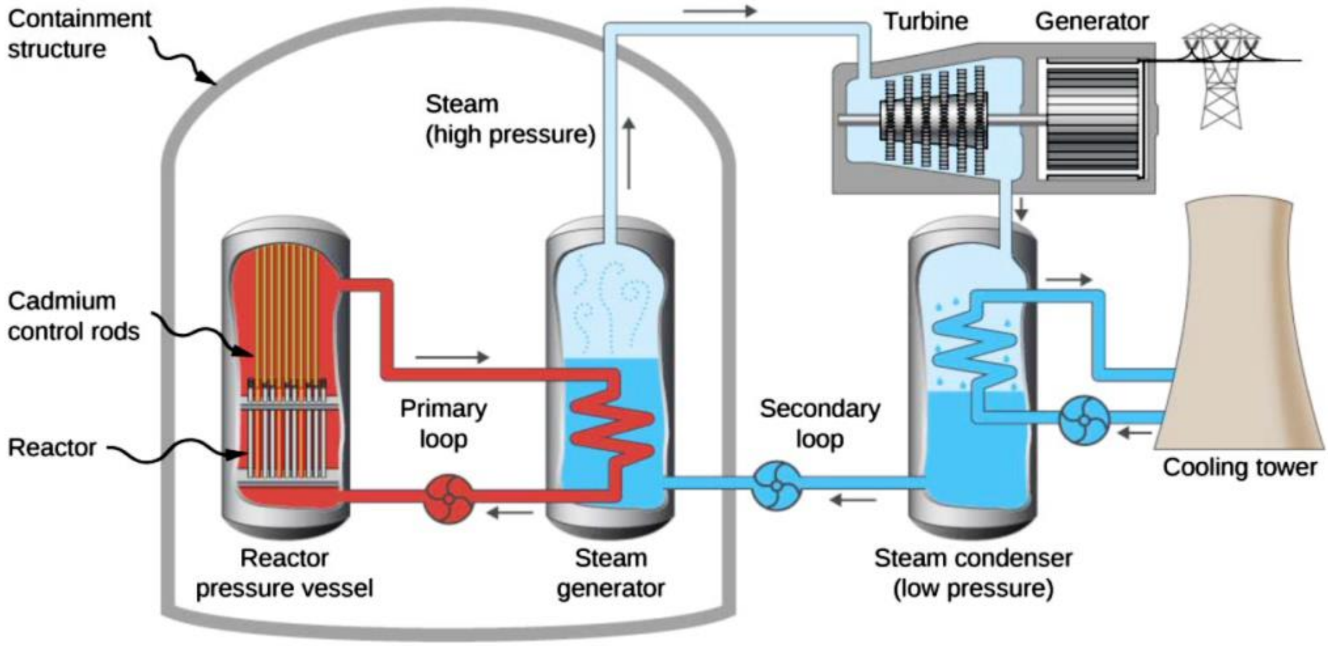
Two (or more) ‘sub-critical’ masses of U-235 (or Pu – 239) are assembled (by a mechanical device or chemical explosion), so that a single ‘supercritical’ mass is obtained. If neutrons enter this supercritical mass, they can initiate an uncontrolled self-sustaining chain reaction. This resulted in an explosion with a tremendous release of energy, a temperature of millions of degrees Kelvin, and pressure of thousands of atmospheres along with harmful radiations a few seconds after the explosion, a huge surging mushroom cloud climbed up to a height of several miles (about 10 miles).

Nuclear fission bombs, using both uranium–235 and plutonium–239, are used. A nuclear bomb produces havoc with life and property.

NUCLEAR REACTOR:

A nuclear reactor is a device in which a controlled fission chain reaction takes place. A nuclear reactor is also known as a nuclear pile or atomic pile.

Such a system was first achieved with uranium as the fuel in 1942 by Enrico Fermi. He used a uranium-235 isotope that releases energy through nuclear fission. The schematic diagram of the nuclear reactor is shown in Figure



The following are the main components of the nuclear reactor:

FISSIONABLE SUBSTANCE:

Nuclear reactors use fuel, typically enriched uranium or plutonium, to sustain the fission chain reaction. The U-235 is fissionable, but uranium from ore typically contains only about 0.7 percent of U-235, with the remaining 99.3 percent being the U-238 isotope. Because uranium-238 tends to absorb neutrons, reactor fuels must be processed to increase the proportion of U-235 to sustain the reaction. This process is called enrichment.

Moderator:

The function of the moderator is to slow down the highly energetic neutrons produced in the process of fission of U-235 to thermal energies. Heavy water (D20), graphite, beryllium, etc., are used as moderators. Ideally, moderators have low atomic weight and low absorption cross-section for neutrons.

Control Rods:

Control rods are made of materials like boron or cadmium that absorb neutrons, regulating the rate of the fission chain reaction. Operators can control the power output and maintain stability by adjusting the position of control rods within the reactor core.

Coolant:

Coolant circulates through the reactor core to transfer heat away from the fuel and other reactor components. Common coolants include water, heavy water, or gases like helium or carbon dioxide. The heated coolant then transfers its thermal energy to a secondary loop containing water, which turns into steam. This steam drives turbines connected to generators, producing electricity.

Protective Shield:

In a nuclear reactor, many harmful radiations are emitted, which are dangerous for all living things. To protect from these radiations, the reactor is surrounded by a massive biological shield.

NUCLEAR FUSION

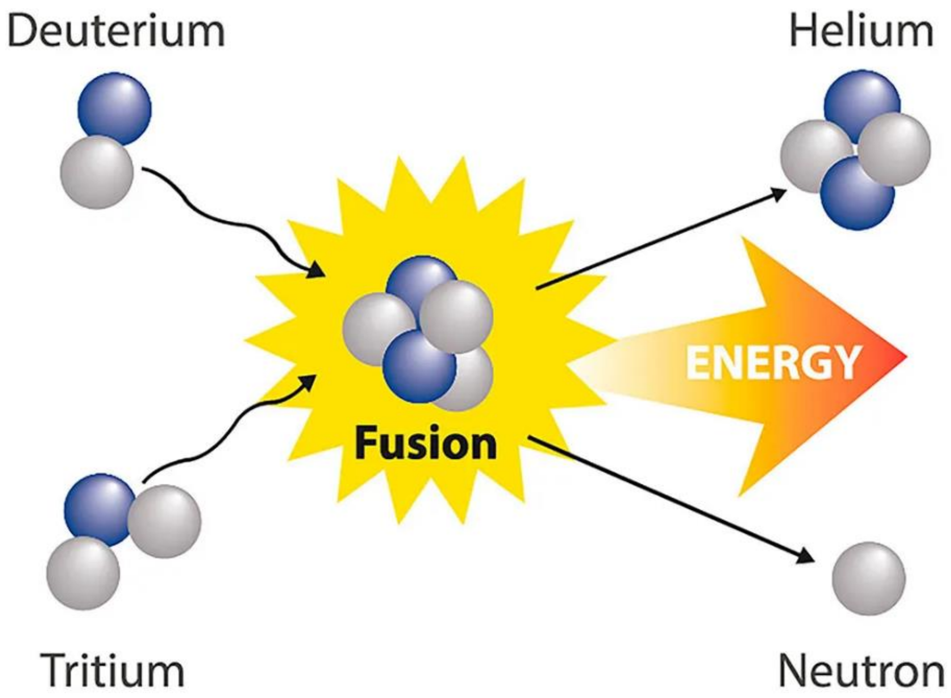
The process of combining two light nuclei to form a heavy nucleus with the release of huge amounts of energy due to mass defect is known as nuclear fusion.
Thermonuclear fusion reactions occur rampantly in the universe – in visible stars and in the sun- but occur too slowly! Some examples of thermonuclear fusion reactions that occur rapidly are given below:

1. Deuteron – Deuteron (D-D) Reactions:
   A D-D (deuteron–deuteron) reaction requires 400 million kelvin temperatures.

$$ {}_1^2H + {}_1^2H \rightarrow {}_2^3He + {}_0^1n \qquad Q = 3.27\ Mev $$
$$ {}_1^2H + {}_1^2H \rightarrow {}_1^3H + {}_1^1H \qquad Q = 4.03\ Mev $$

The figure shows the nucleus of the tritium (${}_1^3H$) so formed can again fuse with a deuterium nucleus (${}_1^2H$) to give the following reaction:

$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n \qquad Q = 17.59\ Mev $$

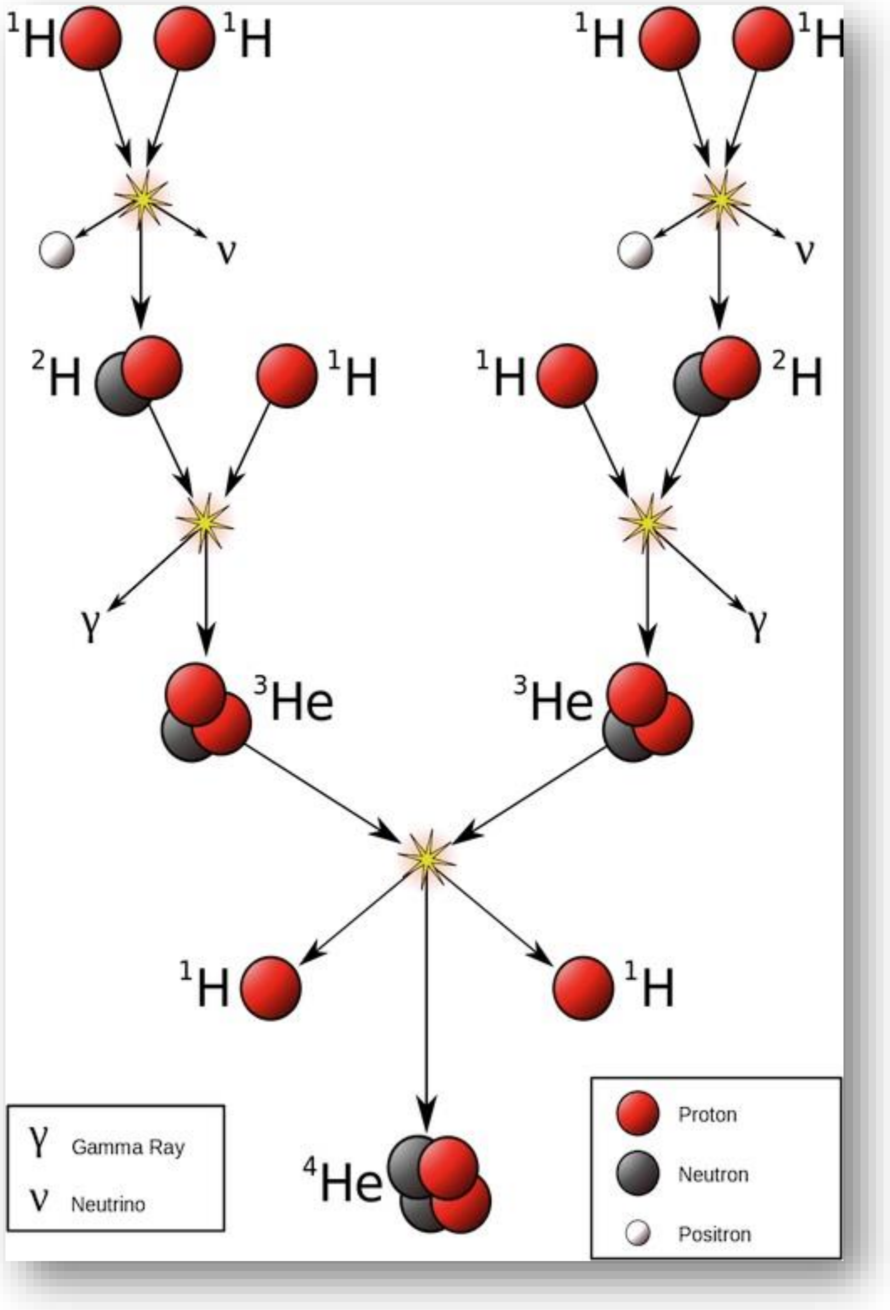


The net result of these two nuclear reactions is that three deuterium (${}_1^2H$) nuclei fuse together to form a helium nucleus (${}_2^4He$) and a neutron with the release of 21.6 MeV (4.03 + 17.59 = 21.62 MeV). This energy of 21.62 MeV is obtained in the form of kinetic energy of proton (${}_1^1H$) and a neutron (${}_0^1n$)

NUCLEAR FUSION IN SUN AND STARS:

Every second, the sun fuses around 500 million metric tons of hydrogen in its core. The core of the sun is incredibly hot, with temperatures reaching about 20 million degrees Celsius, while its surface temperature is around 5 million degrees Celsius.

The sun is a star that is primarily made up of hydrogen (about 75%), helium (about 25%), and trace amounts of other elements. It produces energy through a process called nuclear fusion, where hydrogen atoms combine to form helium atoms, releasing light and heat in the process. The fusion in the sun can take place in two different reaction sequences, the most common of which, is the Proton-Proton (PP) Cycle and the other one is the Carbon-Nitrogen-Oxygen (CNO) Cycle. The Proton-Proton Cycle involves the fusion of protons (hydrogen nuclei) to form helium as shown in the figure



I. Proton-Proton Cycle:

This cycle is predominant in colder regions of the sun and for stars less Luminous than the sun.

These reactions can be represented by the equations

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e + \nu + Q$$
$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \gamma + Q$$
$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H + Q$$

The net Q value of the chain reaction is about 26 MeV

THE CARBON-NITROGEN-OXYGEN (CNO) CYCLE

The Carbon-Nitrogen-Oxygen (CNO) was independently suggested by Hans Bethe in the late 1930s. The CNO cycle is a series of nuclear fusion reactions that convert hydrogen into helium as predicted in figure 27.12, and it is the primary source of energy in stars that are more than 1.3 times as massive as the Sun. This cycle uses carbon, nitrogen, and oxygen as catalysts to convert hydrogen to helium:

$$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma$$

$$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+} + \nu_e$$
$$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma$$

$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma$$
$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e$$
$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He + \gamma$$

In the CNO cycle, four protons fuse, using carbon, nitrogen and oxygen isotopes as a catalyst, to produce one alpha particle, two positrons and two electron neutrinos. Combining all the above reactions, the net reaction for the CNO cycle comes out to be

$$^{1}_{1}H \; ^{4}_{2}He + 2\,\beta^{+} + 2\,\nu_e + 26.7\ Mev$$

We see that the net energy release is nearly the same for both cycles.

NUCLEAR RADIATION EXPOSURE AND ITS BIOLOGICAL EFFECTS:

Exposure is defined as the amount of ionization produced in a unit mass of dry air at standard pressure (STP). Its unit is 1 roentgen= JR= 2.58 X 10^4 Clkg.

There are two main types of radiation exposure: external and internal.

1. External radiation exposure occurs when a person is exposed to radiation from a source outside the body, such as an X-ray machine or a nuclear power plant.
2. Internal radiation exposure occurs when a person ingests or inhales radioactive material, which can then accumulate in the body and emit radiation.

   Radiation exposure can also be measured in other units, including sieverts (Sv), millisieverts (mSv), and microsieverts (μSv).

BIOLOGICAL EFFECTS OF RADIATION:

When matter absorbs radiation, especially living tissue, it can induce significant changes. The biological effects of radiation are diverse and depend on several factors, including:

► Type of radiation: Each type interacts differently. Alpha particles, while unable to penetrate deeply, cause disorder within cells they reach. Beta particles travel farther but deposit less energy, while gamma rays can pierce through tissues, potentially affecting multiple organs.
► Dose absorbed: This quantifies the energy deposited per unit mass of tissue. Higher doses generally translate to more pronounced effects.
► Duration of exposure: Acute (short-term) exposure like an X-ray differs from chronic (long-term) exposure from environmental sources or occupational hazards.
► Individual sensitivity: Age, health status, and genetic predispositions can influence susceptibility. The biological effects of radiation include:
► Acute radiation syndrome (ARS): High-dose exposure can trigger ARS, a complex condition affecting multiple organ systems with symptoms like nausea, vomiting, hair loss, and bone marrow suppression.
► Cancer risk: Chronic low-dose or high-dose exposures can increase the risk of various cancers, depending on the affected tissue.
► Genetic effects: Germ cell mutations can lead to congenital disabilities in offspring.
► Reproductive issues: Fertility can be impaired, and miscarriage risk may increase.
► Developmental effects: Early exposure inutero can affect fetal development, causing physical and cognitive impairments.

DOSIMETRY:

Dosimetry is the science of measuring and quantifying radiation dose. It is a field of physics that deals with the interaction of radiation with matter and the biological effects of radiation exposure. Dosimetry is derived from the Greek word 'dos', meaning 'gift' or giving'. In the context of physics, it represents the scientific discipline that quantifies the amount of radiation 'given' to or absorbed by an object or body. The goal is to determine potential biological effects, ensure safe limits, and monitor radiation exposure.

Key Components of Dosimetry:

1. Absorbed Dose: The amount of radiation energy absorbed per unit mass of the material. Measured in Gray (Gy), it is a pivotal metric in understanding radiation's effect on tissues.

2. Equivalent Dose: Not all radiation types have the same biological impact, even if their absorbed doses are identical. To account for this, radiation weighting factors are introduced to derive the equivalent dose. Measured in Sievert (Sv), it provides a more biologically relevant dose metric.

3. Effective Dose: Considering that different tissues have varying sensitivities to radiation, tissue weighting factors are used. The effective dose, also in Sieverts (Sv), offers a measure that summarizes the potential overall harm to the whole organism.

4. Operational Dose Quantities: These are practical quantities used for routine monitoring in radiological protection. They are designed to estimate effective dose or equivalent dose to a particular tissue. Examples include ambient dose equivalent and personal dose equivalent.

Dosimetry is performed using devices known as dosimeters, which can be worn by people working with or around radioactive materials to monitor their exposure levels. These devices can measure and record the dose of radiation over time.

MEDICAL USES OF NUCLEAR RADIATION:

Medical use of nuclear radiation is quite common in today's hospitals and clinics. It contains various diagnostic and therapeutic applications that control the properties of ionizing radiation to diagnose and treat diseases. Some examples include:

Imaging:

X-rays:

The workhorse of medical imaging, X-rays utilize electromagnetic radiation to reveal fractures, bone structures, and internal injuries.

CT scan,

A CT (computed tomography) scan is an imaging test that helps healthcare providers detect diseases and injuries. It uses a series of X-rays and a computer to create detailed images of your bones and soft tissues.

PET scans

Positron emission tomography (PET) scans detect early signs of cancer, heart disease and brain conditions. It involves an injection of a safe radioactive tracer that helps detect diseased cells

NUCLEAR MEDICINE PROCEDURES

Bone scans:

Radioactive tracers identify bone diseases like osteoporosis and cancer metastases.

Thyroid scans:

Radioactive iodine helps diagnose and treat thyroid disorders.

Lung scans:

Technetium-99m helps assess lung function and detect blood clots. Treatment:

Radiotherapy: Harnessing the destructive power of radiation, targeted beams are used to shrink and destroy cancerous tumors with remarkable precision. This non-invasive therapy plays a crucial role in treating various cancers, often in conjunction with surgery and chemotherapy.

Brachytherapy: Radioactive implants placed directly within tumors deliver high doses of radiation locally, minimizing damage to surrounding tissue. This approach is particularly effective for treating prostate, cervical, and head and neck cancers.

Radioisotope therapy: Radioactive isotopes are used to treat specific conditions like hyperthyroidism (radioactive iodine) and blood disorders (radioactive phosphorus).

Other Applications:

Pain management: Radiofrequency ablation utilizes radio waves to heat and destroy nerve tissue, offering pain relief for chronic conditions like back pain and arthritis.

Sterilization: Medical instruments and equipment are sterilized using gamma radiation, ensuring sterility and preventing infections.

EXPOSURE TO RADIATION:

This process creates charged particles (Ions) and free radicals, which can disrupt molecular structures and biological processes. Examples of ionizing radiation include:

X-rays: Electromagnetic radiation produced by high-energy electron beams or X-ray tubes. X-rays are commonly used in medical imaging, security screening, and industrial applications.

Gamma rays: High-energy electromagnetic radiation emitted by radioactive decay processes, such as
those occurring in radioactive isotopes like cobalt-60 and cesium-137. Gamma rays are used in medical imaging (gamma cameras), radiation therapy, and sterilization processes.

Alpha particles: Alpha particles are emitted during the decay of heavy elements like uranium and radium and have low penetrating power but can cause significant damage if inhaled or ingested.

Beta particles: Beta particles can penetrate deeper into tissues than alpha particles but are less damaging. They are used in medical imaging (positron emission tomography) and radiation therapy.

Neutrons: Neutrons can induce nuclear reactions and are used in neutron activation analysis, neutron radiography, and certain types of cancer therapy.

Cosmic rays: High-energy particles from outer space continuously bombard Earth's atmosphere, generating secondary radiation that reaches the surface.

Industrial applications: Gauges, sterilization processes, and smoke detectors often employ ionizing radiation for various industrial purposes.
These forms of ionizing radiation have various applications in medicine, industry, research, and other fields but require careful handling and monitoring to minimize risks to human health and the environment.

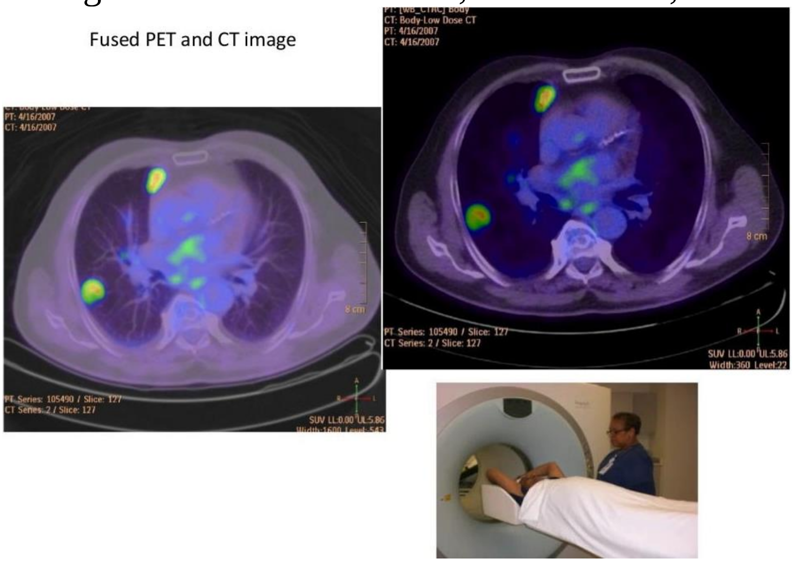
USES OF RADIOACTIVE TRACERS:

One of the most important uses of nuclear radiation is the location and study of diseased tissue. This can be done by radioactive tracers. Radioactive tracers are radioactive substances that are used to track the movement and behavior of specific molecules or compounds in various systems. These tracers emit radiation that can be detected through biochemical reactions, metabolic pathways, fluid flow, and environmental transport. Some examples of the uses of radioactive tracers include:

Medical Imaging:

Positron Emission Tomography (PET): Radiotracers labeled with positron- emitting isotopes (e.g., fluorine-I 8, carbon-11) are injected into the body and used to visualize metabolic activity, blood flow, and receptor binding in tissues. PET imaging is valuable for diagnosing and monitoring diseases such as cancer, heart disease, and neurological disorders.

Fused PET and CT image



INDUSTRIAL PROCESSES:

Flow Visualization: Radiotracers are injected into fluids or gases to track flow patterns and detect leaks or blockages in industrial pipelines, heat exchangers, and reactors. This technique is used in industries such as petrochemicals, food processing, and nuclear power.

Process Optimization: Radiotracers are used to monitor and optimize chemical reactions, mixing processes, and material transport in industrial processes. By tracking the movement of tracers, engineers can identify bottlenecks, improve efficiency, and ensure product quality.

Soil Fertility and Nutrient Uptake: Radioactive isotopes like phosphorus-32 (^{32}P) are used to study nutrient uptake in plants. By tagging fertilizers with these tracers, scientists can track how nutrients move through the soil and are absorbed by plants. This information helps in optimizing fertilizer application, ensuring that crops receive the right amount of nutrients.

Environmental Impact Assessments: Radioactive tracers help in studying the environmental impact of agricultural practices. For instance, they can be used to trace the movement of pollutants or contaminants from agricultural fields to water bodies, enabling better management practices to protect the environment.