Radioactivity

- Radioactivity is a nuclear phenomenon in which an unstable nucleus undergoes decay to form stable nuclei.
- Radioactivity was discovered accidentally by a scientist Henry Becquerel (1896).
- Only those nuclei which are unstable will show the phenomenon of radioactivity.
- Fluorescence is a property shown by fluorescent objects; when visible light falls on a fluorescent object then these objects will also start emitting light.
- Henry Becquerel performed experiments on some fluorescent objectsand he gave a hypothesis that fluorescent objects along with the visible light also emit some kind of radiation as well.
- Experimental set-up:-
  - He took a photographic plate and placed inside a box.He placed a fluorescent object on the top of the box and allowed the sun light to fall on it.
  - As the box is opaque it won't allow the rays of light to pass through it.
  - When the photographic plate will be developed there should be no traces of image on the plate.
  - He repeated the experiment by taking different compounds and observed there was no image formed on the photographic film.
  - This showed that sunlight is the only ray which is emitted in the above case and as the plate was covered with opaque object so the sunlight is not able to reach the plate.
- He then took the compound of uranium known as uranium potassium sulphate.
- When the photographic plate was developed there was a black spot on the photographic plate.
- This shows that some radiation was emitted that reached the photographic plate.
- In order to know from where the radiation was emitted, he kept a blade on top of a box and uranium potassium sulphate compound was placed above the blade.
- After performing the experiment, when the photographic plate was developed, the photo of blade was seen on the plate.

- This shows that the radiation was emitted by the uranium potassium sulphate compound.
- Accidentally while he was performing the experiment it was not sunny that day.
- The result which he got was same i.e. when the photographic plate was developed there was the same image of the blade on the plate.

Conclusion:-

- The radiation was emitted by the uranium potassium sulphate compound and sunlight did not play any role in emitting the radiations.
- After series of experiments he proved that it was uranium alone which was responsible for emitting the radiations.
- He concluded that there are certain elements which emit radiation on their own.
- This phenomenon was named as radioactivity.

Properties of alpha, beta& Gamma rays

Alpha Rays

Alpha rays are the positively charged particles. Alpha-particle is highly active and energetic helium atom that contains two neutrons and protons. These particles have the minimum penetration power and highest ionization power. They can cause serious damage if get into the body due to their high ionization power. They are capable of ionizing numerous atoms by a short distance. It is due to the fact that the radioactive substances that release alpha particles are required to be handled after wearing rubber gloves.

Beta Rays

Beta particles are extremely energetic electrons that are liberated from the inner nucleus. They bear negligible mass and carry the negative charge. A neutron in the nucleus splits into a proton and an electron on the emission of a beta particle. Hence, it is the electron that is emitted by the nucleus at a rapid pace. Beta particles have a higher penetration power when compared to alpha particles and can travel through the skin with ease. Beta particles can be dangerous and any contact with the body must be avoided, though their ionization power is low.

Gamma Rays

The waves arising from the high-frequency end of the electromagnetic spectrum that has no mass are known as gamma rays. They hold the highest power of penetration. They are the most penetrating but least ionizing and very difficult to resist them from entering the body. The Gamma rays carry a large amount of energy and can also travel via thick concrete and thin lead.

The below table describes the characteristics of beta, alpha and gamma radiations and compares the masses and charges of the three rays.

Property	\alpha$\alpha$ ray	\beta$\beta$ ray	\gamma$\gamma$ ray
Nature	Positive charged particles, 2He 4 nucleus	Negatively charged particles (electrons).	Uncharged ?~0.01a, electromagnetic radiation
Charge	+2e	–e	0
Mass	6.6466×10^{-27} kg	9.109×10^{-31} kg	0
Range	~10 cm in air, can be stopped by 1mm of Aluminium	Upto a few m in air, can be stopped by a thin layer of Aluminium	Several m in air, can be stopped by a thick layer of Lead
Natural Sources	By natural radioisotopes e.g.$_{92}U^{236}$	By radioisotopes e.g.$_{29}Co^{68}$	Excited nuclei formed as a result of Gamma decay

Decay in radioactive elements

Alpha decay

In alpha decay, an energetic helium ion (alpha particle) is ejected, leaving a daughter nucleus of atomic number two less than the parent and of atomic mass number four less than the parent. An example is the decay (symbolized by an arrow) of the abundant isotope of uranium, ^{238}U, to a thorium daughter plus an alpha particle.

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} \qquad \begin{array}{l} Q_\alpha = 4.268\ \mathrm{MeV} \\ t_{1/2} = 4.51 \times 10^{9}\ \text{years} \end{array}$$

Beta-minus decay

In beta-minus decay, an energetic negative electron is emitted, producing a daughter nucleus of one higher atomic number and the same mass number. An example is the decay of the uranium daughter product thorium-234 into protactinium-234:

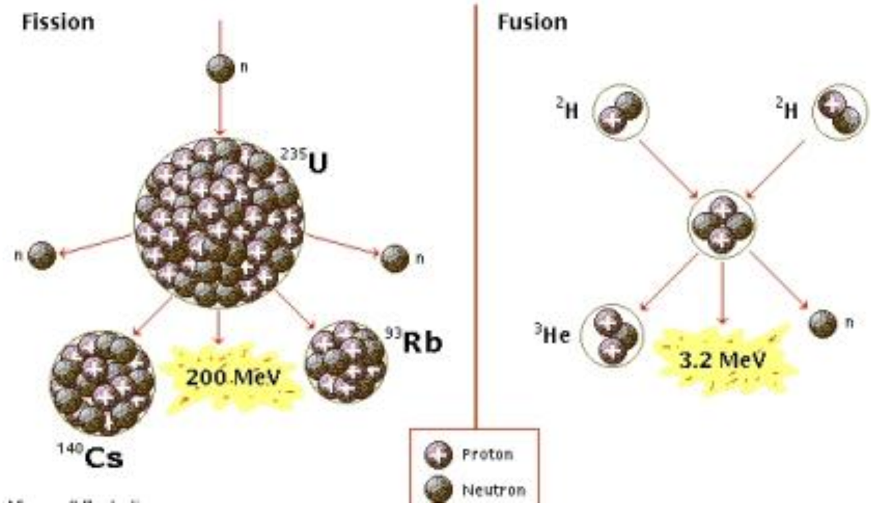
$$^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + e^- + \bar{\nu} \qquad \begin{array}{l} Q_{\beta^+} = .263\ \mathrm{MeV} \\ t_{1/2} = 24.1\ \text{days} \end{array}$$

Gamma decay

A third type of radiation, gamma radiation, usually accompanies alpha or beta decay. Gamma rays are photons and are without rest mass or charge. Alpha or beta decay may simply proceed directly to the ground (lowest energy) state of the daughter nucleus without gamma emission, but the decay may also proceed wholly or partly to higher energy states (excited states) of the daughter.

NUCLEAR FISSION AND FUSION

Mass Defect & Einstein's Equation The mass of the nucleus is actually about 1% smaller than the mass of its individual protons and neutrons. This difference is called the mass defect. The mass defect results from the energy released when the protons and neutrons bind together to form the nucleus. This energy is called the nuclear binding energy. The binding energy determines which nuclei are stable and how much energy is released in a nuclear reaction. The higher the binding energy, the more stable the nucleus. Very heavy nuclei and very light nuclei have low binding energies. This implies: 1. a heavy nucleus will release energy when it splits apart (what we call fission) 2. Two light nuclei will release energy when they join (what we call fusion).



NUCLEAR FISSION

Very large nuclei (mass number greater than 230) tend to be unstable and can split into two or more parts. This is called fission. Fission is not a spontaneous process. It can only occur when a slow moving

- Neutron strikes an unstable nucleus.

In this decay process, the nucleus will split into two nearly equal nuclei and release several free neutrons and huge amounts of energy. These nuclei are isotopes of more stable elements. If left alone, they decay

- Radioactively by emitting alpha or beta particles.

- On average, three neutrons are released. These can go on to be absorbed by other nuclei if they are slowed down by a moderator (a medium, such as graphite, heavy water, and beryllium that causes the neutrons to travel more slowly).
- If these neutrons are absorbed by other nuclei, this causes a chain reaction.

NUCLEAR FUSION

- Nuclear Fusion Very light nuclei can combine to form heavier atoms in a process known as fusion.
- When fusion happens, the products have a larger binding energy than the reactants. The mass defect results in the release of huge amounts of energy.
- Actually produces more energy per gram of products than fission and produces no by-products
- Why isn't it used yet then for energy production?
  - It currently requires more energy to initiate the reaction than it produces.
- Heat produced is so intense that containment vessels melt.

- Why does fusion require energy?

  o To combine, two nuclei must be close enough for the strong nuclear force to join them. But when the positive nuclei approach, the electrostatic force of repulsion is greater than the nuclear force. This means that the nuclei must be HIGHLY energetic to overcome the repulsion force.
  o This means HIGH temperatures (millions of degrees Celsius), which is difficult to achieve while containing the atoms.
- Nuclear fusion is the energy-producing process taking place in the core of the Sun and stars.
  o The core temperature of the Sun is about 15 million °C. At these temperatures, four hydrogen atoms fuse in a series of reactions to form a single helium atom and give off huge amounts of energy.

Radioactive Decay Constant

Decay constant, proportionality between the size of a population of radioactive atoms and the rate at which the population decreases because of radioactive decay. Suppose N is the size of a population of radioactive atoms at a given time t, and dN is the amount by which the population decreases in time dt; then the rate of change is given by the equation $dN/dt = -\lambda N$, where λ is the decay constant. Integration of this equation yields $N = N_0 e^{-\lambda t}$, where N_0 is the size of an initial population of radioactive atoms at time $t = 0$. This shows that the population decays exponentially at a rate that depends on the decay constant. The time required for half of the original population of radioactive atoms to decay is called the half-life. The relationship between the half-life, $T_{1/2}$, and the decay constant is given by $T_{1/2} = 0.693/\lambda$.

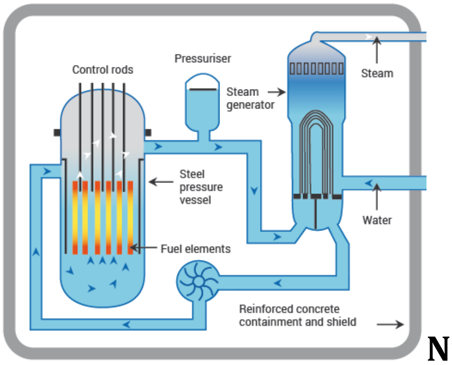
Half Life

Half-life, in radioactivity, the interval of time required for one-half of the atomic nuclei of a radioactive sample to decay (change spontaneously into other nuclear species by emitting particles and energy), or, equivalently, the time interval required for the number of disintegrations per second of a radioactive material to decrease by one-half. The radioactive isotope cobalt-60, which is used for radiotherapy, has, for example, a half-life of 5.26 years. Half-lives are characteristic properties of the various unstable atomic nuclei and the particular way in which they decay. Alpha and beta decay are generally slower processes than gamma decay. Half-lives for beta decay range upward from one-hundredth of a second and, for alpha decay, upward from about one one-millionth of a second. Half-lives for gamma decay may be too short to measure (around 10^{-14} second), though a wide range of half-lives for gamma emission.

Mean life

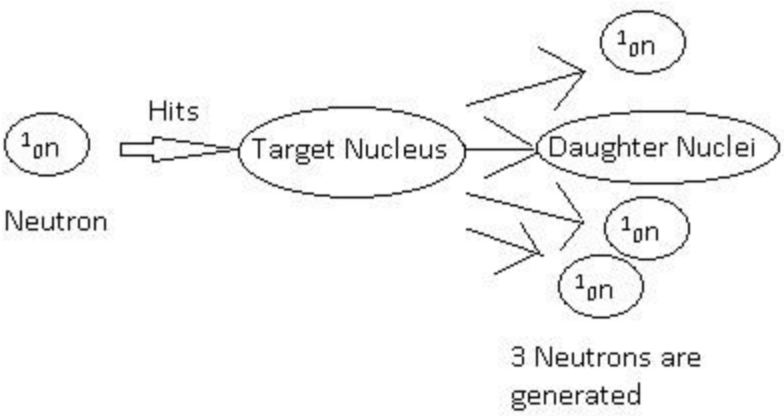
Mean life, in radioactivity, average lifetime of all the nuclei of a particular unstable atomic species. This time interval may be thought of as the sum of the lifetimes of all the individual unstable nuclei in a sample, divided by the total number of unstable nuclei present. The mean life of a particular species of unstable nucleus is always 1.443 times longer than its half-life (time interval required for half the unstable nuclei to decay). Lead-209, for example, decays to bismuth-209 with a mean life of 4.69 hours and a half-life of 3.25 hours.

Nuclear Reactor



Nuclear Reactor

- Nuclear reactors are useful in producing electricity.
- A nuclear reactor is an arrangement to generate electricity whichmakes use of nuclear fission.



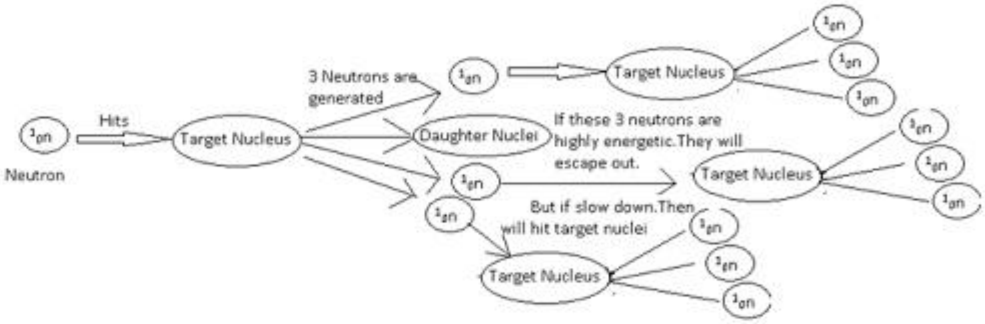
Requirements for controlled nuclear fission in reactor:

1. Neutrons to be slowed down.
   - Neutrons are slowed down by using moderators which are lighter nuclei which slow down fast moving neutrons by elastic collision.
   - Commonly used moderators:-

   1.Water

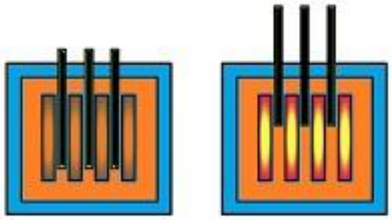
2. Heavy Water
3. Graphite
   - Consequence of use of moderators:-

- Multiplication factor of neutrons increases: - When a neutron hits a target nucleus along with daughter nucleus,it produces 3 neutrons.These 3 neutrons are highly energetic but they need to be slowed down, so they can hit the target nucleus.
- As a result high multiplication factor results in uncontrolled chain reaction.



2. Excess neutrons to be absorbed.
   - As uncontrolled chain reaction is wanted therefore to absorb excess neutrons <u>Control Rods</u> are used.
   - These control rods are inserted in the core of the nuclear reactor.
   - Control rods are capable of initiating (while taking out of the reactor) and stopping(inserting in the nuclear reactor) the nuclear reaction.
   - As they absorb all the excess neutrons there are no neutrons left to start the reaction.
   - Control rods are made up of neutron absorbing materials.
   - They decrease the multiplication factor of neutrons to a very small value.
   - Commonly used material is <u>Cadmium</u>.

<u>Control Rods</u>



Construction of Nuclear Reactor

- The core of the nuclear reactor consists of uranium (${}^{235}U$) in the form of cylindrical rods. These rods are dipped inside a liquid which is the moderator.
- Whenever one neutron strikes this uranium rod nuclear fission reaction starts and 3 fast moving neutrons are produced.

- Because of the moderator these 3 neutrons undergo elastic collision as a result they slow down before they strike the second rod.
- Geometry of the core is such that only one out of 3 neutrons which are emitted strike the next rod making the reaction a controlled one.
- When the control rods are inserted inside they will absorb all the extra neutrons. Since there are no neutrons nuclear fission reaction will stop.
- Large amount of energy is also released in the core.
- In order to extract the energy from the core water at very high pressure is passed through it.
- As hot water passes through it produces steam in the steam generators.
- This steam is used to run the turbines which in turn produce electricity.
- This process will keep on continuing till the uranium on the rods does not get over. Then the rods have to be replaced in the nuclear reactor.

Advantages:-

1. Energy released is extremely large.
2. Needs fuel in extremely small quantity.

Disadvantages:-

1. Spent fuel is highly radioactive and extremely hazardous to all life forms.
2. Accumulation of radioactive waste.