Modern Physics

(Lec-11)

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OUTLINES

- Radioactive Decay Law
- Half- life, Mean life
- Nuclear reaction
- Concept of Fusion, Fission and nuclear chain reaction
- General idea on nuclear reactor and nuclear power plant

Radioactive decay Law

"The rate of radioactive decay of radioactive atoms is directly proportional to the number of intact atoms present at that time".

Let at the beginning of the counting time when $t = 0$, the number of atoms of a radioactive material is N_o. Now if dN number of atoms decay during infinitesimal time dt then the rate of decay of atom is $\frac{dN}{dt}$.

$$\therefore -\frac{dN}{dt} \propto N$$

$$or, \frac{dN}{dt} = -\lambda N$$

Since with the passage of time the number of atoms of the material is decreasing so the negative sign has been used. λ is called the radioactive decay constant of that material.

Radioactive exponential law

If the decay constant of a radioactive substance is λ and the number of intact atoms at time t *is* N *then*

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

$$or, \frac{dN}{dt} = -\lambda N$$

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

At the beginning $t = o, N = N_0$ at $t = t$ and $N = N$.
Now →

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

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

$$\therefore lnN - lnN_0 = -\lambda(t - 0) = -\lambda t$$

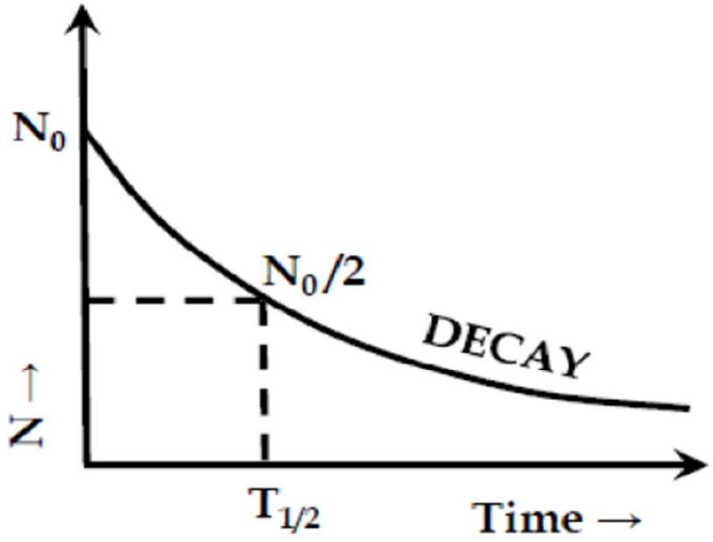
$$\therefore \ln \frac{N}{N_0} = -\lambda t$$

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

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

Cont…

This equation is called the radioactive decay equation. This equation shows that the number of radioactive atoms decay exponentially with time. This is shown in fig. 1.



Half-life

The time required for one half of the radioactive substance to decay is called half-life of that radioactive substance. The time during which the number N number of atoms of a radioactive substance decay into $\frac{N}{2}$ numbers is the half life.

We know,

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

When $t = T_{1/2}$ then $N = \frac{N_0}{2}$

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

$$\text{Or, } ½ = e^{-\lambda T_{\frac{1}{2}}}$$

$$\therefore \ln\left[\frac{1}{2}\right] = -\lambda T_{\frac{1}{2}}$$

$$\therefore -\lambda T_{\frac{1}{2}} = ln1 - ln2$$

$$\therefore -\lambda T_{\frac{1}{2}} = 0 - 0.693$$

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

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

Problem: How long does it take for 60 percent of a sample of Radon to decay, where the half-life of Radon is 3.82 days?

Mean-life

"The sum of the life of each atom of a radioactive substance divided by the number of atoms at the beginning is called radioactivity mean life"

$$\tau = \frac{life\ of\ 1st\ atom + life\ of\ 2nd\ atom + \ ------ + life\ of\ the\ N_0 th\ atom}{N_0}$$

We can write →

$$\tau = \int_0^{N_0} \frac{dN\ t}{N_0} ----(i)$$

We knew,

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

$$\therefore dN = -\lambda N dt$$

$$\therefore dN = -\lambda\, N_0 e^{-\lambda t}\, dt \quad --(ii)$$

Now from equation (i) we have,

$$\tau = \int_0^{N_0} \frac{dN.t}{N_0}$$

$$= \int_{\infty}^{0} \frac{(-\lambda\, N_0 e^{-\lambda t}\, dt)t}{N_0}$$

$$= \int_0^{\infty} \frac{t.\lambda\, N_0 e^{-\lambda t}\, dt}{N_0}$$

$$= \int^{\infty} (\lambda t) e^{-\lambda t}\, dt$$

CONTINUE…

$$= \int_0^{\infty} xe^{-x} \frac{dx}{\lambda}$$

$$= \frac{1}{\lambda} \int_0^{\infty} e^{-x} . x^{2-1} \, dx$$

$$= \frac{1}{\lambda} . \Gamma 2$$

$$\therefore \boldsymbol{\mathcal{T}} = \frac{1}{\lambda}$$

Nuclear Reactions

In a typical nuclear reaction laboratory experiment, a beam of particles of type x is incident on a target containing nuclei of type X. After the reaction, an outgoing particle y is observed in the laboratory, leaving a residual nucleus Y. Symbolically, we write the reaction as

$$x + X \rightarrow y + Y$$

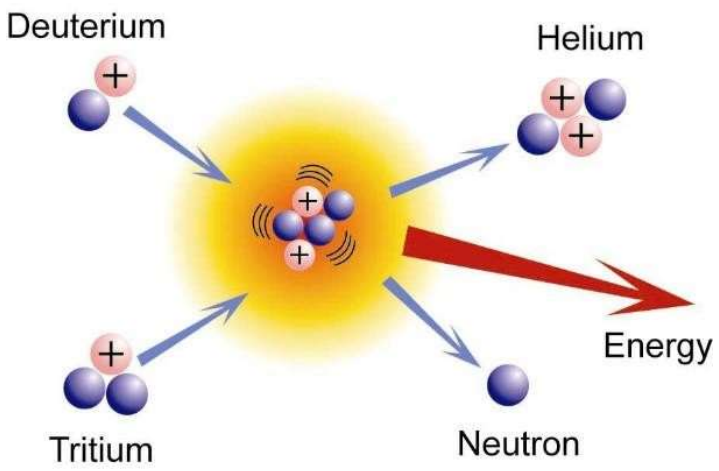
For example,

$$^{2}_{1}H_{1} + ^{63}_{29}Cu_{34} \rightarrow ^{1}_{0}n + \ ^{64}_{30}Zn_{34}$$

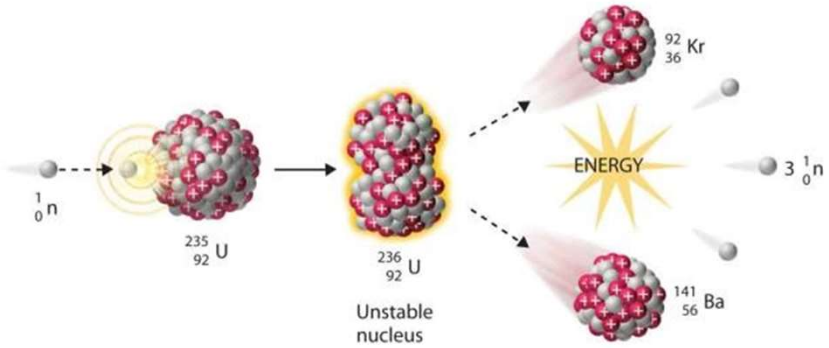
While the number of possible nuclear reactions is immense, there are several types that are more common, or otherwise notable. Some examples include:

- **Nuclear fusion**: The process in which small nuclei fuse together to form a single heavy nucleus is known as fusion. The basic energy production process in the sun is a process called nuclear fusion. For example

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + \ e^{+} + v$$

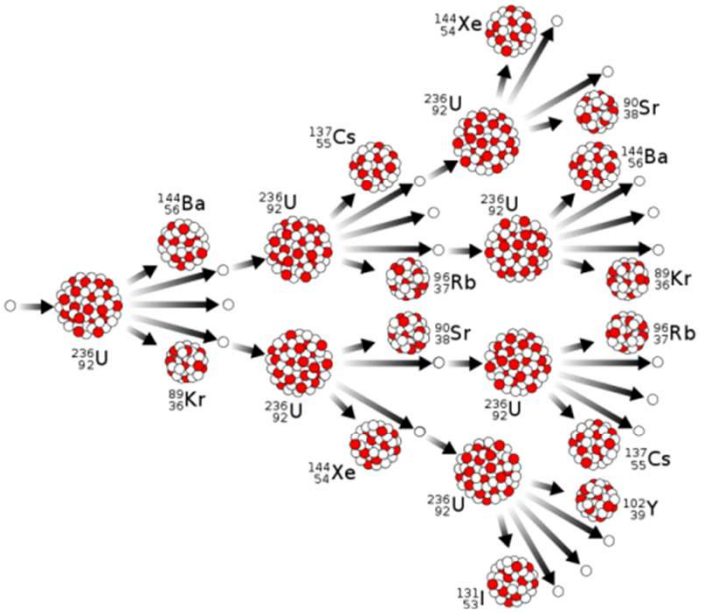


- **Nuclear fission**: The process of breaking up of the nucleus of a heavy atom into two more or less equal nuclei with the release of an enormous amount of energy is known as fission. The new nuclei that result from fission are called fission fragments. For example



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

Nuclear Chain Reactions



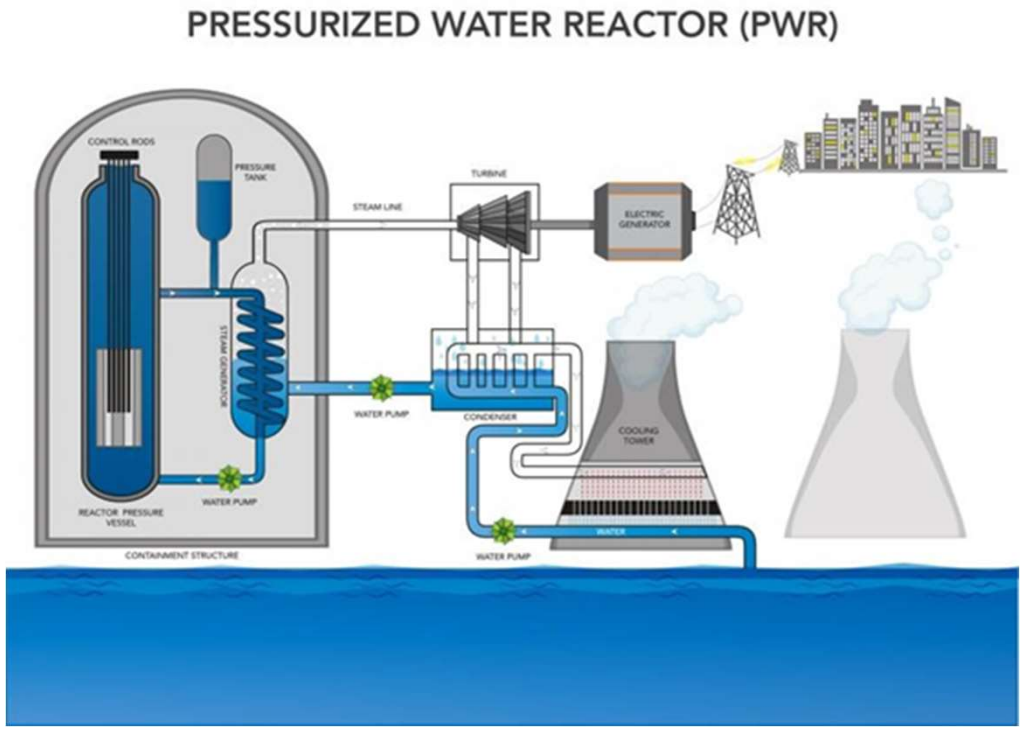
A nuclear chain reaction occurs when one single nuclear reaction causes an average of one or more subsequent nuclear reactions, thus leading to the possibility of a self-propagating series of these reactions. The "one or more" is the key parameter of reactor physics. The number of reactions must be changed (using the control rods) to raise or lower the power so that the number of neutrons present (hence the power generation rate) is either reduced or increased.

Importance of Nuclear Reactions

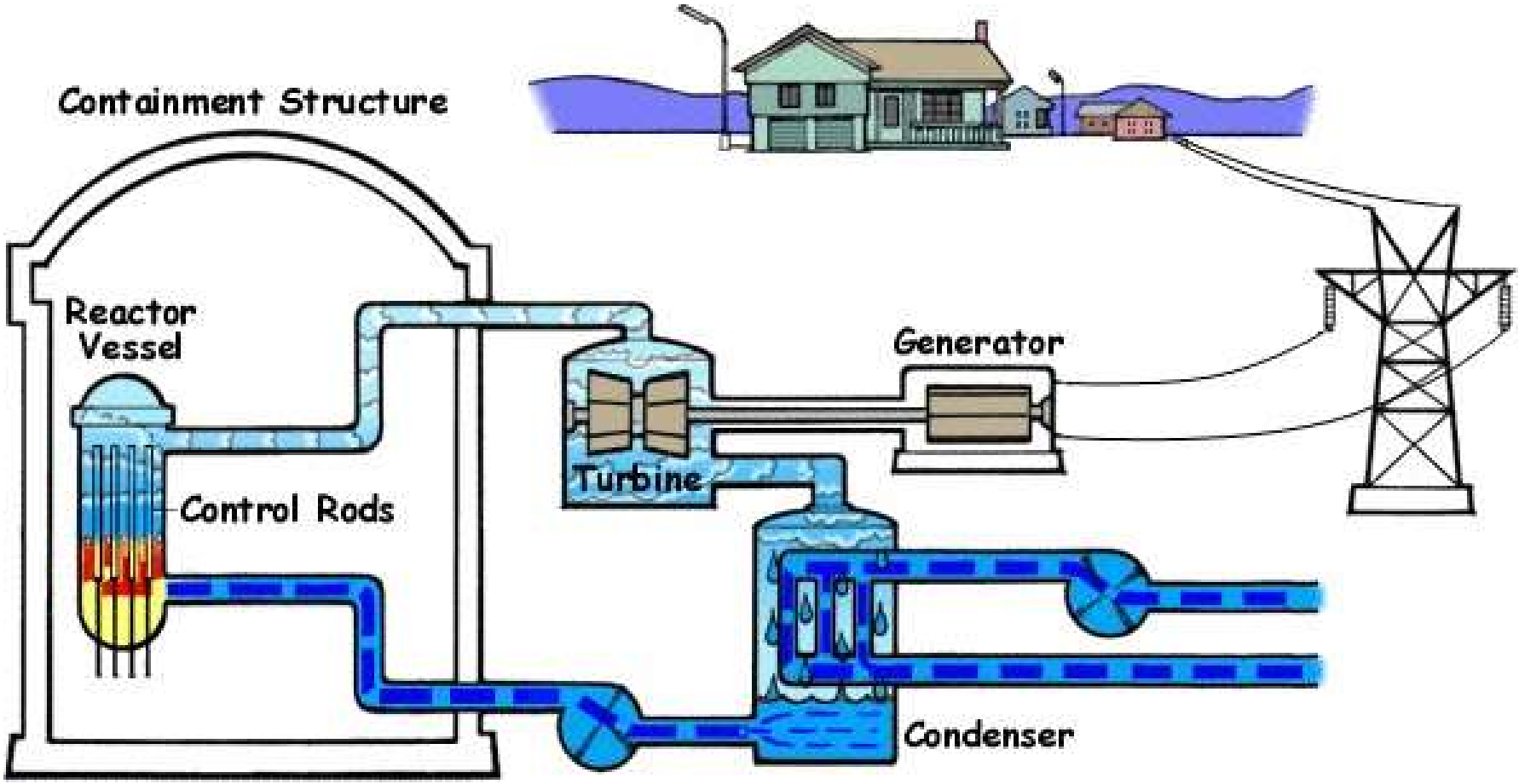
- The first power station to produce electricity by using heat from the splitting of uranium atoms began operating in the 1950s. Today most people are aware of the important contribution nuclear energy makes in providing a significant proportion of the world's low-carbon electricity.
- The applications of nuclear technology outside of civil electricity production in power plants are less well-known.
- Radioisotopes, nuclear power process heat and non-stationary power reactors have essential uses across multiple sectors, including consumer products, food and agriculture, industry, medicine and scientific research, transport, and water resources and the environment.

Nuclear Power plant

- A nuclear power plant is a thermal power station in which the heat source is a nuclear reactor. As is typical of thermal power stations, heat is used to generate steam that drives a steam turbine connected to a generator that produces electricity.



Components of a nuclear reactor



There are several components common to most types of reactors:

Fuel
Uranium is the basic fuel. Usually pellets of uranium oxide (UO_2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.* In a 1000 MWe class PWR there might be 51,000 fuel rods with over 18 million pellets.

Moderator
Material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.

Control rods or blades
These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it.* In some PWR reactors, special control rods are used to enable the core to sustain a low level of power efficiently.

Coolant
A fluid circulating through the core so as to transfer the heat from it. In light water reactors the water moderator functions also as primary coolant. Except in BWRs, there is secondary coolant circuit where the water becomes steam.

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Pressure vessel or pressure tubes

Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

Steam generator

Part of the cooling system of pressurized water reactors (PWR & PHWR) where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit.

Containment

The structure around the reactor and associated steam generators which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any serious malfunction inside. It is typically a metre-thick concrete and steel structure.

Cont…

- How does a nuclear power plant work step by step?
  In a nuclear energy plant, heat is produced from splitting atoms – a process called nuclear fission.

1. **Nuclear reactor** creates heat that is used to make steam.
2. The steam turns a turbine connected to an electromagnet, called a generator.
3. The generator produces electricity.