UNIT 3
MODERN PHYSICS

Properties of Cathode Rays

Cathode rays are the beam of electrons travelling from the negatively-charged cathode to the positively charged anode at the other end of the vacuum tube. These cathode rays travel in a straight-line path at high speed when a voltage difference is applied to the electrodes.

1: Cathode rays travel in a straight line and can cast sharp shadows.

2: Cathode rays are negatively charged.

3: Electric field and magnetic field deflect cathode rays.

4: They are produced at the cathode (negatively charged electrode) and travel towards the anode
y charged electrode) in a vacuum tube.

5: The properties of the cathode rays do not depend on the electrodes and the gas used in the vacuum

6: Speed of cathode rays is slower than light.

7: The objects hit by cathode rays get heated.

8: They can penetrate through thin metal plates.

9: Phosphors glow when cathode rays fall on them.

10: Gas gets ionized by cathode rays.

11: Cathode rays are 180^0 times lighter than hydrogen, the lightest element.

Properties of Positive rays

i. They are the streams of positive ions of the gas enclosed in the discharge tube. The mass of each ion is nearly equal to the mass of the atom.

ii. They are deflected by electric and magnetic fields. Their deflection is opposite to that of cathode rays.

iii. They travel in straight lines.

iv. The velocity of canal rays is much smaller than the velocity of cathode rays.

v. They affect photographic plates.

vi. These rays can produce fluorescence.

vii. They ionize the gas through which they pass.

Positive Ray Analysis — Thomson's Parabola Method

Thomson determined the charge to mass ratio of positive ions by using the apparatus shown in Fig. 5.2. It consists of a discharge tube (A) in which the pressure of the gas is about 10^{-5} m of mercury. The anode is held in a side-tube. In order to ensure the supply of the gas under test, a steady stream of the gas is allowed to flow in through a capillary tube (E) and after circulating in A is pumped off at F. The cathode (C) is perforated with an extremely fine hole. The cathode is cooled by the water-jacket (J). The positive ions produced in A fly towards the cathode and those reaching it axially pass straight through the fine hole and emerge from the opposite end of the cathode as a narrow beam. This beam is then subjected to parallel electric and magnetic fields simultaneously. An electric field is applied between the plates P and Q. The electric field is perpendicular to the positive ray beam. N and S are the poles of a strong electromagnet. After passing through these fields, the beam enters a highly evacuated camera G and is received on a photographic plate R. A liquid air-trap (T) helps to keep the pressure in G quite low, even though pressure in A is comparatively large. The photographic plate, when developed, shows a series of parabolae.

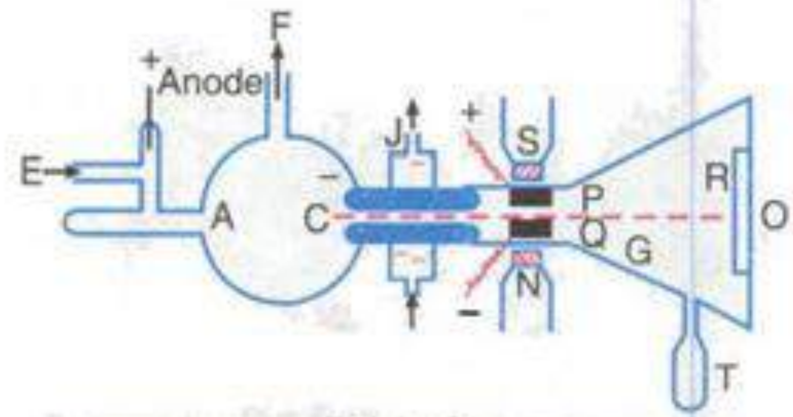


Fig. 5.2

Theory. Consider a positive ion of mass M, charge E and velocity v. When no electric or magnetic field is applied, the positive ion strikes the screen at O. This is called the *undeflected spot.*

Action of Electric Field. Let an electric field of strength X act over a length l of the path of the ion.

$$\left.\begin{array}{l}\text{Displacement of the ion in}\\ \text{passing through the electric field}\end{array}\right\} = s = \frac{1}{2}\left(\frac{XE}{M}\right)\left(\frac{l}{v}\right)^2.$$

After leaving the field, the ion moves in a straight line and finally strikes the plate at a distance x from O. x is proportional to s as well as to the distance between the field and the plate. Hence

$$x \propto \frac{XEl^2}{2Mv^2}$$

$$\text{or} \quad x = k_1 \frac{XE}{Mv^2} \qquad \text{...(1)}$$

Here k_1 is a constant.

Action of Magnetic Field. Suppose a magnetic field of strength B is applied over the same length l in the same direction as that of the electric field. The positive ion will now be deflected by this field in a direction at right angles to that in which it was deflected by the electric field. It will strike the plate at a distance y from O such that oy is perpendicular to ox in the plane of the plate.

$$\left.\begin{array}{l}\text{Displacement of the ion just}\\ \text{emerging from the magnetic field}\end{array}\right\} = s' = \frac{1}{2}\left(\frac{BEv}{M}\right)\left(\frac{l}{v}\right)^2 = \frac{BEl^2}{2Mv}$$

On emerging from the field, the ion moves in a straight line and finally strikes the plate at a distance y from O. y is proportional to s' as well as to the distance between the field and the plate.

Hence, $$y \propto \frac{BEl^2}{2Mv}$$

or $$y = k_2 \frac{BE}{Mv} \qquad \text{...(2)}$$

Here k_2 is another constant.

Action of Combined Electric and Magnetic Fields.

The combined effect of the two fields is found by eliminating v from (1) and (2).

Squaring (2) and dividing by (1),

$$\frac{y^2}{x} = \left(\frac{k_2^{\ 2}}{k_1}\frac{B^2}{X}\right)\frac{E}{M} \qquad \text{...(3)}$$

B and X are constants. If E/M is constant, then by Eq. (3), $\frac{y^2}{x}$ = constant. This is the equation of a parabola. As Eq. (3) is independent of v, particles of same E/M but of different velocities will fall on different points on the *same parabola*.

$\frac{y}{x} = \frac{k_2}{k_1}\frac{B}{X}\, v.$ *i.e.*, $\frac{y}{x} \propto v$. Thus, the position of any individual particle on the parabola will depend on the velocity of the particle.

The ions having different values of E/M will lie along the different parabolas.

For one direction of the magnetic field, one half of the parabola is traced. Reversing the magnetic field, the other half is also traced. When the full parabola is traced, it is easy to draw the axis of symmetry (X-axis).

Determination of *E/M*. The value of E/M can be calculated from Eq. (3) by measuring the coordinates x and y for a point on the parabola, evaluating the constants k_1 and k_2 for the apparatus and knowing B and X.

Determination of Mass. The mass of a positive ion is determined in terms of the mass M_1 of the standard hydrogen ion. A small trace of hydrogen is always present in all samples of gases. Hydrogen, being the lightest element, gives the outermost parabola. Let I and II represent the parabolic traces due to ions of the gas of mass M_2 and the hydrogen ions of mass M_1 respectively (Fig. 5.3). An ordinate a,b,c,d,e is drawn. It cuts the two parabolas at a, b, d, e and the X-axis at c. Let ac and bc represent the two values of y corresponding to a constant value of x on these parabolas. Let us assume that both ions have the same charge. Then from Eq. (3),

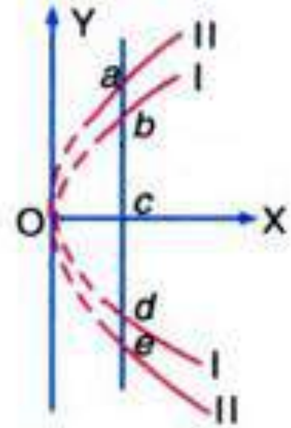


Fig. 5.3

$$\frac{ac^2}{x} = \left(\frac{k_2^2}{k_1}\frac{B^2}{X}\right)\frac{E}{M_1}$$

and
$$\frac{bc^2}{x} = \left(\frac{k_2^2}{k_1}\frac{B^2}{X}\right)\frac{E}{M_2}$$

or
$$\frac{M_2}{M_1} = \frac{ac^2}{bc^2} = \left(\frac{ae}{bd}\right)^2$$

The lengths ae and bd can be measured on the photograph. Hence the parabolic traces enable us to compare the masses of different ions with hydrogen used as a standard.

$$M_2 = \left(\frac{ae}{bd}\right)^2 M_1.$$

Discovery of Stable Isotopes. Using neon gas in his apparatus, Thomson obtained two parabolas for the gas itself, a strong one corresponding to a mass 20 and a much weaker one corresponding to a mass 22. The intensity ratio of the two traces was 9 : 1 which gave the relative abundance of the two isotopes. Thomson, therefore, suggested that neon could exist in the form of two *isotopes*, chemically indistinguishable but with different masses 20 and 22. The actual observed atomic weight (20.2) of neon is the weighted mean of the masses of these two isotopes.

This established the existence of stable isotopes.

Limitations of the Parabola Method :

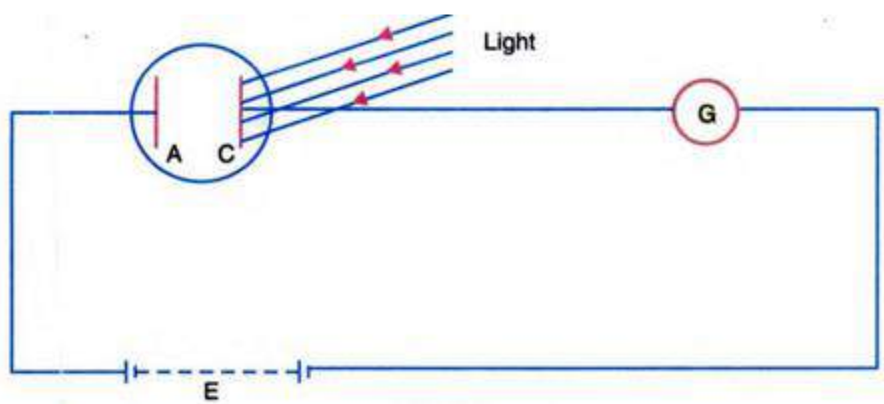
1. Due to the velocity dispersion, each parabolic trace is of very low intensity.

2. The traces on the photographic plate are blurred and have no definite edges. Hence accurate measurements are not possible.

3. The influence of secondary rays makes analysis difficult.

The Photoelectric Effect

Whenever light or electromagnetic radiations (such as X-rays, Ultraviolet rays) fall on a metal surface, it emits electrons. *This process of emission of electrons from a metal plate, when illuminated by light of suitable wavelength, is called the photoelectric effect.* The electrons emitted are known as the photoelectrons. In the case of alkali metals, photoelectric emission occurs even under the action of visible light. Zinc, cadmium etc., are sensitive to only ultraviolet light.



Laws of photoelectric emission. (i) *For every metal, there is a particular minimum frequency of the incident light, below which there is no photoelectric emission, whatever be the intensity of the radiation. This minimum frequency, which can cause photoelectric emission, is called the threshold frequency.*

(ii) *The strength of the photoelectric current is directly proportional to the intensity of the incident light, provided the frequency is greater than the threshold frequency.*

(iii) *The velocity and hence the energy of the emitted photoelectrons is independent of the intensity of light and depends only on the frequency of the incident light and the nature of the metal.*

(iv) *Photoelectric emission is an instantaneous process. The time lag, if any, between incidence of radiation and emission of the electrons, is never more than* 3×10^{-9} *sec.*

Einstein's Photoelectric Equation

According to Einstein, light of frequency ν consists of a shower of corpuscles or photons each of energy $h\nu$. When a photon of light of frequency ν is incident on a metal, the energy is completely transferred to a free electron in the metal. A part of the energy acquired by the electron is used to pull out the electron from the surface of the metal and the rest of it is utilised in imparting K.E. to the emitted electron. Let ϕ be the energy spent in extracting the electron from the emitter to which it is bound (photoelectric work function) and $\frac{1}{2} mv^2$ the K.E. of the photoelectron.

Then
$$h\nu = \phi + \frac{1}{2} mv^2 \qquad ...(1)$$

This relation is known as the *Einstein's Photoelectric equation.* If ν_o is the threshold frequency which just ejects an electron from the metal without any velocity then, $\phi = h\nu_o$.

$\therefore$
$$h\nu = h\nu_o + \frac{1}{2} mv_{max}^2 \qquad ...(2)$$

where v_{max} is the maximum velocity acquired by the electron.

or
$$\frac{1}{2} mv^2{}_{max} = h(\nu - \nu_0) \qquad ...(3)$$

Notes. (*i*) *The work function of a metal may be defined as the energy which is just sufficient to liberate electrons from the metal surface with zero velocity.*

(*ii*) Equation (3) suggests that the energy of the emitted photoelectrons is independent of the intensity of the incident radiation but increases with the frequency.

Experimental verification of Einstein's Photoelectric Equation—Millikan's Experiment.

Theory. Millikan's experiment is based on what is known as the "*stopping potential*". The stopping potential is the necessary retarding potential difference required in order to just halt the most energetic photoelectron emitted.

$$\left.\begin{array}{l}\text{The K.E. of a photoelectron leaving}\\ \text{the surface of a metal irradiated with}\\ \text{light of frequency } \nu\end{array}\right\} = \frac{1}{2}mv_{max}^2 = h\nu - \phi$$

Let V be the P.D. which is applied between the emitter and a collecting electrode in order to prevent the photoelectron from just leaving the emitter, the emitter being maintained at a positive potential with respect to the collector. Then,

$$eV = \frac{1}{2}mv_{max}^2$$

$$\therefore \quad eV = h\nu - \phi$$

$$\text{or} \quad V = \frac{h}{e}\nu - \frac{\phi}{e} \qquad \text{...(1)}$$

ϕ is constant for a given metal; h and e are also constants.

Hence, Equation (1) represents a straight line. V is measured for different values of ν. A graph is then plotted between the stopping potential (V) taken along the Y-axis and the frequency of light (ν) taken along the X-axis. The graph is a straight line (Fig. 8.9). The slope of the straight line

$$\tan\theta = \frac{h}{e}$$

$$\therefore \quad h = e\tan\theta \qquad \text{...(2)}$$

Hence the value of h (Planck's constant) can be calculated. The intercept on the X-axis gives the threshold frequency ν_o for the given emitter. From this, photoelectric work function $= \phi = h\nu_o$ can be calculated.

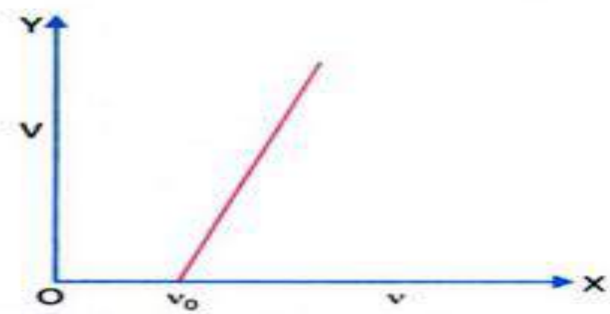
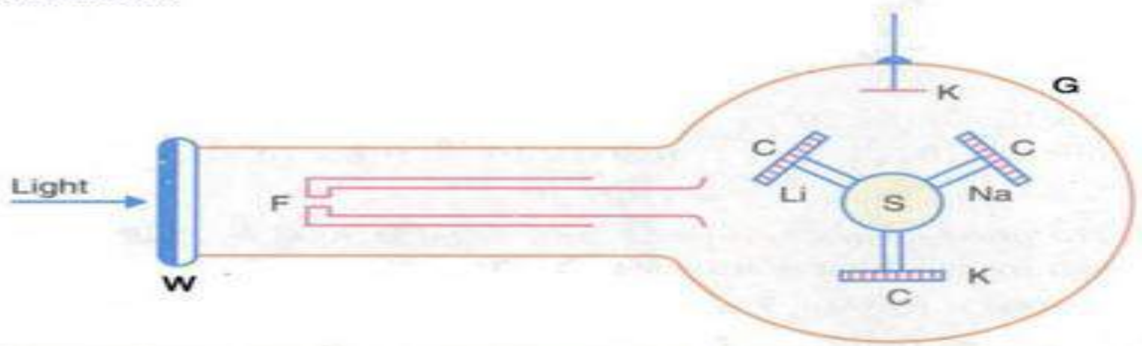


Fig. 8.9



Experiment. Millikan's apparatus is shown in Fig.

Alkali metals are employed as emitters, since they readily exhibit photoelectric emission even with visible light. Cylindrical blocks (*C*) of sodium, potassium or lithium are mounted on **a** spindle ***S* at the** centre of the glass flask *G*. **The** flask **is evacuated to a very high** vacuum to free the **metals from all absorbed gases and to** prevent their oxidation. **The spindle can be rotated from outside** by an electromagnet. **As each metal block passes by** the adjustable sharp **edge *K*, a** thin **layer** of it is removed, thus exposing a fresh **surface** of the metal to the irradiating light entering the flask through a quartz window *W*. Monochromatic light provided **by a** spectroscope is used to illuminate **the** fresh metal surfaces. The photoelectrons are collected by a Faraday cylinder ***F***. The Faraday cylinder is made of copper oxide which **is not** photosensitive. The photocurrent is measured by an electrometer connected to the Faraday cylinder.

Thus radioactivity can be defined as:-

The phenomenon in which the nucleus of the atom of an element undergoes spontaneous and uncontrollable disintegration (or decay) and emit α, β or γ-rays.

- **Radioactivity is of the following two types which are:**

a) Natural radioactivity

b)Artificial Radioactivity

Natural Radioactivity

is the process of spontaneous (i.e. without external means, by it self) disintegration of the nuclei of heavy elements with the emission of radiation.

-these are unstable nuclei found in nature.

Natural radioactivity

- The element whose nuclei spontaneous disintegrate are called *radioactive element*.
- Example of natural radioactivity are:-

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

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

$$^{226}_{88}Ra \longrightarrow {}^{222}_{86}Th + {}^{4}_{2}He$$

Artificial Radioactivity

- Is the process in which a stable (non-radioactive) nucleus is changed into an unstable (radioactive) nucleus by bombarding it with appropriate atomic projectiles like **α, neutron, proton**.

Example of Artificial radioactivity

- $^{27}_{13}Al + {}^{4}_{2}He \longrightarrow {}^{30}_{15}P + {}^{1}_{0}n$
- $^{10}_{5}B + {}^{4}_{2}He \longrightarrow {}^{13}_{7}N + {}^{1}_{0}n$
- $^{13}_{7}N \longrightarrow {}^{14}_{6}C + {}^{0}_{+1}e$

The differences between natural and artificial radioactivity

Natural radioactivity	Artificial radioactivity
Is spontaneous, since in natural radioactivity, the nuclei of heavy atom disintegrate on their own accord, forming slightly lighter and more stable nuclei and emitting α,β,γ radiations.	Is not spontaneous, since in it the nuclei of the atoms have to be bombarded by fast moving particles like α, neutrons, protons, deuterons.
Is uncontrolled and hence it can not be slowed down or accelerated by any means.	Can be controlled by controlling the speed of the bombarding particles used for bringing about the artificial radioactivity
Is usually shown by heavy elements.	Can be induced even in light element.

Isotopes

Isotope are the atoms of the same elements which have the same atomic number (Z) or the same number of protons (p) but different mass number s(A). For example

H^{2}_{1} **(A = 2,Z =1),** H^{1}_{1} **(A = 1, Z= 1),** these are isotopes of hydrogen.

Isotopes of chlorine

$^{35}_{17}\mathrm{Cl}$	$^{37}_{17}\mathrm{Cl}$
chlorine - 35	**chlorine - 37**

Uses of Radioactive Isotopes

- **Diagnosis of diseases.**

Isotopes with a short half-life give off lots of energy (γ-rays) in a short time has been used to detect the exact position of the tumour in the human body.

Therefore, Isotopes are useful in medical imaging.

- The isotopes with high energy γ rays has been used for the treatment of cancer. The treatment of diseases by the use of radioactive isotopes is called *Radiotherapy*
- Syringes, dressings, surgical gloves and instruments, and heart valves can be sterilized after packaging by using radiation.
- Radiation sterilization can be used where more traditional methods, such as heat treatment, cannot be used, such as in the sterilization of powders and ointments and in biological preparations like tissue grafts.

- In agriculture, radioactive materials are used to improve food crops, preserve food, and control insect pests.
- They are also used to measure soil moisture content, erosion rates, salinity, and the efficiency of fertilizer uptake in the soil.
  - Radioactive materials are used as tracers to measure environmental processes, including the monitoring of silt, water and pollutants.
  - They are used to measure and map effluent and pollution discharges from factories and sewerage plants, and the movement of sand around harbours, rivers and bays. Radioactive materials used for such purposes have short half-lives and decay to background levels within days.

In Industry

- Radioactive materials are used in industrial radiography, civil engineering, materials analysis, measuring devices, process control in factories, oil and mineral exploration, and checking oil and gas pipelines for leaks and weaknesses.

(ii) The are used to measure the thickness of paper and plastics during manufacturing.

(iii) To checking the height of fluid when filling bottles in factories.

One of the most common uses of radioactive materials in the home is in smoke detectors. Most of these life-saving devices contain tiny amounts of radioactive material which make the detectors sensitive to smoke.

The radiation dose to the occupants of the house is very much less than that from background radiation.

- Many satellites use radioactive decay from isotopes with long half-lives for power because energy can be produced for a long time without refueling.
- The isotope carbon-14 is used by archeologists to determine age.
- Radioactive isotopes are used to detect the leakage or crack in the underground oil pipes, gas pipes and water

Nuclear Fission

- Is a nuclear reaction in which a heavy nucleus, when bombarded with slow moving neutrons, split into two nuclei of near equal mass with the release of anomalous amount of energy.

Example of nuclear fission

- $$\ {}^{235}_{92}U + \underbrace{{}^{1}_{0}n}_{A}(slow) \xrightarrow{B} \underbrace{{}^{141}_{56}Ba + {}^{92}_{36}Kr}_{C} + 3\,{}^{1}_{0}n + \underbrace{E}_{D}$$

Where
A = Thermal neutron
B = Fission
C = Fission product
D = Huge amount of energy

- Is a kind of furnace in which controlled fission of a radioactive material like U-235 takes place and a manageable amount of nuclear energy (atomic energy) is produced at a steady slow rate.

Heat energy produced in the fussion of u-235 nucleus by slow neutrons taking place in the atomic reactor has been used to generate electricity

It produces fissionable material like plutonium which is used in atomic bomb.

It is also used for the production of fast neutrons that are needed for nuclear bombardment

Nuclear Fusion

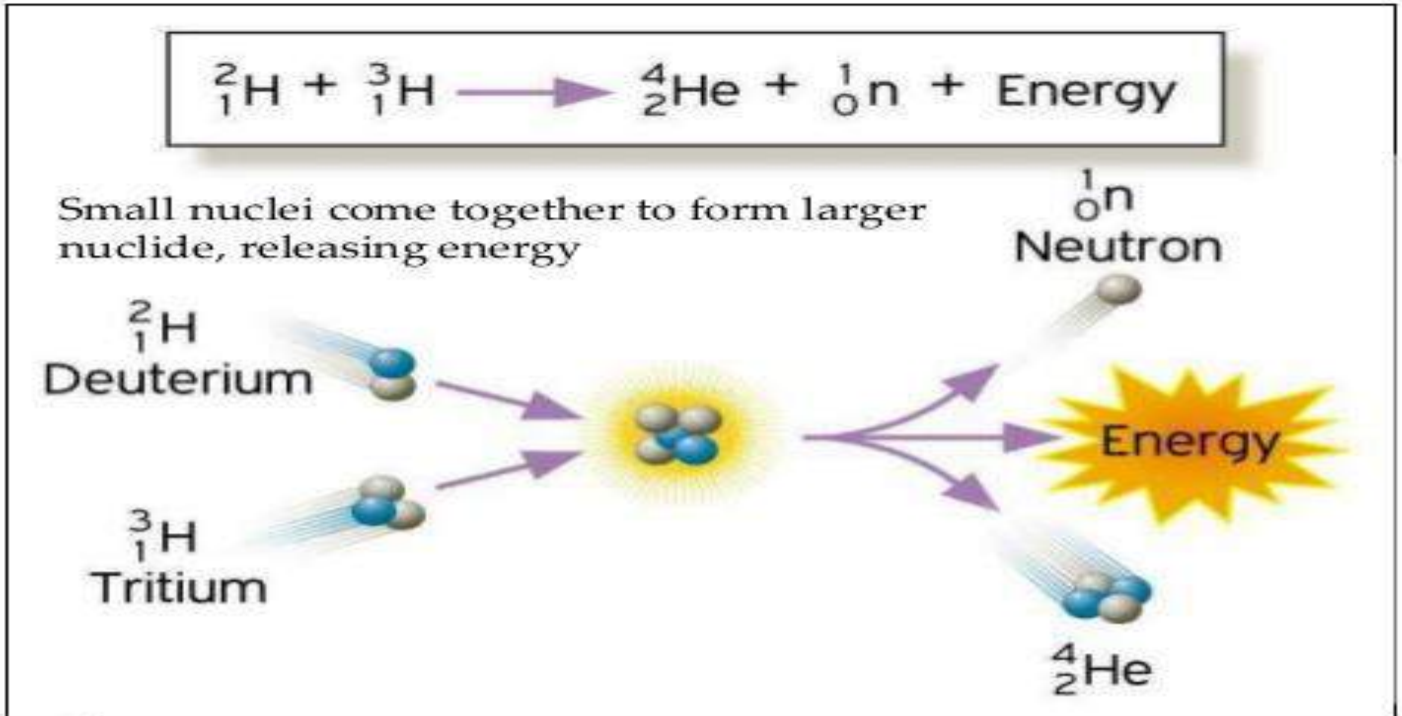
- Is the nuclear reaction in which lighter nuclei combine together to form a single heavy and more stable nucleus and large amount of energy is released.

Example of nuclear fusion reaction

- $\underset{A}{{}^{2}_{1}H} + \underset{B}{{}^{3}_{1}H} \longrightarrow \underset{C}{{}^{4}_{2}He} + \underset{D}{{}^{1}_{0}n} + \underset{E}{17.6MeV}$

A= Deuterium
B= Tritium
C = α- Particle
D= Neutron
E = Anomalous amount of energy

Fusion: Small Nuclei Form Larger Nuclide, Release Energy



This type of Fusion is being Examined as An alternative Energy source On Earth.

- GOOD
  - A controlled reaction in a reactor used to produce cleaner, inexpensive electricity
- EVIL
  - A fission bomb starts a fusion chain reaction to create an incredibly powerful weapon – thermonuclear weapons (H-bombs), MUCH more destructive than atomic bombs.

Differences between Nuclear fusion and Nuclear fission

NUCLEAR FISSION	NUCLEAR FUSION
A heavy nucleus breaks up to form two lighter nuclei.	Two light nuclei combine to form a heavy nucleus.
It involves a chain reaction.	Chain reaction is not involved.
The heavy nucleus is bombarded with neutrons.	Light nuclei are heated to an extremely high temperature.
We have proper mechanisms to control fission reaction for generating electricity.	Proper mechanisms to control fusion reaction are yet to be developed.
Disposal of nuclear waste is a great environmental problem.	Disposal of nuclear waste is not involved.
Raw material is not easily available and is costly.	Raw material is comparatively cheap and easily available.