specially stable nuclei. A **magic number** *is the number of nuclear particles in a completed shell of protons or neutrons.*

All elements with atomic number equal to 83 or less have one more stable nuclides with the exception of technetium (Z = 43) and promethium (Z = 61).

## 8.5 Nuclear Transformations or Nuclear Transmutation

In 1919, Ernest Rutherford discovered that it is possible to change the nucleus of one element into the nucleus of another element by processes that can be controlled in the laboratory. *The conversion (change) of one element to another by bomarding the nucleus of the element with nuclear particles of nuclei is called* ***nuclear transformation*** *or* ***nuclear transmutation.***

Rutherford bombarded nitrogen –14 with alpha particles from the radioactive decay of radium. The product nuclides were oxygen –17 plus a proton. The reaction is

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

In this reaction, an atom of nitrogen has been transferred into an atom of oxygen.

Bombardment of beryllium with alpha particles generates particles with a mass approximately that of proton and no charge. The particles were called neutrons by Chadwick (1932). The reaction that resulted in the discovery of neutron is

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

The reaction can be described as an ($\alpha$ , $n$) reaction between $^{9}_{4}Be$ and $^{12}_{6}C$. The first letter indicating the incoming particle and the second, the outgoing particle.

In 1933, Irene and Joliot-Curie, while treating light elements such as boron or aluminium with alpha particles, detected the emission of positrons and neutrons. They observed that the emission of positrons does not stop when the source of $\alpha$-particles is removed. The reactions are

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

$$^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^{0}_{1}e$$

Phosphorus –30 was the first radioactive nucleus produced in the laboratory. Since then over a thousand radioactive isotopes have been made.

Elements of larger atomic number merely scatter, or deflect, alpha particles from natural source, rather than giving a transformation (transmutation) reaction. These elements have nuclei of large positive charge, and the alpha particle must be travelling very fast in order to penetrate the nucleus and react. Alpha particles from natural sources do not have sufficient kinetic energy. To shoot charged particles into heavy nuclei, it is necessary to accelerate the charged particles.

A **particle accelerator** *is a device used to accelerate electrons, protons, and alpha particles and other ions to very high speeds.* Many methods have been devised to accelerate charged particles, using strong magnetic and electrostatic fields. The **particle accelerators,** popularly called **"atom smashers"** bear such names as **cyclotron** and **synchrotron.** With the accelerators (cyclotron) available in 1934, it was not possible to induce radioactivity in the elements beyond potassium. However, a neutron is electrically neutral. Enrico Fermi reasoned that a neutron's entry into a nucleus would not be opposed by repulsive forces. It should be possible to transform

all known elements by exposure to neutron sources. He was correct. Practically all known elements have been transformed, and many transuranium elements – elements with atomic numbers greater than 92 have been synthesized. For example,

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U \longrightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

$$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

**Nuclear reactors,** in which controlled fission reactions are carried out, are excellent sources of neutrons. Neutrons produced this way are used to bombard atomic nuclei to synthesize useful isotopes. For examples, cobalt -60, used in radiation therapy for cancer, is produced by neutron capture. Iron –58 is placed in a nuclear reactor, where it is bomarded by neutrons. The following sequence of reactions takes place.

$$^{58}_{26}Fe + ^{1}_{0}n \longrightarrow ^{59}_{26}Fe \quad ; \quad ^{59}_{26}Fe \longrightarrow ^{59}_{27}Co + ^{0}_{-1}e$$

$$^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{60}_{27}Co$$

Elements with larger atomic numbers normally formed in small quantities in particle accelerators. For example, curium –242 is formed when a plutonium –239 target is struck with accelerated alpha particles.

$$^{239}_{94}Pu + ^{4}_{2}He \longrightarrow ^{242}_{96}Cm + ^{1}_{0}n$$

In 1994 a team of European scientists synthesized element 111 by bombarding a bismuth target for several days with a beam of nickel atoms.

$$^{209}_{83}Bi + ^{64}_{28}Ni \longrightarrow ^{272}_{111}X + ^{1}_{0}n$$

Amazingly, their discovery was based on the detection of only three atoms of the new elements. The nuclei are short-lived, and they undergo alpha decay within milliseconds of their synthesis. The same group of the scientists also reported the synthesis of element 112 in 1996. The names and symbols have not yet been chosen for these new elements.

## 8.6 The Activity of a Radioactive Substance

The **activity** *of a radioactive material is defined as the rate at which the nuclei of its constituents decay.* The rate of nuclear disintegration is proportional to the number of unstable nuclei present in a sample. If N be the number of parent nuclei in a given sample, then

$$\text{Rate of decay} = -\frac{dN}{dt} = kN$$

where $k$ is the rate constant and t is the time. The unit of activity is, therefore, disintegration per second. The SI unit activity is **Becqueral (Bq)** which is defined as one disintegration per second. The activity is, of course, expressed in the **Curei (C*i*)** unit, which is the rate of decay of $3.7 \times 10^{10}$ disintegrations per second. The relation between the two units is

1 $C_i$ = $3.70 \times 10^{10}$ disintegrations per second (d ps)

1 millicurie (m $C_i$) = $3.7 \times 10^{7}$ disintegrations per second

1 microcurie ($\mu C_i$) = $3.7 \times 10^{4}$ disintegrations per second

## 8.7 Detection and measurement of radioactivity

The detection and measurement of radioactivity of any sample is based on the detection, identification and measurement of the radiations emitted by the sample. The α- and β-radiations can be detected and measured by the extent of ionization caused by them in the gas through which they pass. Some important methods employed for this purpose are described below:

**1. Geiger-Mueller counter (gas ionization method):** This method is used for detecting and measuring the rate of emission of α- or β-particles. The counter consists of a cylindrical metal tube (cathode) fitted with a thin mica window at one end. A thin metal rod is fitted along its axis (anode) and kept insulated from the cylinder. The tube is filled with argon gas at low pressure (about 0.1m). A high potential up to 1000 volts is applied between the rod (anode) and the outer tube (cathode). Radiation enters the counter tube through the thin mica window. It strikes argon atoms inside the tube and ionizes them. The positive argon ions move to the cathode and the electrons to the anode. This creates an electrical pulse which is amplified, and is recorded in an automatic counter. The latest models of G.M. counters can measure up to 100000 counts per second. A typical G.M. counter is shown in Fig. 8.3.

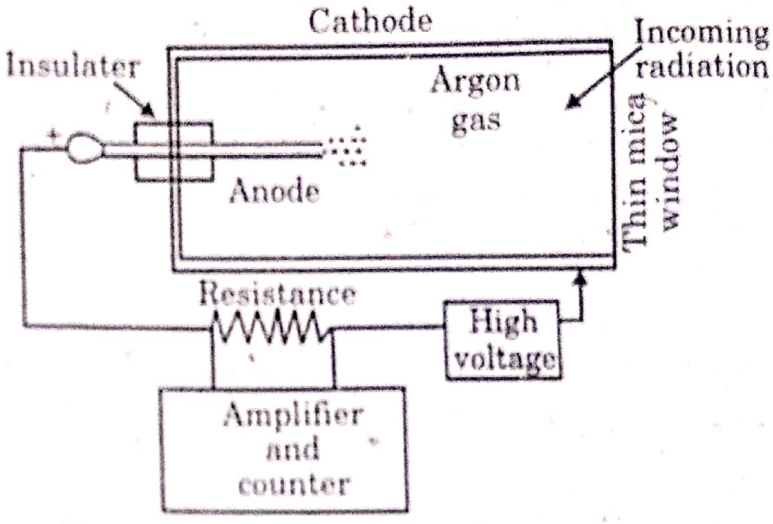

Fig. 8.3 The Geiger Muller Counter

**2. Scintillation counter:** A scintillation is a substance which emits a small flash of light when struck by a fast charged particle. Rutherford used a spinthariscope (Fig. 8.4) for the detection and counting of α-particles. The radioactive substance mounted on the tip of the wire emitted α-particles. Each particle on striking the Zn S screen produced a flash of light. These flashes of light (scintillations) could be seen through the eye piece. With this device it was possible to count of α-particles from 50 to 200 per second.

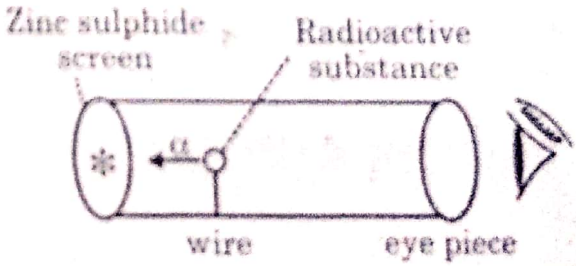

Fig. 8.4 Spinthariscope

**A modern scintillation counter** also works on the above principle and is widely used for the measurements of α - or β - particles. Instead of the Zn S screen, a crystal of sodium iodide (activated with thallium) is employed. The sample of the radioactive substance contained in a small vial, is placed in "well" cut into the crystal. The radiation from the sample hit the crystal wall and produce the flashes of

light. These fall on a photomultiplier tube, an ultrasensitive photocell, which produces a pulse electric current for each flash of light, which is amplified and is recorded in a mechanical counter.

Such a scintillation counter can measure radiation upto a million per second

**3. Photographic method.** Determination of radiation by photographic method is also called **autoradiography.** In this method ionizing radiation interacts with the silver halide in photographic emulsions. When a radioactive sample is placed on a film of photographic emulsion of silver in photographic film. The film is developed and viewed under a powerful microscope.

As α- or β-particles pass through the film, they leave a track of black particles. These particles can be counted. In this way the type of radiation and its intensity can be known. However, γ-radiation darken the photographic film uniformly. The intensity of the blackening at a given place will be a function of exposure time and amount of activity at that place used similarly are cloud chambers.

**4. Wilson Cloud chambers.** Wilson (1912) derived a technique of detecting the radioactivity. This technique is based upon the ionization property of the radioactive emissions. The apparatus consists of a chamber fitted with a glass window and a piston. In an experiment, a gas or air saturated with water vapour is enclosed in the chamber and the piston is rapidly moved upto bring about cooling due to sudden expansion. The air inside the chamber becomes super saturated with water vapours. At this stage, the radiation from the radioactive material are made to enter the chamber through the window. The ions produced due to the ionizing power of the radiation act as nuclei upon which droplets of water condense, and thus a foggy trace is formed along the path traversed by the radioactive emission. This is immediately photographed. Similarly, α– or β– particle form trial of bubbles as they pass through liquid hydrogen.

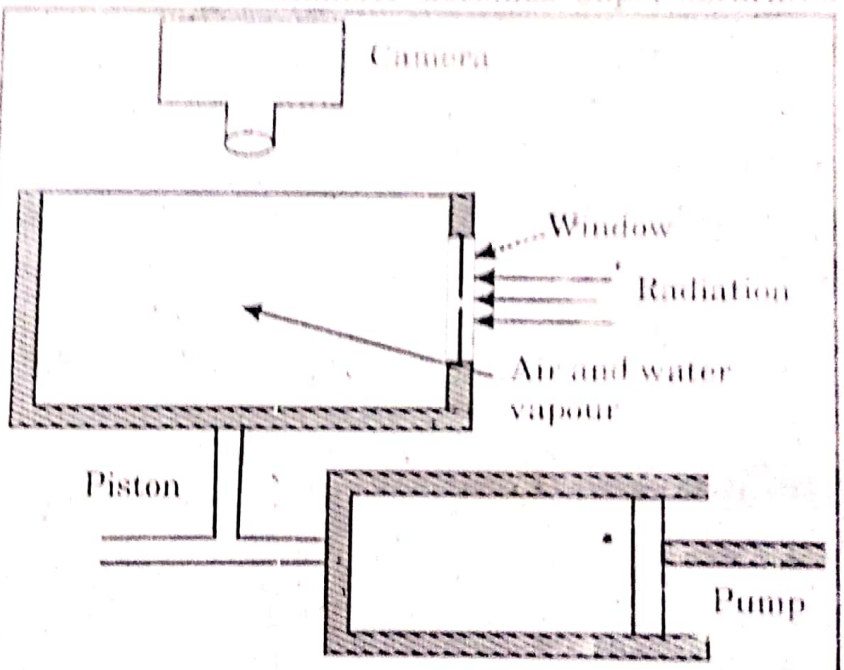


Fig. 8.5: Wilson Cloud Chamber Apparatus

## 8.8 Rate of radioactivity disintegration.

Atoms of all radioactive elements are undergoing spontaneous disintegration. The rates of decay of radioactive nuclides follow first order kinetics and are not affected by external factors like temperature, pressure, chemical combination, etc. Therefore, the number of nuclei disintegrating per unite time (i.e., rate of

radioactive decay) is proportional to the number of radioactive nuclei in the sample. If N be the number of unstable nuclide in a given sample at time t and dN of them decay in time interval dt, then according to law of mass action,

$$\text{Rate of decay} = -\frac{dN}{dt} \propto N$$

$$\text{or} \quad \text{Rate of decay} = -\frac{dN}{dt} = kN \qquad (1)$$

Where $-\frac{dN}{dt}$ means the rate of decrease in the number of unstable nuclide in the given sample and $k$ is known as **radioactive decay constant** or **disintegration constant.** It represents the fraction of total number of unstable nuclei in a sample transferred per unit time and is often expressed in reciprocal second ($s^{-1}$). Eq. (1) can be written in the form

$$-\frac{dN}{N} = k dt \qquad (2)$$

On integration Eq. (2), we have

$$-\int \frac{dN}{N} = k \int dt$$

or $-ln\ N = kt + C$ (Integration constant) (3)

When t = 0, then $N = N_0$. Thus

$$C = -ln\ N_0$$

Substituting the value of C in Eq. (3), we get

$$-\ln N = kt - \ln N_o$$

$$\text{or} \quad \ln \frac{N_o}{N} = kt$$

$$\text{or} \quad k = \frac{1}{t} \ln \frac{N_o}{N}$$

$$\text{or} \quad k = \frac{2.303}{t} \log \frac{N_o}{N} \quad or\ t = \frac{2.303}{k} \log \frac{N_o}{N} \qquad (4)$$

Eq. (4) is the integrated fOrm of the first order rate equation.

**Definition of radioactive decay constant ($k$)**

Eq. (1) written above may be written as

$$k = \frac{-dN/dt}{N}$$

Hence, *radioactive decay constant may be defined as the ratio of the amount of the substance which disintegrates in a unit time to the amount of the substance present.* The rate constant is a characteristic of the radioactive nuclide, each nuclide having a different value.

**Half-life:** The stability of a nuclide is measured by its half-life, $t_{1/2}$. Considering the rate equation (4), at half-life time $t_{1/2}$, $N = \frac{1}{2}N_0$

$$t_{1/2} = \frac{2.303}{k} \log \frac{N_o}{N_{0/2}} = \frac{2.303}{k} \log 2 = \frac{0.693}{k}$$