Unit-3
Nuclear Physics

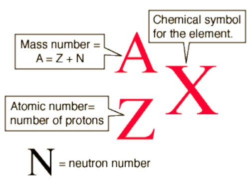
Introduction:

The branch of physics concerned with the study and understanding of the atomic nucleus, including its composition and the forces which bind it together, is called nuclear physics.

Nucleus

The **atomic nucleus** is the small, dense region at the center of an atom . IT consists of the elementary particles, protons and neutrons which are known as nucleons. A proton has positive charge of the same magnitude as that of electron and its rest mass is about 1836 times the mass of an electron. A neutron is electrically neutral, whose mass is almost equal to the mass of the proton. The nucleons inside the nucleus are held together by strong attractive forces called nuclear forces.

The conventional symbol for nuclear species known as nuclide , follow the pattern



Classification of Nuclei:

(i) Isotopes

Isotopes are atoms of the same element having the same atomic number Z but different mass number A. The nuclei $_1H^1$, $_1H^2$ and $_1H^3$ are the isotopes of hydrogen. In other words isotopes of an element contain the same number of protons but different number of neutrons. As the atoms of isotopes have identical electronic structure, they have identical chemical properties but different physical properties. They are placed in the same location in the periodic table.

(ii) Isobars

Isobars are atoms of different elements having the same mass number A, but different atomic number Z. The nuclei $_8O^{16}$ and $_7N^{16}$ represent two isobars. Since isobars are atoms of different elements, they have different physical and chemical properties.

(iii) Isotones

Isotones are atoms of different elements having the same number of neutrons. $_6C^{14}$ and $_8O^{16}$ are some examples of isotones.

(iv) Mirror Nuclei :

Mirror Nuclei are nuclei, havig the same mass number A but with the proton and Neutron number interchanged. For Example $_4Be^7$ (Z= 4 & N= 3) and $_3Li^7$ (Z= 3 & N= 4) are mirror nuclei.

General properties of nucleus

1. Nuclear size

According to Rutherford's αparticle scattering experiment nuclear radius, is approximately of the order of 10^{-14} to 10^{-15}m. If the nucleus is assumed to be spherical,

The volume of the nucleus is directly proportional to the number of Nucleons

$$Volume \propto A$$

$$\frac{4}{3}\pi R^3 \propto A$$

Where R is the Nuclear Radius

Hence $R^3 \propto \frac{3}{4\pi} A$

$$R \propto \left(\frac{3}{4\pi}\right)^3 A^{1/3}$$

$$R = C \left(\frac{3}{4\pi}\right)^3 A^{1/3}$$

Where C is the proportionality constant let $R_0 = C \left(\frac{3}{4\pi}\right)^3$

$$R = R_0 A^{1/3}$$

where R_0 is the constant of proportionality and is equal to $1.3 * 10^{-15}$m

2. Nuclear density

The nuclear density ρ_N can be calculated from the mass and size of the nucleus.

$$\rho_N = \frac{\text{Nuclear mass}}{\text{Nuclear Volume}}$$

$$\rho_N = \frac{A * (\text{mass of a nucleon})}{\frac{4}{3}\pi R^3}$$

$$\rho_N = \frac{3M}{4\pi R_0^3}$$

Above equation shows that nuclear density is independent of mass number.

Substituting the known values, the nuclear density is calculated as $1.45 * 10^{17}$ kg m^{-3}

which is almost a constant for all the nuclei irrespective of its size.

The high value of the nuclear density shows that the nuclear matter is in an extremely compressed state.

3. Nuclear charge

The charge of a nucleus is due to the protons present in it. Each proton has a positive charge equal to $1.6 * 10^{-19}$ C.

The nuclear charge = Ze, where Z is the atomic number.

4. *Nuclear mass*

As the nucleus contains protons and neutrons, the mass of the nucleus is assumed to be the mass of its constituents.

Assumed nuclear mass = $Zm_P + Nm_n$

where m_p and m_n are the mass of a proton and a neutron respectively. However, from the measurement of mass by mass spectrometers, it is found that the mass of a stable nucleus (m) is less than the total mass of the nucleons.

i.e Real mass of a nucleus, $m < (Zm_p + Nm_n)$

$Zm_p + Nm_N - m = \Delta m$

where Δm is the mass defect

Thus, the difference in the total mass of the nucleons and the actual mass of the nucleus is known as the mass defect.

Atomic mass unit

It is convenient to express the mass of a nucleus in atomic mass unit (amu), though the unit of mass is kg. One atomic mass unit is considered as one twelfth of the mass of carbon atom $_6C^{12}$. Carbon of atomic number 6 and mass number 12 has mass equal to 12 amu.

1 amu = $1.66 * 10^{-27}$ kg

The mass of a proton, m_p = 1.007276 amu

This is equal to the difference in mass of the hydrogen atom which is 1.007825 amu and the mass of electron.

The mass of a neutron, m_n = 1.008665 amu

The Energy equivalent of 1 amu = 931 MeV

Binding energy

When the protons and neutrons combine to form a nucleus, the mass that disappears (mass defect, Δm) is converted into an equivalent amount of energy (Δmc^2). This energy is called the binding energy of the nucleus.

$$\text{Binding energy} = [Zm_P + Nm_n - m]\, c^2$$
$$= \Delta m\, c^2$$

The binding energy of a nucleus determines its stability against disintegration. In other words, if the binding energy is large, the nucleus is stable and vice versa.

The binding energy per nucleon is

BE/ A = Binding energy of the nucleus / Total number of nucleons

Nuclear Models :

To understand the observed properties of the nucleus, adequate knowledge of inter nucleon interaction and there arrangements is necessary.

Nuclear models are proposed to understand or explain the observed properties of the nucleus with certain approximations. These nuclear models have their own benefits and limitations**.**

1. Liquid Drop Model

Liquid drop model was proposed by Neils Bohr in 1936 . He pointed out that the strong , short range, attractive forces between the nucleons are analogous to those acting between the molecules of a liquid .

The similarities between the nucleus and a liquid drop are the following:

(i) In the stable state, the shape of liquid drop is spherical due to the symmetrical surface tension forces. Similarly the nucleus is also nearly spherical due to the nuclear forces. The nucleons inside the nucleus behave just like the behavior of molecules in a liquid. On this basis, the radius of nucleus must be proportional to the cube root of its mass number. This fact has been experimentally verified.

(ii) The density of spherical drop of liquid does not depend on its volume (or radius) similarly the density of nucleus is also independent of its volume (or mass number A)

(iii) The molecules evaporate from a liquid drop on raising the temperature of the liquid, due to their increased energy of thermal agitation. Similarly when energy is given to the nucleus by bombarding it with nuclear projectiles, a compound nucleus is formed which emits nuclear radiation almost immediately.

(iv) The nuclear forces are short range forces, similarly as that of liquid , in which the inter molecular forces are short range forces.

(v) When a small drop of liquid is allowed to oscillate, it breaks up in to two smaller drops of equal size . The process of nuclear fission is similar in which the nucleus breakup in to two smaller nuclei.

Merits of liquid drop model

1. It explains the spherical shape of most nuclei.

2. It helps to predict the nuclear binding energy and also to assess how much is available for consumption.

3. It helps to explain the stability of nuclei.

4. The radioactive phenomenon can be explained with the help of this model.

5. This model explains the phenomenon of artificial radioactivity.

6. Nuclear fission can be understood on the basis of this model.

Demerits of liquid drop model

1. It is a crude model. It does not explain all the properties of the nucleus.

2. It does not explain the high stability of nuclei with the magic number.

3. The concept of pairing cannot be explained with this model.

4. The discontinuities in B / E nucleon cannot be explained.

Magic Numbers in Nuclear Structure

When a nucleus has an even number of protons and neutrons, such a nucleus is more stable than with the odd numbers. This number is known as "magic numbers" and they offer stability to the atom. Following is the sequence of magic number:

2, 8, 20, 28, 50, 82, 126.

When nuclei will have both neutron number and proton number equal to one of the magic numbers, they are known as "doubly magic". Calcium is an example of a nucleus that has a doubly magic number.

2. Nuclear Shell Model

The nuclear shell model is a model of the atomic nucleus. It uses the Pauli exclusion principle to explain the nucleus structure in terms of energy levels. It basically explains the distribution of energy levels into different nucleus atom shells and nucleus atom sub shells. A shell is described as the energy level where particles having the same energy exists.

In this model, all the nuclear particles are paired one-to-one, neutron with a neutron, and proton with a proton. The paired neutrons and protons in nuclear energy levels are filled when the number of neutrons or protons is equal to 2, 8,20,28,50,82, or 126. These are the magic numbers that show the most stable nuclei.

The unpaired ones are responsible for the properties of a nucleus and valence electrons are responsible for different chemical properties of elements. With the help of the shell model, we can accurately predict the properties of nuclei such as angular momentum.

The shell structure applies to both neutron and proton separately.

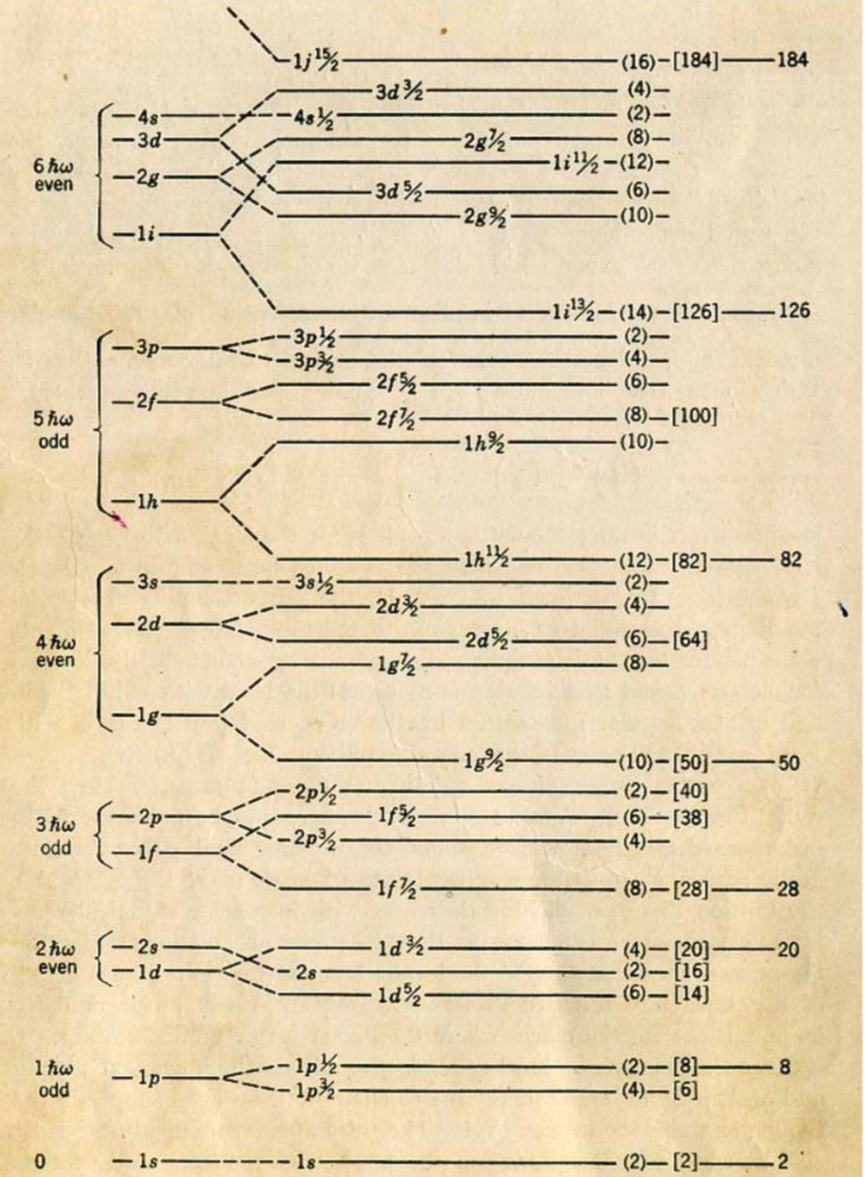


Fig. IV.3. Schematic diagram of nuclear level systems with spin-orbit coupling.

Merits of Nuclear Shell Model :

Magic numbers are explained successfully with the nuclear shell model.

Ground state spin and nuclear angular momenta of nuclei calculated using shell model have been found to be correct.

Demerits of Nuclear Shell Model :

(i) There exists difference between shell-model wave functions and the real states of the nucleus.

(ii) The Large value of Q the quadrupole moment in many nuclei cannot be explained with this mode.

(iii) The strong spin-orbit interaction, are certainly not applicable in this model .

(iv) The shell model cannot be applied to many heavy nuclei .

Particle Accelerators :

A particle accelerator is a machine that uses to accelerate charged particles to very high speeds and energies, and to contain them in well-defined beams.

Linear Particle Accelerator (LINAC)

A **linear particle accelerator** (LINAC) is a type of particle accelerator that greatly increases the kinetic energy of charged subatomic particles or ions by subjecting the charged particles to a series of oscillating electric potentials along a linear beam line.

Principle:

1. There is no electric field inside a hollow charged conductor.

2. Under the action of an a.c. field , a charged particle would experience acceleration for half the cycle and de acceleration for the next half cycle . If there a particle is kept in the field for accelerating half cycle and then shielded from it for the nex half cycle it would experience the ‘ regenerative’ accelerating action of the field .

Construction:

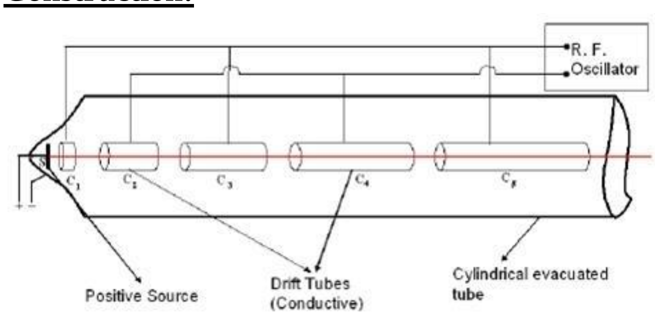


Figure (1) shows the setup used in LINAC. A series of cylindrical conductor’s are kept inside a long evacuated tube and the charged particle (the proton) is made to travel down the tube along the axis of the cylinders. Alternate cylinders are connected together and for accelerating potential, A high voltage and high frequency a.c. source (500 KV, 200 MHz) is used.

Working :

Positive ions enter along the axis of the accelerator from an ion source through an aperture A . Suppose a positive ion leave A and accelerated during the half cycle, when the cylinder 1 is negative with respective to A . Let ‘q’ be the charge and ‘m’ is the mass of the ion and ‘V’ potential of drift tube 1 with respect o A.
Then velocity v_1 of the ion on reaching the cylinder is given by :

$$\frac{1}{2}\, m v_1^2 = qV$$

$$v_1 = \sqrt{\frac{2qV}{m}} \quad \ldots\ldots (1)$$

The length of the cylinder 1 is so adjusted that as the positive ion comes out of it, the cylinder has a positive potential and the next cylinder (cylinder-2) has a negative potential. The positive ion again accelerated in the space between the cylinder 1 and 2 . On reaching the cylinder 2 , the velocity v_2 of the positive ion is given by :

$$\frac{1}{2}\, mv_2^2 = 2qV$$

$$v_2 = \sqrt{2}\sqrt{\frac{2qV}{m}}$$

$$v_2 = \sqrt{2}v_1 \quad \ldots..(2)$$

This shows that v_2 is $\sqrt{2}$ times of v_1 i.e. length of the cylinder 2 also must be $\sqrt{2}$ times of the length of cylinder 2 .

For successive acceleration in successive gaps the tubes 1,2,3, etc must have length proportional to 1, $\sqrt{2}$, $\sqrt{3}$ etc

i.e. $l_1 : l_2 : l_3 = 1 : \sqrt{2} : \sqrt{3} : \ etc$

Energy of the ion:

Let n be the number of gaps that the ion travels in the accelerator and v_n be th final velocity acquired by the ion, then

Velocity of the ion ,as it emerges out of the nth tube

$$v_n = \sqrt{n}\sqrt{\frac{2qV}{m}} \quad \ldots\ldots (3)$$

Therefore the Kinetic energy (K.E.) acquired by the ion

$$\frac{1}{2}\, mv_n^2 = nqV$$

Thus the final energy of the ion depends upon

(i) The total number of gaps
(ii) The energy gained in each gap

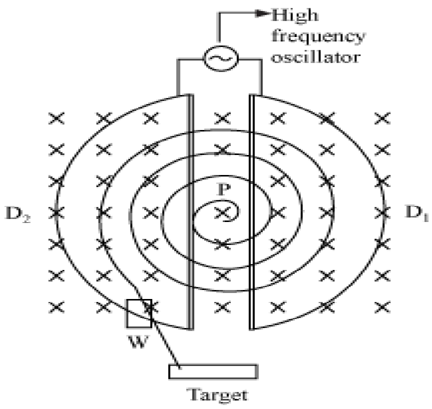
Limitation of LINAC:

(i) The length of accelerator become in conventionally large and it is difficult to maintain vacuum in large chamber.
(ii) The ion current available in the form of short interval pulses because the ions are injected at an appropriate moment.

Cyclotron :

Introduction :

A **cyclotron** is a type of particle accelerator invented by Ernest O. Lawrence in 1932. It is used to accelerate positively charges particles like proton and deuterons to very high energies so that these particles may produce disintegration.



Construction :

A cyclotron consists of a cylindrical cavity which is divided in to two called dees placed in an evacuated chamber between the poles of a magnet. An ion source which consist of a heating filament and a gas Hydrogen or deuterium is placed near the midpoint o the gap between the 'dees' .

An alternating potential difference of the order of 10^4 volts is applied between the dees with the help of Radio frequency oscillator.

Principle of Working :

When an ion of mass 'm' and charge q gets inside a dee which is at negative potential ,it experiences no electrical force because the electric field is zero inside a hollow charge conductor. However under the action of magnetic field , ion describes a circular orbit with a constant speed $'v'$ and radius 'r' given by

$qvB = \frac{mv^2}{r}$ ……..(1)

$r = \frac{mv}{qB}$ ………(2) where 'B' is the magnetic induction

The angular velocity $'\omega'$of the ion in its circular path is given by

$\omega = \frac{v}{r} = \frac{qB}{m}$ ……(3)

The time taken by the ion to travel the semi circular path

$t = \frac{\pi}{\omega} = \frac{\pi m}{qB}$ …….(4)

The potential difference between the dees oscillate with a frequency equal to 'ω' . In this way, the potential difference between the dees is in resonance with the circular motion of the ions.

When the ion completes half revolution , the polarity of the dees is reversed. Therefore the ion receives again small acceleration while crossing the gap between two dees . Then th next half cycle described by the ion has large radius but the same angular velocity .

The process repeats itself several times, until the radius attains a maximum value r_{max} approximately equal to the radius 'R' of th dees. The magnetic field at the edge of the dees is decreased sharply so that the ion moves tangentially and escaping out through an opening 'A'

Energy of an ion :

Let r_{max} be the radius of the outermost orbit described by the ion and v_{max} is th maximumvelocity gained by the ion in its final orbit. Then the equation of motion of the ion in a magnetic field is

$$qv_{max}B = \frac{mv_{max}^2}{r_{max}}$$

Or $v_{max} = \frac{Bqr_{max}}{m}$

The energy of the ion

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

$$E = \frac{B^2 r_{max}^2}{2} \left[\frac{q^2}{2}\right] \quad \text{.........(5)}$$

Condition of resonance:

The condition for acceleration of the ion in the inter-dee gap is that :

Half the time period of the time taken by the ion to travel the semi circular path = oscillation of the applied high frequency voltage

i.e. $\frac{T}{2} = \frac{\pi m}{qB}$

or $T = \frac{2\pi m}{qB}$

therefore frequency of the oscillator

$$f = \frac{qB}{2\pi m} \quad \text{.......(6)}$$

Limitation of Cyclotron :

1. The energy to which particles can be accelerated in a cyclotron is limited due to the variation of mass with velocity.As the energy increases ,the velocity of the particle also increases, resulting in a change of mass according to the relation $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$ where

   m_0 is the rest mass of the particle
2. Uncharged particles cannot be accelerated by a cyclotron.
3. Only charged particles like protons, deuterons and alpha particles can be accelerated by the cyclotron and electron cannot be accelerated, because the mass of electron is very small and a small increase in energy of electron makes it move with very high speed and as a result the electrons go quickly out of step with oscillating electric field.

4. The energy limitation of the normal, fixed frequency cyclotron can be removed and the ions accelerated indefinitely if the applied frequency is varied to match exactly the ion rotation frequency.

Synchrotron :

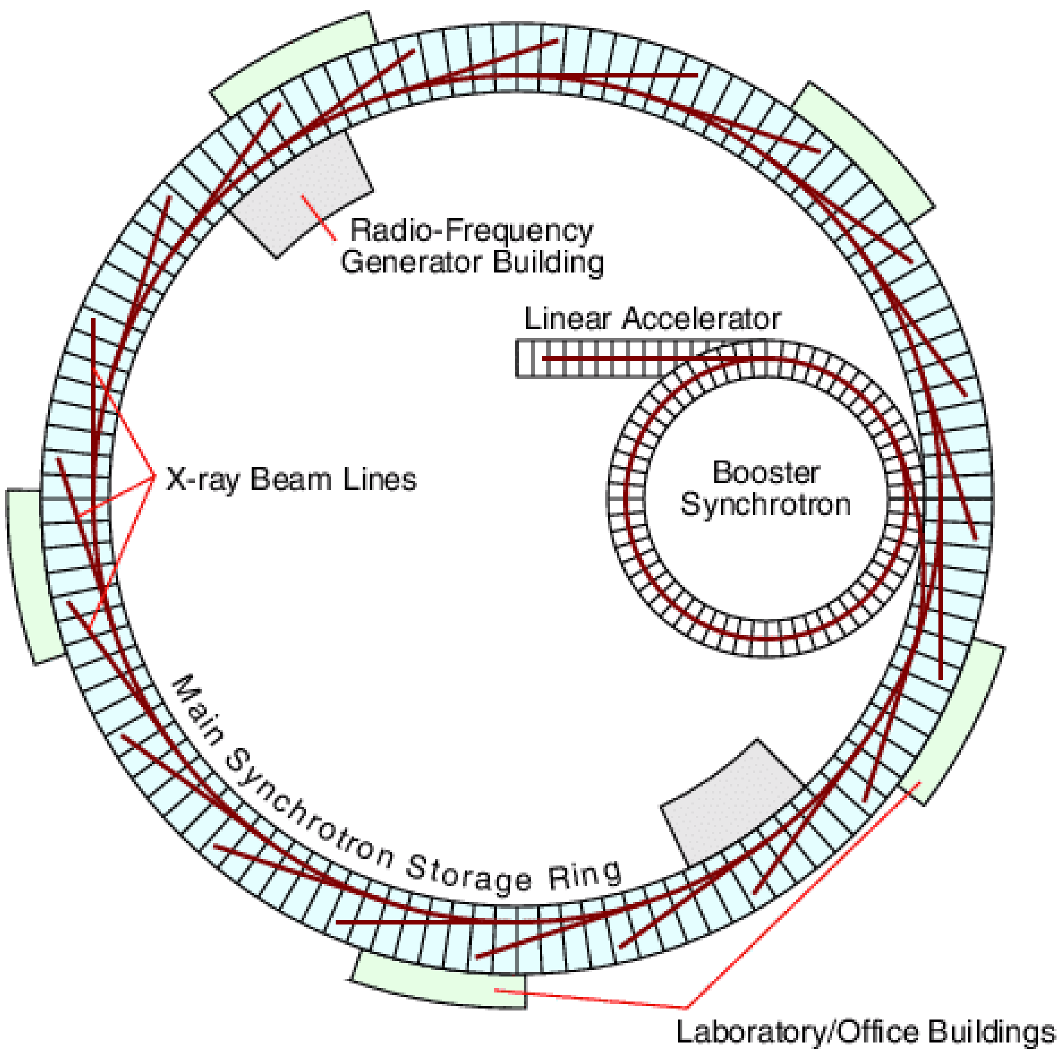
If we wish to accelerate the particles to still higher energies by cyclotrons or synchrocyclotrons, we have to build machines with larger magnets. Magnet is the costliest part of a cyclotron. Synchrotron is a cyclotron with provision to increase the strength of the magnetic field with increase in the particle energy. It allows a better control over the beam. That is, in a synchrotron the rate of change of magnetic field (dB/dt) is synchronized with the increasing kinetic energy in order to keep the orbital radius constant.

Synchrotrons have been designed to accelerate different particles and named accordingly like electron synchrotron, proton synchrotron etc.

Various parts of a synchrotron are as follows:

1. **Source:** That emits the desired charged particles.
2. **LINAC:** It accelerates particles to the energies upto MeV.
3. **Booster ring:** It is placed between LINAC and main synchrotron ring to act as a bridge, which boosts up the particles from MeV to GeV. When the electrons / particles have sufficient energy to produce light, an injection system transfers them from booster ring to the storage ring.
4. **Storage ring:** Particles are injected into the storage ring in the form of disrete pulses, therefore they exist inside the storage ring as bunches. In storage ring electrons circulate upto from 4 to 12 hours. The magnetic field needs to be applied only at certain places and not throughout the entire circular volume as in a cyclotron. Particles are confined to circular path by annular magnets placed at fixed locations and produce photons every time when magnets change their direction of flow. Thus the storage ring has a number of straight sections. A photon port present at the end of each straight section, allows photons to travel through beam lines. Particle energy achievable using a synchrotron is of the order of TeV (tera eV).

5. **Beam Line:** In synchrotron electrons are accelerated to extremely high energy and then make them change direction periodically. The resulting photons frequency fall in the range of X-rays. These X-ray beams emitted by the electrons are directed toward "beamlines" that surround the storage ring in the experimental hall. Each beamline is designed for use with a specific technique or for a specific type of research and ends up in experimental stations called end stations.



A

synchrotron is an extremely powerful source of X-rays.

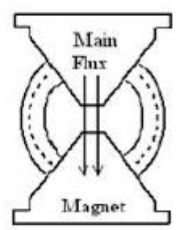
The working of synchrotron depends on one physical phenomenon: When a moving electron changes direction, it emits energy. When the electron is moving fast enough, the emitted energy is at X-ray wavelength.

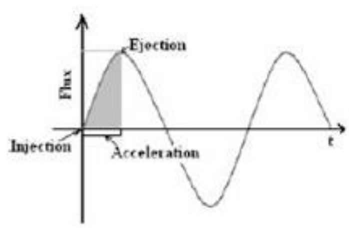
Betatron :

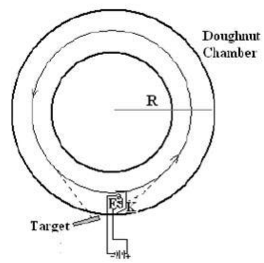
Betatron is a particle accelerating machine which is used to accelerate the high speed electrons (beta particls) to very high energies. It was constructed by D.W. Kerst in 1941. Unlike the cyclotron in which the orbit radius of the orbiting particle increases continuously, the electron in betatron are made to orbit in a stable radius.The orbit radius is kept fixed by changing the magnetic field in an appropriate manner.

Construction:

It consist of a doughnut shaped vacuum chamber placed between th pole pieces of two electromagnet, The electromagnets are energized by an alternating current. The magnet produces a strong magnetic field in the doughnut.The electrons are produced by the electron gun and are allowed to move in a circular orbit of constant radius in the vacuum chamber .







Theory :

Consider an electron orbiting in an orbit of radius 'r' in a magnetic field having an instantaneous flux density B at the position of the orbit. Since the flux density is made to change in a betatron, the flux through the orbit ϕ will change at a rate $\frac{d\phi}{dt}$ and will consequently introduced emf of magnitude $\frac{d\phi}{dt}$.

The work done on an electron of charge 'e' in one revolution

$$= Ee = -e\frac{d\phi}{dt} \quad \ldots\ldots\ldots\ldots..(1)$$

However we can also write work

$$W = F.2\pi r \quad \ldots\ldots\ldots\ldots \quad (2)$$

On equating eq. (1) and (2)

$$F = -\frac{e}{2\pi r}\frac{d\phi}{dt} \quad \ldots\ldots\ldots \quad (3)$$

The tangential force 'F' acting on the electron can also be calculated from the fact that

Force = Rate of chang of momentum

The momentum $p = mv$ can be calculated as

$$qvB = \frac{mv^2}{r}$$

$$v = \frac{Ber}{m}$$

The momentum P is, therefore , $P = mv = Ber$ ……. (4)

$$F = \frac{dP}{dt}$$

$$F = \frac{d}{dt}\ (Ber)$$

For an orbit of constant radius

$$F = er\ \frac{dB}{dt} \quad ……..(5)$$

Equating eq (3) and (5) we get

$$er\ \frac{dB}{dt} = \frac{e}{2\pi r}\ \frac{d\phi}{dt}$$

Or $d\phi = 2\pi r^2 dB$

On integrating $\int_0^{\phi} d\phi = 2\pi r^2 \int_0^{B} dB$

Or $\boldsymbol{\phi = 2\pi r^2 B}$ ….. (6)

Equation (6) is known as betatron condition .

If the field had remained constant, the flux through an orbit of radius ‘r’ would have been $\boldsymbol{\pi r^2 B}$**.** Eq. (6) therefore shows that in order to maintain a stable radius , we must arrange the field producing pole pieces in such a way that flux at the position of the stable orbit is twice what it would have been for uniform constant magnetic field.

<u>Geiger - Muller counter :</u>

Introduction :

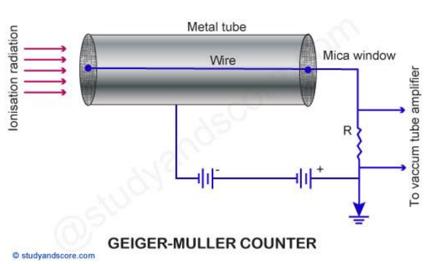
‘Geiger Muller Counter’ or ‘GM counter’ is a ‘particle detector’ to measure the ionizing radiation such as alpha, beta, and gamma particles. It was developed by Geiger and Muller in the year 1928.

It is widely used in applications like radiological protection, radiation dosimetry, and experimental physics.

Principle

GM counter is based on the fact that "Radiation ionizes the gas through which they pass and produces few. Ions." If the applied voltage is strong enough, these ion produce a secondary avalanche whose total effect will be proportional to the energy associated with the primary ionizing event.
If the applied potential difference is very high, the secondary ionization phenomenon becomes so dominant that the primary ionizing event loses its importance. In other words, the size of the final pulse produced depends only on the triggering off of ionization by an ionizing particle but independent of the energy of this particle.
A high energy particle entering through the mica window will cause one or more of the argon atoms to ionize. The electrons and ions of argon thus produced cause other argon atoms to ionize in a cascade effect. The result of this one event is sudden, massive electrical discharge that causes a current pulse. The current through R produces a voltage pulse of the order of 10μV. An electron pulse amplifier accepts the small pulse voltage and amplifies them to about 5 to 50 V. The amplified output is then applied to a counter. As each incoming particle produces a pulse, the number of incoming particles can be counted.

Construction :

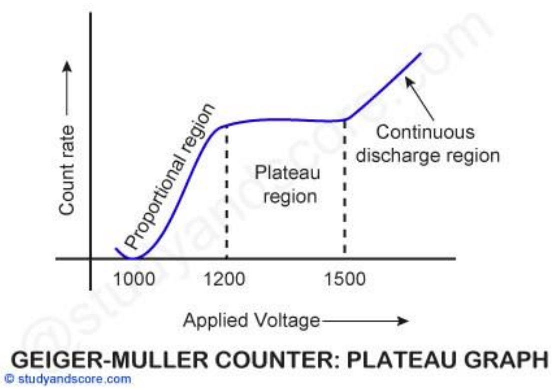


It consists of a hollow metal case enclosed in a thin glass tube. This hollow metal case acts as a cathode. A fine tungsten wire is stretched along the axis of the tube and is insulated by ebonite plugs. This fine tungsten wire acts as anode.

The GM tube is evacuated and then partially filled with a mixture of 90% argon at 10 cm pressure and 10% ethyl alcohol vapors at 1cm pressure. The fine tungsten wire is connected to positive terminal of a high tension battery through a resistance R and the negative terminal is connected to the metal tube. The direct current voltage is kept slightly less than that which will cause a discharge between the electrodes. At one end of the tube a thin window of mica is arranged to allow the entry of radiation into the tube.

Working of Geiger-Muller counter

The tube is filled with Argon gas, and around voltage of +400 Volts is applied to the thin wire in the middle. When a particle arrives into the tube, it takes an electron from Argon atom. The electron is attracted to the central wire and as it rushes towards the wire, the electron will knock other electrons from Argon atoms, causing an "avalanche". Thus one single incoming particle will cause many electrons to arrive at the wire, creating a pulse which can be amplified and counted. This gives us a very sensitive detector.



GEIGER-MULLER COUNTER: PLATEAU GRAPH

There is a threshold below which the tube doesn't work. This can be several hundred volts. After this, the number of pulses is proportional to the voltage. This region is known as proportional region. If the applied voltage is increased further, then a point will be reached after which the count rate remains constant over a certain region. This region is known as plateau region or Geiger region. This region is used for Geiger Muller operation.

Beyond the plateau region the applied electric field is so high that a continuous discharge takes place in the tube and the count rate increases very rapidly. It does not require any ionization event to happen so that the tube must not be used in this region.

The Geiger Muller counter can account for about 500 particles per second. The GM counter will not register those particles that pass through it in the dead time. Dead time refers to the time taken by the tube to recover between counts. It requires about 200 µs for the tube to recover. If lot of particles enters the GM tube at a rapid rate, the tube will not have time to recover and some particles may not be counted.

The efficiency of the counter is defined as the ration of the observed counts per second to the number of ionizing particles entering the counter per second. Counting efficiency is defined as the ability of counting of the GM counter.

Counting efficiency, η = 1- exp (spl)

Where,

s = specific ionization at one atmosphere

p= pressure in atmosphere

l = path length of the ionization particle in the counter

Mass spectrometer

In 1919 Aston developed the first really good mass spectrograph, an instrument for measuring the masses of isotopes. His apparatus gave accuracies of one part in 1000.
A simpler form of the mass spectrograph than Aston's is that due to Bainbridge (1933) and a plan view of this is shown in Figure 1.

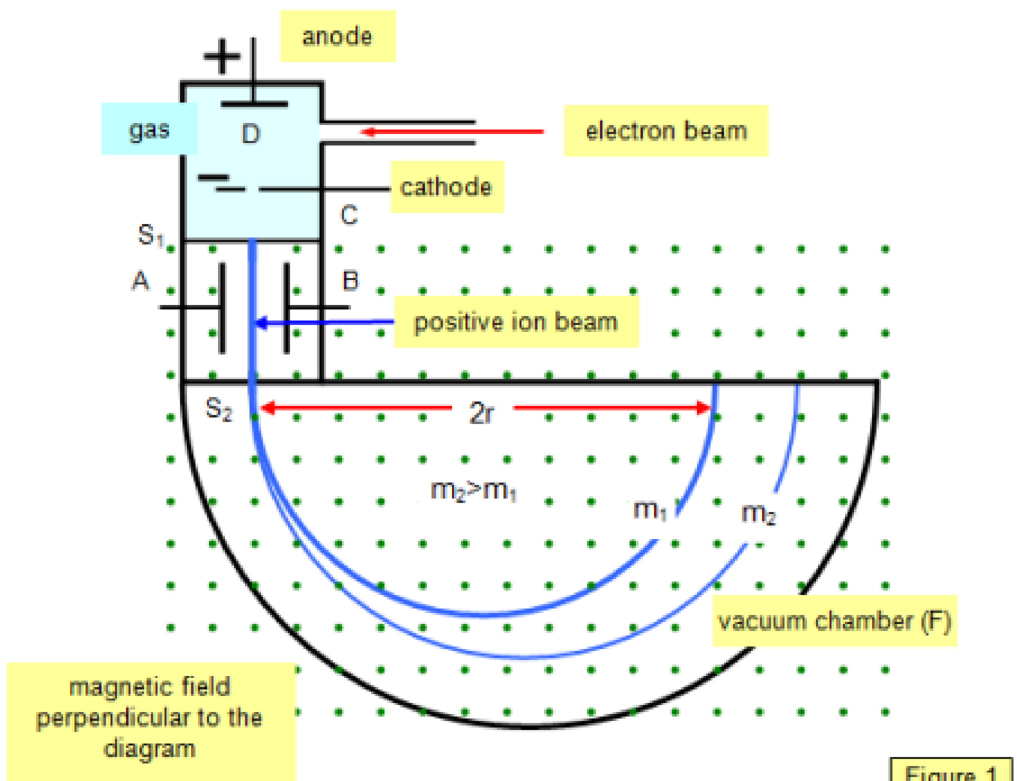


Figure 1

Ions are formed at D and pass through the cathode C and then through a slit S_1. They then travel between two plates A and B, between which a potential (V) is applied. A magnetic field (strength B) is applied at right angles to the electrostatic field and so the electrostatic and electromagnetic forces act in opposite directions to each other.

A particle with a charge q and velocity v will only pass through the next slit S_2 if the resultant force on it is zero – that is it is traveling in a straight line. That is if:

Electromagnetic force (Bqv) = Electrostatic force (qE)

Therefore, for the particle to pass through S_2:

Velocity of particle (v) = E/B

But this is a constant, and so only particles with a certain velocity enter the deflection chamber F. For this reason the combination of slits and deflecting plates is called a **velocity selector**.
In the deflection chamber the ions are affected by the magnetic fields alone and so move in circular paths, the lighter ions having the larger path radius. If the mass of an ion is M, its charge q and its velocity v then:

$Bqv = Mv^2/r$

where r is the radius of the path. Therefore r = Mv/(Bq)   and so:

$$\text{Mass of ion (M)} = rB^2q/E$$

The radius of the path in the deflection chamber is directly proportional to the mass of the ion.
The detection is by either a photographic plate or a collector that produces a small current when the ions fall on it. The magnetic field may be varied, so changing the radii of the particles' paths so that ions of different masses fall on a fixed collector.

This method of analysis is very accurate and can detect differences in the masses of two ions as small as one part in 10^9.
Figure 2 shows the appearance of the photographic plate when a gas containing two isotopes is used. Note the wider line for the mass m_1, showing its relatively greater abundance.

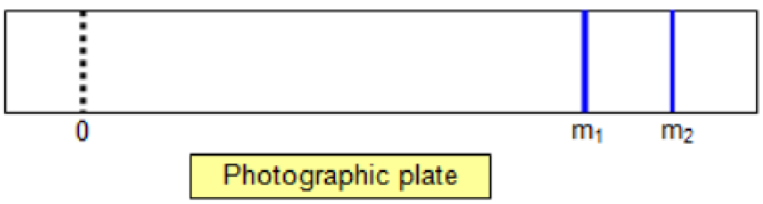


Figure 2

<u>Aston's Mass Spectrograph</u>

The apparatus used by Aston is shown in the figure…

The stream of positive ions from a discharge tube after passing through two narrow slits S_1 and S_2 enters the electric field between metal plates P_1 and P_2. Due to electric field **E**, all positive ions the same q/m value are not only deviated by an angle θ but are dispersed by an angle $d\theta$ due to their different velocities.

The beam is then allowed to pass through a magnetic field M acting at right angle to the electric field which deviates the particles by an angle ϕ and reconverges them by $d\phi$. Direction and magnitude of the field so adjusted that it produces a deviation of the beam in opposite direction and brings all ions having same q/m value (but different velocities) to a focus at one point F. ions having different q/m values are brought to focus at different points on the photographic plate.

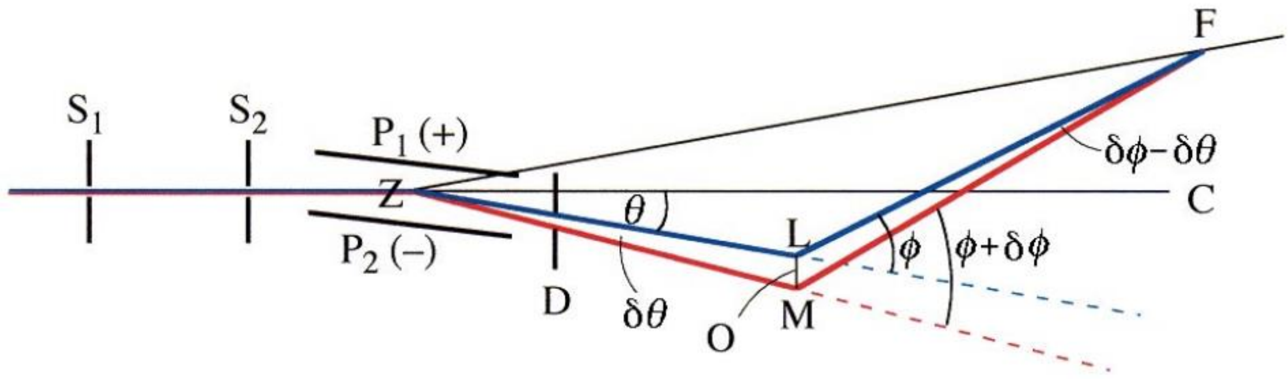


Fig. 6 The paths of the particles in Aston's mass spectrograph. The particles have the same mass value but varying velocities. The path of the fastest particles is shown in blue and that of the slowest in red. For clarity the electric and magnetic deflections are shown as abrupt changes in direction, rather than the actual continuous changes shown in Figs. 2 and 3.

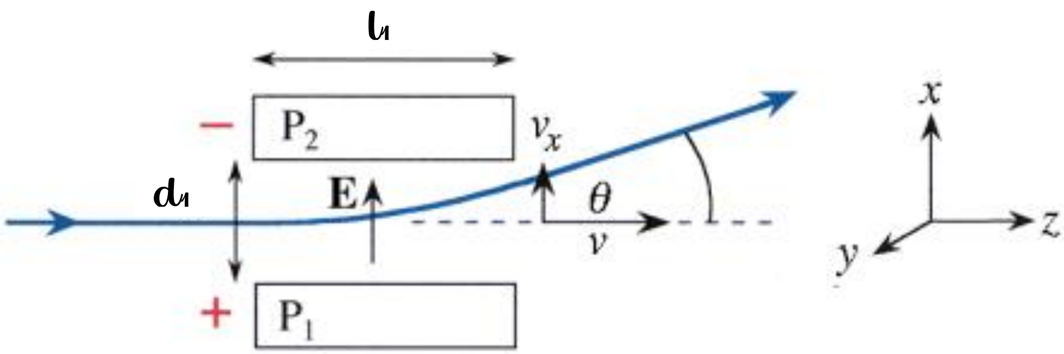


Fig. 2 The deflection of positively charged particles by an electric field.

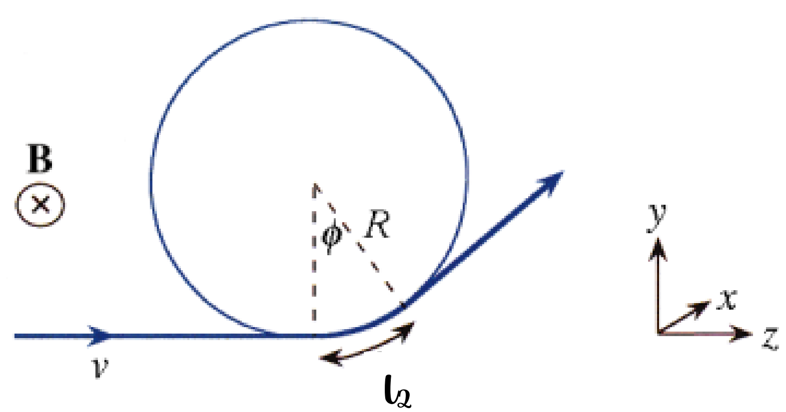


Fig. 3 The deflection of positively charged particles by a magnetic field. The direction of the field is down, perpendicular to the plane of the diagram.

Condition of focussing:

Consider a group of ions having the same q/m value but moving with different velocities.

I) Let **E** be strength of electric field, l_1 length of the electric field and let q, m and v be charge,

mass and velocity of the ion.

Then, linear displacement of ion from its path due to electric field

$$d_1 = \frac{1}{2}\frac{qE}{m}\frac{l_1^2}{v^2}$$

Angular deviation of the beam

$$\theta = \frac{d_1}{l_1} = \frac{1}{2}\frac{qE}{m}\frac{l_1}{v^2}$$

And angular dispersion of the beam

$$d\theta = -\frac{qEl_1}{m}\frac{dv}{v^3}$$

$$\therefore \qquad \frac{d\theta}{\theta} = -\frac{2dv}{v} \qquad \text{...1}$$

II) Similarly, if **B** is strength of magnetic field and l_2 is length of path in the magnetic field,

Then, linear displacement of ion from its path due to magnetic field

$$d_2 = \frac{1}{2}\frac{Bqv}{m}\frac{l_2^2}{v^2}$$

Deviation produced due to magnetic field $\phi = \frac{d_2}{l_2} = \frac{1}{2}\frac{Bq}{mv} l_2$

And angular dispersion

$$d\phi = -\frac{1}{2}\frac{Bql_2}{m}\frac{dv}{v^2}$$

$$\therefore \qquad \frac{d\phi}{\phi} = -\frac{dv}{v} \qquad \text{...2}$$

From eqns. 1 and 2, we get

$$\frac{d\theta}{\theta} = -\frac{2d\phi}{\phi}$$

Hence

$$\frac{d\emptyset}{d\theta} = \frac{\emptyset}{2\theta}$$

If the distance between the centres of E and B fields

$ZO = a$

The distance between points O and F

$OF = b$

In the absence of B field, width of the beam after travelling distance a+b will be = $(a + b)d\theta$

Magnetic field produces a convergence of dϕ in the distance b. Therefore, the width of the converged beam= $bd\emptyset$

Hence, the condition of focusing is given by

$$(a+b)d\theta = bd\emptyset$$

$$\frac{a+b}{b} = \frac{a}{b} + 1 = \frac{d\emptyset}{d\theta} = \frac{\emptyset}{2\theta}$$

$$\frac{a}{b} = \frac{\emptyset}{2\theta} - 1$$

$$\frac{a}{b} = \frac{\emptyset - 2\theta}{2\theta}$$

This is the required condition for focusing. This gives the position of the photographic plate for recording the beam.

Since electric and magnetic fields produce deflections in the opposite directions, therefore the ions passing through the diaphragm D, meet at a single point F, for a given value of q/m, provided the condition of focusing is met.