12.1 Birth of Modern Physics

By 1880, most physicists thought that important laws in physics were already discovered and all that remained was their refined applications. During 1890 to 1920, new phenomena were discovered which could not be explained by Newtonian mechanics, thermodynamics and Maxwell's theory of electromagnetism. Submicroscopic discoveries made could not be explained by classical physics. This led to the development of new discipline in physics known as Quantum mechanics.

The Discovery of an electron

The electron was discovered during experiments on passing electric current through gases in the discharge tube. Highly evacuated discharge tube becomes dark and a diffused spot is observed on the screen in front of the cathode. It indicated emission of invisible rays from the cathode which were named cathode rays.

In 1895, Jean Perin observed that under the influence of an electric field, the diffused spot on the screen shifted in the direction opposite to the field indicating that the cathode rays are the stream of negatively charged particles. As the charge can be possessed by mass, it was concluded that the cathode rays must possess mass. It also indicated that these charged particles existed as discrete entity. In 1874, G. Jhonstone Stoney experimentally demonstrated the existence of such charged particles. In 1891, he named this particle as 'electron'.

J. J. Thomson conducted experiments of passing charge through the discharge tubes filled with gases at low pressure. On reducing the pressure of gas in the discharge tube, Faraday dark space and Crookes dark space were observed. Hertz, who experimentally proved the existence of electromagnetic rays believed that electromagnetic rays are produced from cathode. Julius Plucker discovered that magnetic field affects the cathode rays. Thomson showed that the cathode rays in Hertz experiment were affected by electric field. This showed that the cathode rays cannot be electromagnetic rays.

J. J. Thomson experimentally determined the ratio of charge to mass of an electron and found it to be 1.8×10^{11} C / kg. Earlier, the ratio of charge to mass was determined for different ions with the experiments of electrolysis. This ratio for hydrogen ion was 9.6×10^{7} C / kg. Hence, Thomson concluded that the mass of electron should be 10^{-3} to 10^{-4} times the mass of hydrogen ion. Thomson called these particles (electrons) as primordial particles.

In 1909, Millikan estimated the charge of electron with the help of a series of his famous 'oil drop' experiments as -1.602×10^{-19} C. Combining the results of Thomson and Millikan, mass of the electron was known. As the atom as a whole was known to be electrically neutral, scientists concluded that it must have some particles carrying positive charge of the same amount as that of negative charge of electrons.

Discovery of X - rays

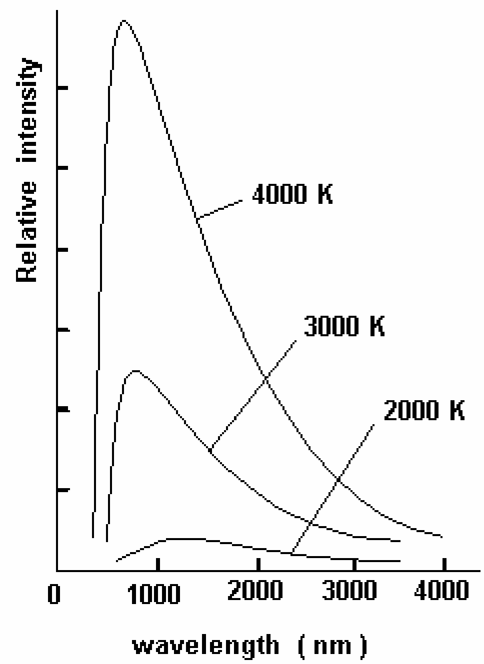
In 1885, Wilhem Rontgen while studying the characteristics of cathode rays accidentally discovered X-rays. He also determined the properties of X-rays and got a Nobel prize in 1901 for this discovery. Later scientists studied the diffraction of X-rays by crystals and Bragg obtained the spectrum of X-ray by making electrons collide with solid substances.

In 1896, Becquerel studied the type of the visible light emitted by different substances when X-rays are incident on them. He also observed that invisible radiations affecting photographic plates were emitted by the atoms of uranium. In 1898, Madam Curie also did similar experiments with some other compounds. Such radiations were named radioactive radiations and the phenomenon was called radioactivity by her.

In 1908, Rutherford measured the number of α-particles emitted by one gram of Radium and their total charge and concluded that the charge of α-particle is twice that of the β-particle.

Black body Radiation:

In 1897, Lummer and Pringsheim measured the intensities of different wavelengths of radiations emitted by black body using Bolometer (a device made from thermocouple) and plotted them as shown in the graph.



Wien derived the equation $E_\lambda = \frac{a}{\lambda^5} e^{-b/(\lambda t)}$ for the energy density at wavelength λ at time t, a being the proportionality constant. This equation is found to be valid for small wavelengths but fails for the longer wavelengths.

Rayleigh and Jeans gave the equation $E_\lambda = \frac{8\pi kT}{\lambda^4}$ which is valid for longer wavelengths but not the smaller.

Here, $\int_0^\infty \frac{8\pi kT}{\lambda^4} = \infty$. This shows that the total energy of radiation is infinite which is absurd. This is known as ultraviolet catastrophe.

Thus, all above attempts based on thermodynamics and electromagnetic theories failed to explain the energy distribution curves of black body radiation.

Finally, in 1900 A.D., Max Planck explained these experimental results.

Planck's hypothesis:

Planck suggested that the walls of cavity emitting radiations are made of electric dipoles. According to their temperatures, different dipoles oscillate with different frequencies and emit radiations of frequencies same as the frequencies of their oscillations.

According to classical physics, an oscillator may possess any amount of energy in a continuously varying energy. But Planck hypothesized that the oscillator can possess only such discrete values of energies depending on its frequency as given by the equation
$E_n = nhf$, where n = 1, 2, 3, ... and $h = 6.625 \times 10^{-34}$ Js is Planck's universal constant.

Thus, the energy of radiation of frequency f may be considered to be made up of many quanta of energy hf and a radiation may be made of quanta of different frequencies. The quantum of radiation energy is called 'photon'.

The radiation of different frequencies is the collection of photons of various frequencies. If an oscillator possesses energy 3hf, it may be considered equivalent to a collection of 3 photons.

Based on his hypothesis, Planck derived the equation of spectral emissive power of a perfect black body:

$$W_f = \frac{2\pi h}{c^2} \cdot \frac{f^3}{\exp\left(\frac{hf}{kT}\right) - 1},$$ (This equation is only for information.)

where c = velocity of light in vacuum,

T = absolute temperature of a perfect black body,

k = Boltzmann's constant

Energy distribution curves could be explained satisfactorily by the above equation. Even Stefan-Boltzmann's law can be derived from this equation.

Progress of Quantum Theory:

i) In 1905, Einstein explained the photoelectric theory using Planck's Quantum Theory.

ii) After the discovery of an electron, radioactivity in which α - and β - particles and γ - rays are emitted was discovered. From the knowledge that the atom is neutral, it was concluded that the positive and negative charges in an atom must be in equal amount.

iii) Thomson and then Rutherford gave the model of an atom. Later, In 1913, Bohr introduced quantum theory to explain the structure of the atom.

iv) Frank and Hertz provided experimental support to Bohr's theory.

v) In 1916, Einstein proposed that the photon also possesses quantized momentum.

vi) In 1923, Compton gave an experimental support to the photon theory by attributing the properties of a particle to a photon.

vii) In 1923, De-Broglie hypothesized wave nature of material particles.

viii) In 1927, Davisson and Germer gave experimental proof of De Broglie's matter waves.

ix) Heisenberg gave uncertainty principle and Schrodinger established a differential equation to understand the behaviour of matter particles and within six months solved some problems regarding them.

x) Max Born and Dirac also contributed in the development of quantum mechanics.

xi) The relativistic quantum mechanics was also developed. Einstein's theory of relativity also played a useful role in the development of the modern physics.

12.2 Emission of Electrons

Metals have free electrons (valence electrons). To be freed from the metal, they need some minimum energy, called work function of the metal. Its unit is electron volt (eV).

The work function of a metal depends upon the type of the metal and its temperature. To free them, energy may be supplied by any one of the following methods.

(1) Thermionic Emission:

When current is passed through a filament so that it gets heated sufficiently, free electrons from the metal of the filament get emitted. Such emission occurs in diode, triode and TV tube (Cathode ray tube).

(2) Field Emission:

When a metal is subjected to strong electric fields of the order of 10^8 V / m, electrons get emitted from the metal.

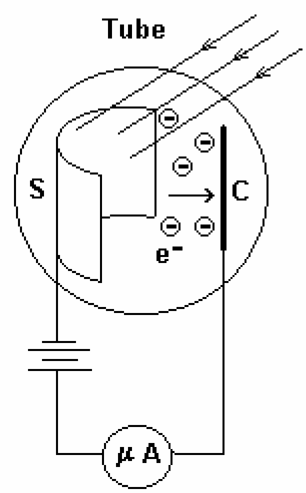
(3) Photoelectric Emission:

When electromagnetic radiation of sufficiently high frequency is incident on a clean metal surface, free electrons are emitted from the surface. This method is called photoelectric emission and the electrons so emitted are called the photo electrons.

12.3 Photoelectric Effect

In 1887, Hertz discovered photoelectric effect while studying emission of electromagnetic waves by spark discharge. He observed that if cathode is irradiated with ultraviolet radiations, spark of high voltage passes through the gap between the electrodes.

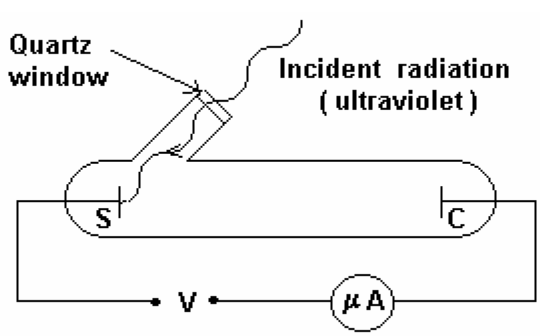
In 1888, Hallwachs further developed this idea. He observed that when negatively charged zinc plate with an electroscope is irradiated with ultraviolet light, negative charge on the plate decreased. If neutral plate was used, it became positive and a positive plate more positive. He concluded that under the effect of ultraviolet light, negatively charged particles are emitted and called them photo electrons.



The figure shows evacuated photo tube containing photo sensitive surface S which is kept at a negative potential with respect to collector C. When light of sufficiently high frequency is made incident on S, it emits photo electrons which are accelerated towards the collector and current of an order of micro ampere flows through the circuit.

For emission of photo electrons, the frequency of the incident light should be more than some minimum called threshold frequency (f_0) whose value depends on the type of the metal. For most of the metals, threshold frequency lies in ultraviolet band of electromagnetic spectrum. For example, the threshold frequencies of zinc, cadmium, magnesium lie in the ultraviolet region while those of alkali metals like lithium, sodium, potassium, rubidium, calcium lie in the visible region.

12.3 (a) Experimental Study of the photoelectric effect and its results:



The experimental arrangement to study the photoelectric effect is shown in the figure. The ultraviolet rays entering quartz window are incident on the photo-sensitive surface S, known as cathode. Collector C is kept at different positive or negative voltage with respect to S.

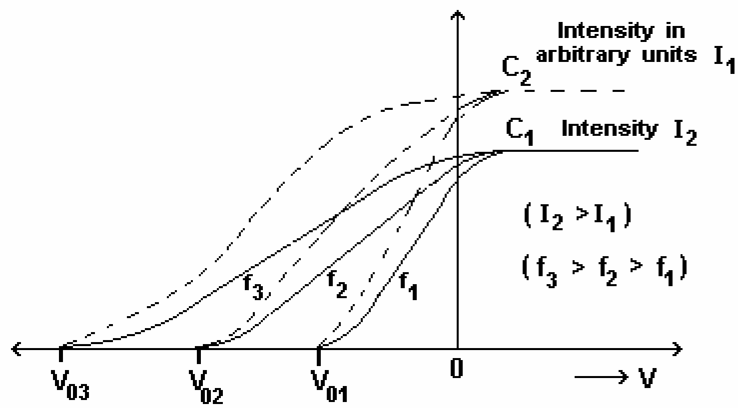
The photoelectric effect can be studied with reference to the frequency and intensity of the incident light, number of photoelectrons emitted and their maximum energy.

When proper positive potential is applied to collector C, all the photoelectrons are attracted towards it and the maximum current recorded by the micro-ammeter gives an idea of the number of photo electrons.

When negative potential is applied to the collector, only such electrons which have sufficient energy to overcome the negative potential may reach the collector. On making collector more negative, photoelectric current decreases and becomes zero at or lower than some specific negative potential. This minimum negative potential of the collector with respect to the photo-sensitive surface at which photoelectric current becomes zero is called stopping potential.

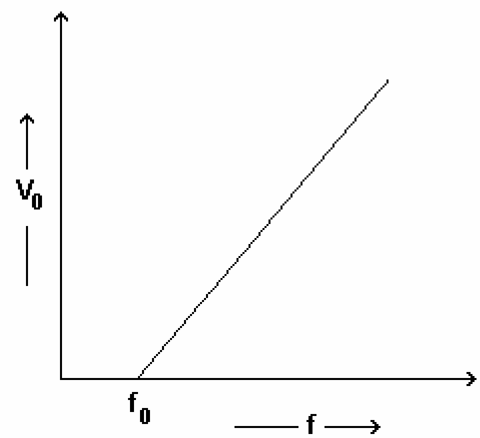
According to the definition of stopping potential, electron on the surface of the photosensitive surface having maximum velocity, v_{max}, just reaches the collector plate overcoming stopping potential V_0. In the process, the work eV_0 done by it is at the cost of its kinetic energy, $(1/2)\, m v^2_{max}$.

$$\therefore \quad \frac{1}{2} m v^2_{max} = e V_0$$



The graphs of photoelectric current versus the potential of collector with respect to the emitter for different intensities and frequencies of incident light are shown in the figure.

It can be seen from the figure that for a given intensity, stopping potential depends on frequency and is thus independent of intensity of light. Also, for a given frequency, maximum saturation current depends on the intensity of light and is thus independent of its frequency.



(1) The maximum energy of photo-electron depends on the frequency of incident light and not on its intensity.

(2) The number of photo-electrons increases with increase in intensity of incident light.

(3) The phenomenon of photo-emission is instantaneous. Within 10^{-9} s, after light is incident, photo-electrons are emitted.

The graph of stopping potential versus frequency is shown in the figure. This graph is linear.

12.3 (b) Photoelectric Effect and Wave Theory of Light:

Wave theory fails to explain the characteristics of photoelectric effect.

(1) According to the wave theory, energy and intensity of light wave depend on its amplitude. Hence energy of photo-electrons should increase with intensity of light. But experimental results indicate that the energy of photo-electrons does not depend upon the intensity of light.

(2) According to the wave theory, energy of light has no relation with its frequency. Hence, change in energy of photo-electrons with the change in frequency cannot be explained.

(3) Photo-electrons are emitted spontaneously. This cannot be explained by wave theory. Free electron in a metal is emitted only when it gets certain minimum energy called "work function" (ϕ) of the metal. If the light has wave nature, free electron in metal may get energy gradually and some time elapses before it gets energy equal to its work function and gets emitted. This is in contradiction to the spontaneous emission.

(4) With less intense light, the emission of electrons will be slower as per the wave theory. But with light of sufficiently high frequency, emission of photo-electrons is immediate even if its intensity is low.

12.3 (c) Einstein's Explanation:

In 1905, Einstein explained photo-electric effect using Planck's hypothesis.

Planck had assumed that the emission of radiant energy occurs as photons, but after emission it transmits as a wave. Einstein assumed that emission, transmission and absorption of light take place in the form of photons.

According to Einstein, when light in the form of photon is incident on a metal, it is totally absorbed or does not lose its energy at all. The electron which receives hf amount of energy of photon spends energy equal to its binding energy and gets immediately emitted with the remaining energy.

Thus, $eV_0 = \frac{1}{2} m v^2_{max} = hf - \phi = hf - hf_0$

$$\therefore \quad V_0 = \left(\frac{h}{e}\right)(f - f_0)$$

According to this equation, the graph of V_0 versus f (as shown on the previous page) is a straight line with slope h / e and intercept on X-axis, f_0. Thus, experimental plot of the graph of 'V_0 versus f' could be satisfactorily explained by Einstein for which Einstein got a Nobel prize.

The intensity of light incident on the metal surface is the amount of light energy incident per second per unit area normal to the surface. According to the photon theory of light, intensity of light

I = nhf, where, n = number of photons incident per second per unit area and
hf = energy of photon of light of frequency f.

Thus, according to the photon theory, more the intensity of light, more is the number of photons incident per second. Hence, more photo-electrons are emitted and the current increases with intensity. Thus, photo-electric effect could be satisfactorily explained with the photon theory.

12.4 Photon

In photo-electric effect, photon interacted with electron as a quantum of energy. In Compton effect, photons of X-rays were scattered by electrons as if they are real particles. In fact, Compton effect was successfully explained by treating photons as real particles and applying the laws of conservation of momentum and energy. Thus, as a result of the study of photo-electric effect and Compton effect, following properties were attributed to a photon.

(1) Photon can be considered a real particle having mass $m = \frac{hf}{c^2}$. ($\because$ $E = mc^2$)

(2) Energy of a photon of frequency f is hf.

(3) According to Einstein's special theory of relativity the relation between energy (E) and momentum (p) of a particle is $E = \sqrt{p^2c^2 + {m_0}^2c^4}$,

where c = velocity of light in vacuum,

m_0 = rest mass of the particle.

If the rest mass of the particle is zero, $E = pc$

(In fact, rest mass of the photon moving with the velocity of light is practically meaningless as to observe it, we should be in a reference frame moving with the velocity of light.)

$\therefore$ Momentum of photon of frequency f is $p = \frac{E}{c} = \frac{hf}{c}$.

(4) Like a real particle, photon interacts with other particles following the laws of conservation of momentum and energy.

12.5 Photo cell

A schematic diagram of a photo cell is shown in the figure. In some photo cells, instead of different photo-sensitive layers, a single layer of photo-sensitive material is made on the wall of the photo cell. The wall of the photo cell is made of glass or quartz.

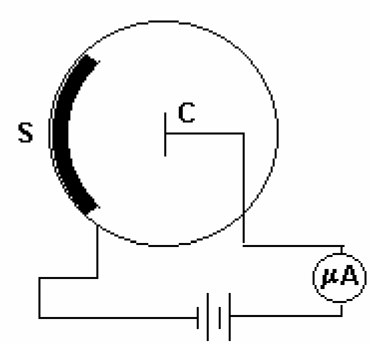
The photo electric current changes with the intensity of incident light. This property is used in designing control systems using photo cell. Photo cells can be used

(1) in light meters used in photographic camera,
(2) to switch off and on street light automatically in the morning and evening respectively,

(3) for counting the number of persons and vehicles on the road when they cut off the light incident on a photo cell from across the road and also for measuring the speed of the vehicles using two photo cells with a definite distance between them,

(4) as burglar alarm as well as fire alarm,
(5) to study astronomical phenomena and measure temperature of stars and study their spectra,

(6) to control temperatures of furnaces and chemical reactions,
(7) in television and film.



C : Collector
S : Photo-sensitive layer

12.6 Dual Nature of Radiation and Matter (De Broglie's Hypothesis)

Phenomena of light like interference, diffraction and polarization can be explained by wave theory and not by particle nature of light. Interference is the true test of wave nature of light.

Energy distribution in perfect black body radiation, photo electric effect and Compton effect can be explained by particle nature of light and not by wave theory. The concept of quantum mechanics is applied even to the motion of electrons in an atom in Bohr's atomic model.

In 1823, Louis de Broglie hypothesized that just as the electromagnetic radiation shows particle aspect, particles like electrons should exhibit wave aspect. "Nature should be symmetric with respect to radiation and particles. The dual nature of radiation must be a part of some general law of nature." Both radiation and particles may not exhibit both the wave and particle nature simultaneously in the same situation.

Momentum of photon is $p = h / \lambda$.

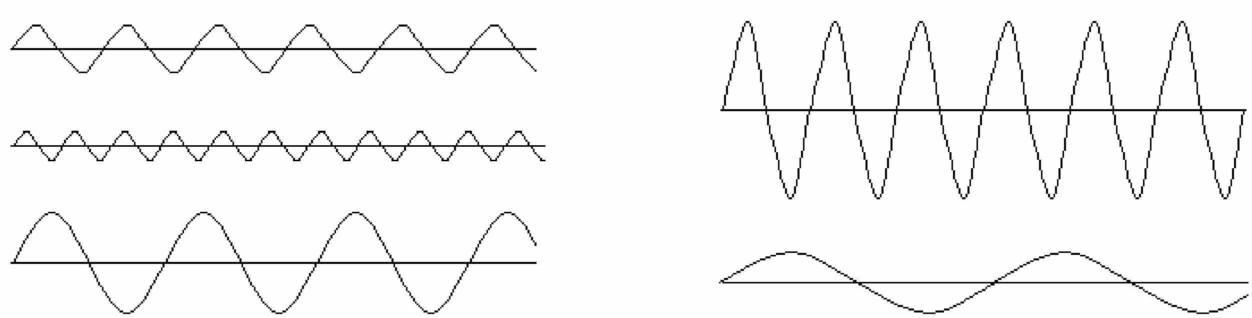
De Broglie hypothesized that this equation is applicable to particle also. If m is the mass of the particle and v its velocity, then its momentum, $p = mv = h / \lambda$..

$$\therefore \quad \lambda = \frac{h}{mv}$$

Wavelength of the matter wave for the particle as given by this equation is called de Broglie wavelength. When particle acts as a wave, its particle nature should be forgotten and it should be understood as a wave having wavelength as given by the above equation.

According to classical mechanics, particle is a point like object having position and momentum, whereas wave is a disturbance in some space. To consider wave activity of a wave representing a particle, a concept of wave packet is introduced.

When many harmonic waves with continuously changing wavelengths superpose over each other, non-zero displacement of the resulting wave limited to a small part of the space can represent a particle.

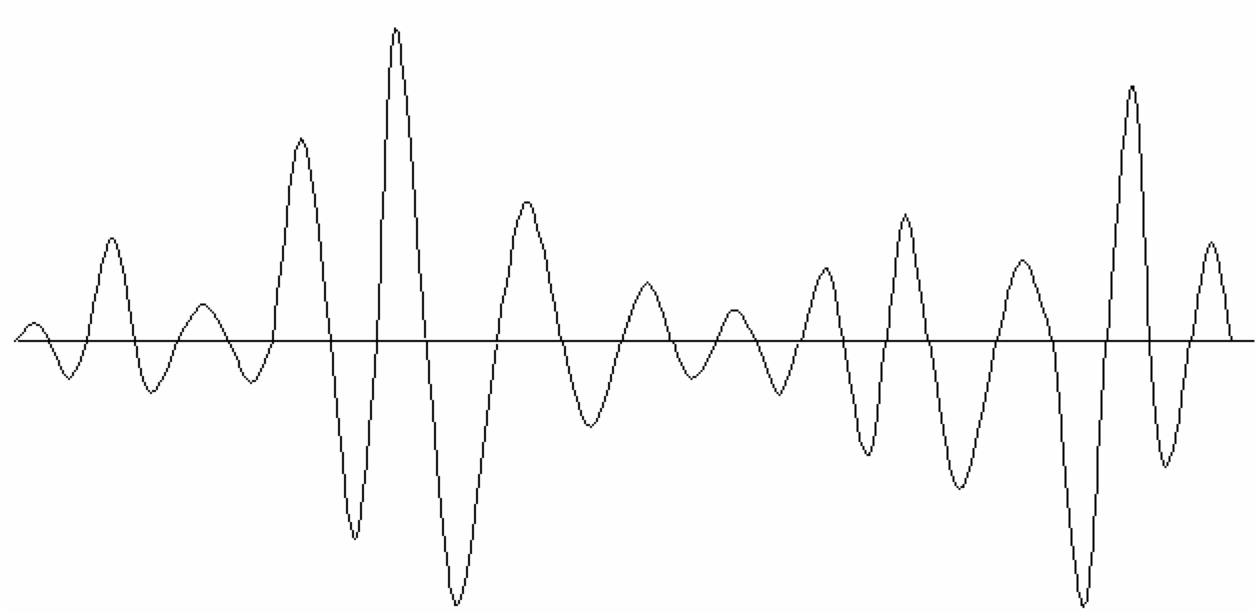


The above figure shows some harmonic waves. A resulting wave obtained by the superposition of such waves representing a wave packet is shown on the next page.

The probability of finding a particle is more in the region of its greater displacement. For a single harmonic wave, such a probability is the same anywhere on its path. This means that the position of the particle is uncertain. But the wavelength of the single harmonic wave being definite, its momentum according to the equation $p = h / \lambda$ is definite.

A wave packet is a group of waves of slightly different wavelengths. Hence a particle cannot have definite wavelength. To represent a particle, if more waves are superposed and the wave

packet is made finite, the position of the particle will be more definite. But in such a wave packet the wavelength of the wave packet and hence its momentum becomes uncertain.



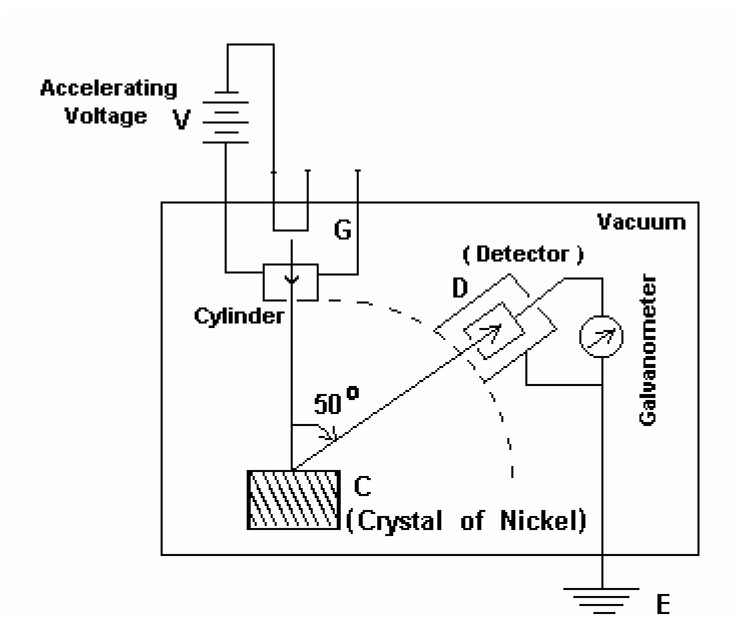
This led to Heisenberg's uncertainty principle according to which if the uncertainty in the x-coordinate of the position of a particle is Δx and uncertainty in the x-component of its momentum is Δp, then

$\Delta x \cdot \Delta p \approx h / 2\pi = \hbar$ **(h cross or h cut)**

$\therefore \quad \Delta x \to 0 \Rightarrow \Delta p \to \infty$ **and** $\Delta p \to 0 \Rightarrow \Delta x \to \infty$

12.7 Davisson-Germer Experiment

In 1927, Davisson and Germer performed experiments to study scattering of electrons by a piece of Nickel placed in vacuum. The device used by them is shown in the figure.



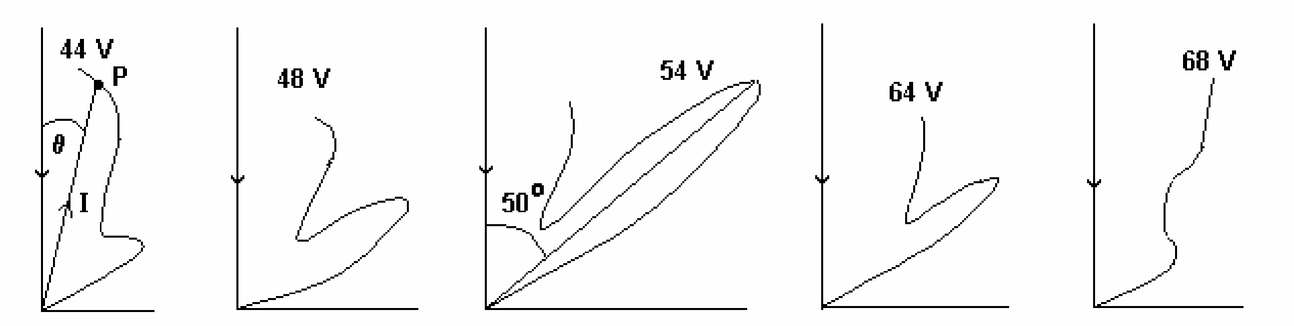
G is the electron gun having tungsten filament coated with barium oxide. Filament when heated with low voltage emits electrons which are accelerated using high voltage. The electrons pass through a cylinder and form a thin beam which is made incident on a piece of Nickel and get scattered by the atoms of Nickel. The electrons scattered in different directions are detected by a detector D which can be moved on a circular scale as shown in the figure. The current though the detector is measured by the galvanometer which indicates the number of electrons scattered in that direction.

According to classical physics, the number of electrons scattered in different directions does not depend on the angle of scattering or the energy of the incident electrons. Davisson and Germer confirmed this using the piece of Nickel as the scatterer.

During the experiments, a bottle of liquefied air burst and damaged the piece of Nickel. They heated the Nickel piece to high temperature and cooled to level its surface. Experiments with this piece of Nickel resulted in electron diffraction similar to the diffraction of X-rays by a crystal. This happened because on heating and cooling the piece of Nickel, it was converted into a single crystal.

In this experiment, the intensity of electron beam scattered at different angles of scattering can be measured for the given accelerating voltage. Angle of scattering (θ) is the angle between the incident beam and scattered beam of electrons. The graph in polar coordinates of intensity $\rightarrow \theta$ for the observations taken by Davisson and Germer between 44 V and 68 V are shown qualitatively in the figure given below.

The graphs indicate angle at which maximum scattering occurs for a given voltage. It is 50° for 54 V.



(a) (b) (c) (d) (e)

If the accelerating voltage is V and charge of an electron is e, energy of electron is

$$\frac{1}{2}mv^2 = eV \qquad \therefore \; mv = \sqrt{2meV}$$

$$\therefore \text{ wavelength, } \lambda = \frac{h}{mv} = \frac{h}{\sqrt{2meV}}$$

Putting V = 54 volt, h = 6.62×10^{-34} J-s, m = 9.1×10^{-31} kg and e = 1.6×10^{-19} C, the value of λ works out to be 1.66×10^{-10} m which matched very well with the value obtained in the above experiment.

12.8 Electron Microscope

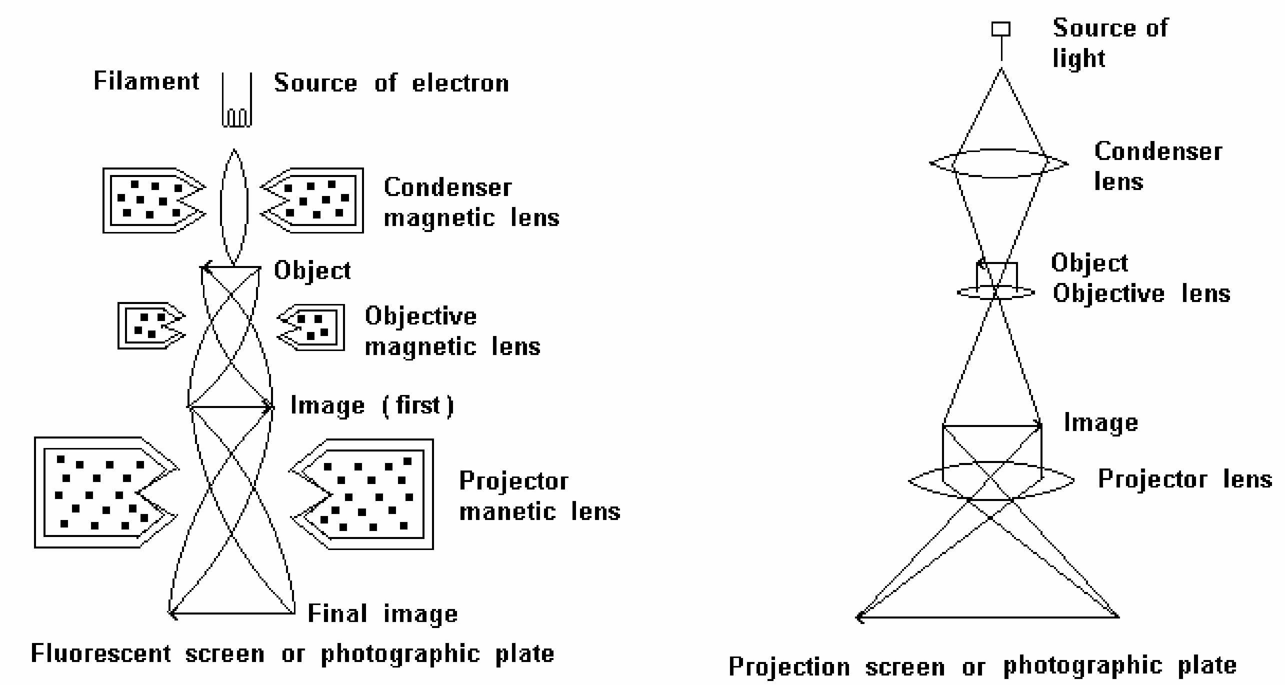
Two nearby objects can be seen as distinct and separate with the optical instruments having high resolving power. In compound microscope, diffraction limits the resolution. More the wavelength of incident light, less is the resolution. The resolving power and magnification can be increased by using ultraviolet light having low wavelength.

An electron can act as a wave and its desired wavelength can be obtained by accelerating it. The microscope which uses the wave nature of an electron is called an electron microscope.

The wavelength of an electron being very small, highly resolved and magnified image can be obtained using the electron microscope.

Just as lens is used to focus light in optical microscope, electric and magnetic fields are used to focus the electrons in an electron microscope.

Schematic diagram of an electron microscope and a corresponding optical microscope are shown side by side in the following figures.



Electron microscope

Optical microscope

Electrons emitted from the filament are accelerated with a p.d. of 10^6 V. Wavelength of the electron beam depends upon the velocity of the electrons. The magnetic lens focuses these electrons just as light rays are focused by a simple lens. The beam of electrons is incident on the object lying in its passage and it is partially absorbed by it.

On the other side of the object, there is a magnetic objective lens which gives a magnified image of the object. This image acts as an object for another magnetic lens (projector magnetic lens). This lens works as an eye piece just as in optical microscope and gives final magnified image of the object on a fluorescent screen or a photographic plate. This image is seen as shadow as in X-ray photographs.

The above arrangement is kept in an almost evacuated chamber so that the electrons may not collide with the air particles.

Electron microscope can magnify even the object of the size of 10 nm to 10^6 times with enough resolution. With electron microscope, one can study structures of an atom, crystal and textile fibres, purity of different surfaces, colloids, polymers, paper, paints, plastic, lubricating oil, bacteria and virus.