: Quantum Theory and Black Body Radiation :

Classical mechanics are applied to the objects which are observable with the instruments. The classical concept cannot be applied to the sub atomic particles and elementary particles which are not observable with instruments. The study of phenomena relating to the atoms, nuclei and elementary particles are referred as quantum physics. The basic mathematical theory of quantum physics is known as quantum mechanics.

In Rutherford atom model we have seen that the classical mechanics failed to explain the stability of the atoms. As a result of this, Bohr's applied Planck's quantum concept to the atom model. Again in the study spectral distribution of energy in black body radiation the classical electromagnetic theory led to wrong result. Later on Max Planck gave a revolutionary idea for energy distribution of black body radiation which is known as Planck's law. According to him energy change in black body radiation takes place in a discrete manner, as an integral multiple of a bundle of small energy hγ which is called as quantum or photon. This law was successful in explaining the spectral energy distribution in black body radiation.

Important applications of quantum theory of radiations:

a) Photoelectric effect
b) Compton effect etc.

Photo electric effect: When metal surfaces are exposed to high frequency electromagnetic radiation like ultraviolet and visible light, charged particles are released from the metal surface. This phenomenon was first observed by Henrich Hertz in 1873. Later on this phenomenon was discovered by Hallwachs and his collaborators in 1887. They observed that when zinc is irradiated with ultraviolet light it lost negative charges This phenomenon was named as photoelectric effect. The experimental arrangement to study photoelectric effect by Hallwachs and his collaborators is shown in the fig.1.When light falls on the metal plate E electrons are ejected and are collected by the positively charged detector C. The current resulting from the flow of ejected electrons are measured by a sensitive ammeter.

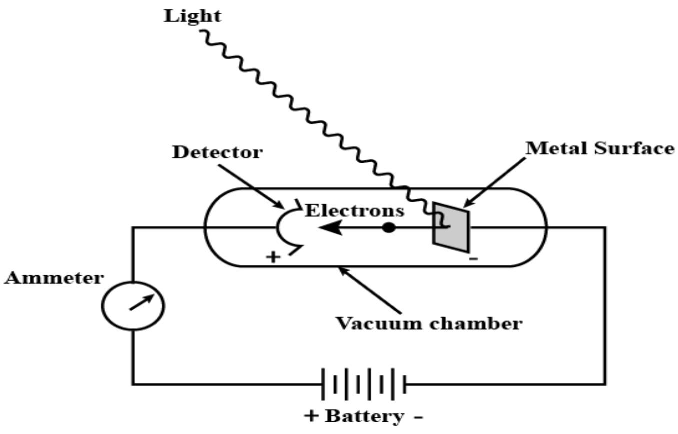

Fig 1

i) Variation of current with intensity of light: Initially the collector C is kept highly positive. When the light falls on metal surface the electron are ejected from the surface. The rate of electrons emission is proportional to the intensity of light used. Greater the intensity of the light greater the numbers of electrons ejected and hence stronger the current that results. fig2

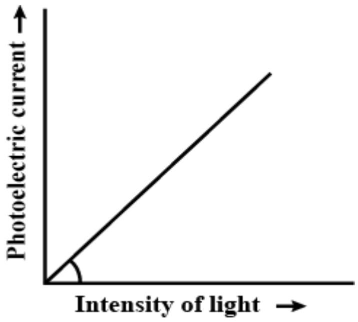

fig2

ii) Variation of velocity and hence kinetic energy of electrons with intensity of light: Whatever be the intensity of the incident light used, the velocity and kinetic energy of the emission electrons remain the same, provided the frequency of the incident light remains the same.

iii) Variation of current with negative potential: When C is made negative with respect to metal surface E, the electrons move in a retarding electric field. It is observed that current decreases rapidly and vanishes at V= -Vo. If intensity of the incident light is increased the current increases in positive potential region but again becomes zero at V= -Vo. The potential Vo is called as stopping potential for that particular frequency. At potential Vo, the electron from E just fail to reach C, so photoelectric current is zero. As the potential at C is made more and more negative, the fastest electron will be prevented from reaching C. The magnitude of stopping potential Vo increases linearly with frequency of the light used.

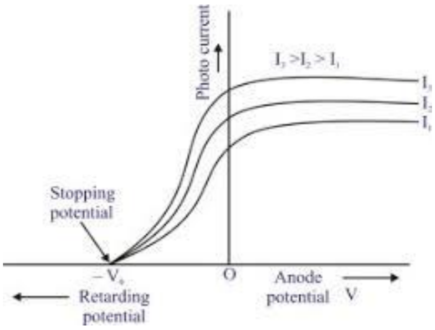

Fig3

iv) Variation of maximum velocity and kinetic energy of the electrons with frequency of the incident light: The maximum velocity and kinetic energy of the ejected photoelectrons is directly proportional to the frequency of the incident light. However there exists a minimum frequency which varies with the nature of the emitter which is called as threshold frequency. Below the threshold frequency, no electrons are emitted from the metal surface.

Conclusions: This effect cannot be explained on the basis of electromagnetic theory of light. According to electromagnetic theory of radiation the more intense light radiation having stronger electric field, would produce more energetic electron. Also the existence of threshold frequency is difficult to explain. Later on it was left to Albert Einstein to propose an entirely different explanation to this problem.

Einstein's theory of photo electric effect: To explain this effect Einstein in 1905 proposed an entirely different explanation on the basis of Plank's quantum hypothesis. According to him, monochromatic light of frequency γ consists of photons of energy

$$E == h\gamma \text{ ....(1)}$$

Which moves with velocity of light . When such a photon strikes an atom it gives up its energy completely to an orbital electron. This energy may be sufficient to release the electron from the metal surface. If the minimum work to be done to release the electron from the metal surface is Wo, when a photon of energy $h\gamma$ strikes the atom then the remaining energy $h\gamma$ – Wo is available in imparting kinetic energy to the photoelectron. If m is the mass and $Vmax$ is the maximum velocity of the photoelectron, then

$$\frac{1}{2}mVmax^2 = h\gamma - Wo \text{ ....(2)}$$

This is known as Einstein's Photoelectric equation

If Vo be the stopping potential, then

$$\frac{1}{2}mVmax^2 = eVo \text{ ....(3)}$$

So comparing equations (2) & (3) we get

$$eVo = h\gamma - Wo$$

$$Vo = \frac{h}{e}\gamma - \frac{Wo}{e} \text{ ....(4)}$$

Which shows that stopping potential is linear function of frequency of the incident radiation. The photon with threshold frequency impart just enough energy to eject an electron from the metal surface with zero velocity, so

$$Wo = h\gamma_\circ \text{ ....(5)}$$

When the experimental data relating to maximum kinetic energy of the photoelectrons are plotted against the frequency of the incident radiation then a straight line is obtained as shown in fig 2, which cut the frequency axis at $\gamma_\circ$ .The Einstein's equation is sometimes written as

$$\frac{1}{2}mVmax^2 = h(\gamma - \gamma_\circ) \text{.....................(6)}$$

When γ is less than $\gamma_\circ$, $\frac{1}{2}mVmax^2$ will be negative, which means that no photoelectrons will be ejected. $\gamma_\circ$ is called as threshold frequency which value varies from substance to substance. The quantity $h\gamma_\circ$ is called as photoelectric work function which is equal to the work to be done to extract an electron from the bondage of the emitter.

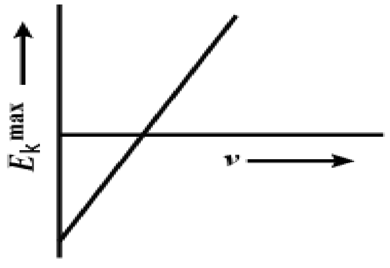

Fig4

For the incident light having frequency between zero and threshold frequency, there are no photo electrons emitted, since incident photon has less energy then the work function of the material. Above the threshold frequency, photo emission takes place. The stopping potential which measure maximum kinetic energy is directly proportional to frequency of the light.

Velocity distribution among photoelectrons:

From photoelectric effect we only get information about fastest electron, but there are slower electron also who cannot reach the collector. The photoelectrons that are coming out of the plate have all possible energy up to a maximu $\frac{1}{2}mVmax^2$= eVo , here Vo being the stopping potential. Distribution of various electrons in a metal followed the Fermi Dirac statistic. The free electrons in a metal surface situated in various energy states. The highest energy level is called as Fermi level. The electrons which are in Fermi level need smallest external energy from the incident photon to come out of the surface and the other electrons in the lower energy state requires more energy to come out.

So for an electron which is in Fermi level the energy equation is

$$\frac{1}{2}mVmax^2 = h\gamma - \text{Wo}$$

And an inner electron requires higher energy from the incident photon to comes out of the surface, so the energy equation for such an electron is

$$\frac{1}{2}mVmax^2 \leq h\gamma - \text{Wo}$$

Thus photo electric effect establishes the photon or quantum nature of light.

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