DUAL NATURE OF RADIATION AND MATTER

3 PHOTOELECTRIC EFFECT

When light of sufficiently small wavelength is incident on a metal surface, electrons are ejected from the metal. This phenomenon is called photoelectric effect and the electrons ejected are called photoelectrons. An experimental setup was arranged to study photoelectric effect, and the results obtained from the experiment are

(i) When light of sufficiently small wavelength falls a metal surface, the metal emits photoelectrons. This emission of photoelectrons is instantaneous.

(ii) The photoelectric current i.e., the number of photoelectrons emitted per second depends on the intensity of the incident light.

(iii) The maximum kinetic energy with which electrons come out of the metal depends only on frequency of incident light and is independent of intensity of light.

(iv) There is a threshold wavelength for a given metal such that if the wavelength of incident light is greater than the threshold, there will be no emission of photoelectrons.

Einstein's theory of photoelectric effect: Soon after the publication of results of photoelectric effect, efforts were made to explain the result. Wave theory which considered light as wave failed on all counts to explain photoelectric effect. The main cause for this failure was inability of wave theory to consider the energy of light quantised and not distributed continuously. In 1900 Planck proposed that radiation from a hot body consists of small packets of energy called 'quantas'. The energy of a quanta is given by $h\nu$ (ν being frequency of radiation). Einstein getting a hint from this proposed theory that light wave also consists of packets of energy or quantas whose energy is also given by '$h\nu$'. He called these quantas as photons.

Einstein postulated that a photon of incident light interacts with a metal electron and transfers its energy to electron in two ways. A part of the energy of the incident photon is used up in liberating the metal electron against the attractive forces of surrounding ions inside the metal; the remaining energy is spent in giving kinetic energy to ejected photoelectrons. If ν be the frequency of incident light W_0 be the minimum energy required to liberate an electron from the surface and E_K be the maximum kinetic energy of the emitted free electrons, then

$$h\nu = W_0 + E_K \quad \dots (8)$$

W_0 is called the work function and it obviously depends on the nature of metal. Equation (8) is called **Einstein photoelectric equation.**

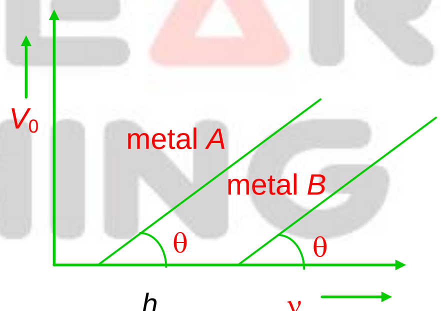
Stopping potential: This is the smallest magnitude of anode potential which just stops the electron with maximum kinetic energy from reaching the anode.

As $K.E_{max.} = h\nu - W_0$

So, if stopping potential for a given photoelectric emission is V_0 then $eV_0 = KE_{max} = h\nu - W_0$

$$V_0 = \left(\frac{h}{e}\right)\nu - \frac{W_0}{e} \quad \dots (9)$$

If we plot a curve between V_0 and ν we can get the value of Planck's constant by measuring slope.

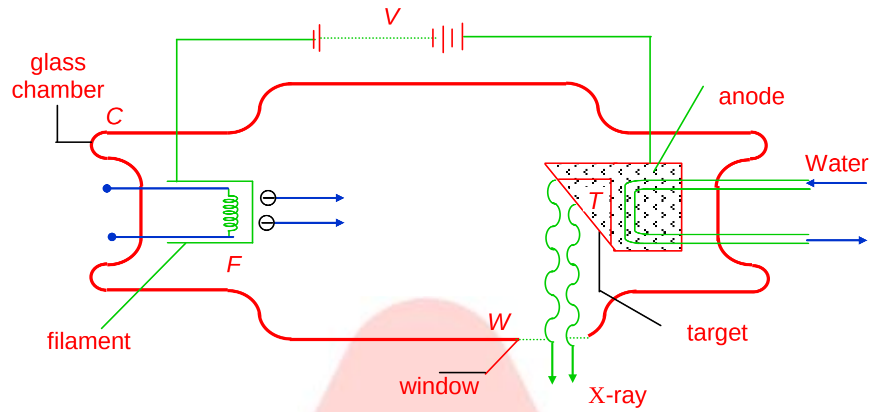


$\tan\theta = \frac{h}{e}$

4 X-RAYS

PRODUCTION OF X-RAYS

When highly energetic electrons are made to strike a metal target, electromagnetic radiation comes out. A large part of this radiation has wavelength of the order of 1Å and is called X-rays. The device which is used to produce X-rays is called Coolidge tube as shown below.



A filament *F* and a metallic target *T* are fixed in an evacuated glass chamber *C*. The filament is heated electrically and emits electrons by thermionic emission. A constant potential difference of several kilovolts is maintained between the filament and the target using a DC power supply so that the target is at a higher potential than the filament. The electrons emitted by the filament are, therefore, accelerated by the electric field set up between the filament and the target and hit the target with a very high speed. These electrons are stopped by the target and in the process X-rays are emitted. These X-rays are brought out of the tube through a window *W* made of thin mica or mylar or some such material which does not absorb X-rays appreciably. In process, large amount of heat is developed, and thus an arrangement is provided to cool down the tube continuously by running water.

4.1 CONTINUOUS AND CHARACTERISTIC X-RAYS

When X-rays coming from a Coolidge tube are investigated for the wavelength present. We find that X-rays can be divided in two categories based on the mechanism of their generation. These X-rays are called continuous and characteristic X-rays. These X-rays have their origin in the manner in which the highly energetic electron loses its kinetic energy. As the fast moving electrons enter metal target, they starts losing their energy by collisions with the atoms of metal target. At each such collision either of the following two processes take place.

(i) Electron loses its kinetic energy and a part of this lost kinetic energy is converted into a photon of electromagnetic radiation and the increases the kinetic energy of the target atoms, which ultimately heats up the target. This electromagnetic radiation is nothing but continuous X-rays. The fraction of kinetic energy converting into energy of photon varies from one collision to the other and the energy of such photon will be maximum when electron converts all its energy into a photon in the first collision itself.

If electrons are accelerated through a potential difference *V*, then maximum energy of emitted photon could be

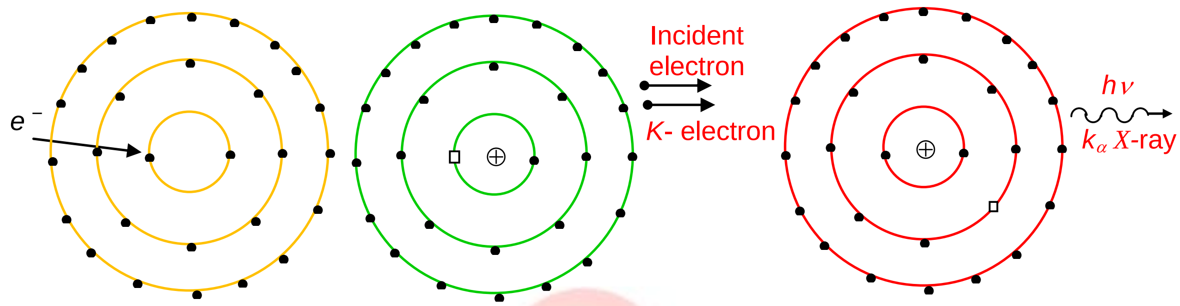
$$E_{max} = eV$$

$$\frac{hc}{\lambda_{min}} = eV$$

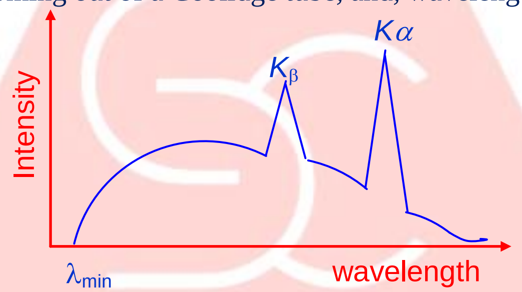
$$\lambda_{min} = \frac{hc}{eV} \qquad \dots (10)$$

λ_{min} is also called cut off wavelength. Since electron may loose very small energy in a given collision, the upper value of λ will approach to infinity. However both the cases e.g. electron converting all its energy in one go and loosing very small energy will have very small probability. That explains the origin of continuous X-ray. We can also see from the discussion, which we have had on continuous X-rays that λ_{min} depends only on accelerating voltage applied on the electron and not on the material of the target.

(ii) The electron knocks out an inner shell electron of the atom with which it collides. Let us take a hypothetical case of a target atom whose *K*- shell electron has been knocked out as shown.



This will create a vacancy in K-shell. Sensing this vacancy an electron from a higher energy state may make a transition to this vacant state. When such a transition takes place the difference of energy is converted into photon of electromagnetic radiation, which is called characteristic X-rays. Now depending upon which shell electron makes a transition to K-shell we may have different K X-rays e.g. if electron from L shell jumps to K shell we have $K\alpha$, if electron from M shell jumps to K shell we have K_β X-ray and so on. Similarly if vacancy has been caused in L shell we may have L_α, L_β X-ray etc depending upon, whether we have transition of electron from M shell or N shell. Since emission of characteristic X-ray involves the inner material energy levels of target atom, hence the wavelength of characteristic X-ray will depend on the target. If we plot curve between intensity of different wavelength component of X-ray coming out of a Coolidge tube, and, wavelength, it is like figure given below



As we can see from the curve, at certain clearly defined wavelengths the intensity of X-rays is very large. These X-rays are known as characteristic X-rays. It is also clear from the curve that $\lambda_{K\beta}$ is less than $\lambda_{K\alpha}$, however intensity of K_α transition is more as compared to the intensity of K_β transition, it is primarily because transition probability of K_α is more as compared to transition probability of K_β. At other wavelengths intensity varies gradually and these are called continuous X-rays.

Moseley's law: Moseley conducted many experiments on characteristic X-rays, the findings of which played an important role in developing the concept of atomic number. Moseley's observations can be expressed as

$$\sqrt{\nu} = a(Z - b) \qquad \ldots (11)$$

where a and b are constants. Z is the atomic number of target atom and ν is the frequency of characteristic X-rays. Moseley's law can be easily understood on the basis of Bohr's atomic model. Let us consider an atom from which an electron from K–shell has been knocked out, an L shell electron which is about to make transition to the vacant site will find the charge of nucleus is screeened by the spherical cloud of remaining one electron in the K shell. If the effect of outer electrons and other L-electrons are neglected then electron making the transition will find a charge $(Z\text{-}1)e$ at the centre. Hence we may expect Bohr's model to give expected result if we replace Z by $(Z\text{-}1)$.

According to Bohr's model, the energy released during a transition from $n = 2$ to $n = 1$ is given by

$$\Delta E = Rhc\,(Z-1)^2\left(\frac{1}{1^2} - \frac{1}{2^2}\right)$$

$$h\nu = Rhc\left(\frac{3}{4}\right)(Z-1)^2$$

$$\nu = \sqrt{\frac{3Rc}{4}}\,(Z-1)$$

Which is same as Moseley's equation with $b = 1$ & $a = \sqrt{\frac{3Rc}{4}}$.

4.2 PROPERTIES OF X-RAYS

(i) X-rays being an electromagnetic wave travel with a speed equal to the speed of light.
(ii) X-rays are not responsive to electric or magnetic field.
(iii) X-rays when pass through gases, produce ionisation.
(iv) X-rays affect photographic plates and exhibit the phenomenon of fluorescence.