Chapter Eleven - DUAL NATURE OF RADIATION AND MATTER

01. Why the free electrons cannot normally escape out of the metal surface ?

Ans- If an electron attempts to come out of the metal, the metal surface acquires a positive charge and pulls the electron back to the metal. The free electron is thus held inside the metal surface by the attractive forces of the ions. The electron can come out of the metal surface only if it has got sufficient energy to overcome the attractive pull.

02. What is work function of a metal surface ? On what factors t depends?

A certain minimum amount of energy is required to be given to an electron to pull it out from the surface of the metal. This minimum energy required by an electron to escape from the metal surface is called the work function of the metal.

It is denoted by φ_0 and measured in eV (electron volt).

The work function (φ_0) depends on the properties of the metal and the nature of its surface

03. What is one electron volt ?

It is the energy gained by an electron when accelerated by a potential difference of 1 volt .

So that 1 eV = 1e x 1V = 1.602×10^{-19}C x 1V = 1.602×10^{-19} J.

04. Name the processes required for the electron emission from the metal surface .

The minimum energy required for the electron emission from the metal surface can be supplied to the free electrons by any one of the following physical processes:

(i) Thermionic emission: By suitably heating, sufficient thermal energy can be imparted to the free electrons to enable them to come out of the metal.

(ii) Field emission: By applying a very strong electric field (of the order of 10^8 V/m) to a metal, electrons can be pulled out of the metal, as in a spark plug.

(iii) Photo-electric emission: When light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface. These photo(light)-generated electrons are called photoelectrons.

05.What is threshold frequency? On which factor it depends ?

No electrons were emitted from a metal surface at all when the frequency of the incident light was smaller than a certain minimum value, called the threshold frequency.

This minimum frequency depends on the nature of the material of the emitter plate.

06. What are photosensitive substances ?

The substances , emit electrons when they are illuminated by light are called photosensitive substances .

The electrons emitted , when they are illuminated by light are called photoelectrons.

The phenomenon is called photo electric effect .

e.g. Metals like zinc, cadmium, magnesium, etc., responded to ultraviolet light .

Alkali metals such as lithium, sodium, potassium, caesium and rubidium were sensitive to visible light.

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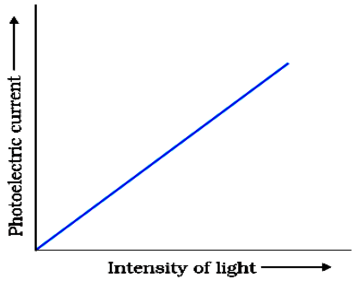
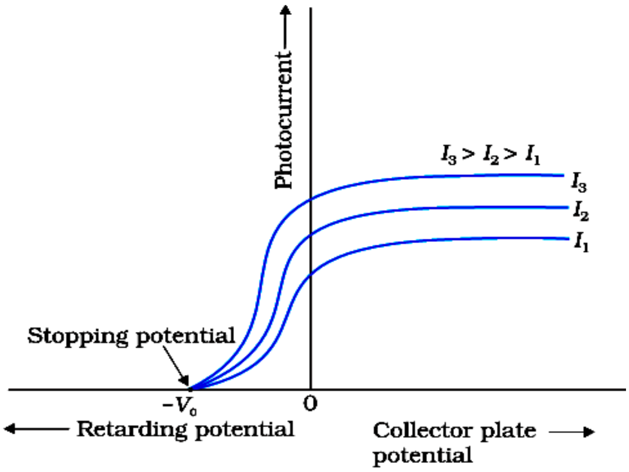
EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT

A. Effect of intensity of light on photocurrent

Keeping the frequency of the incident radiation and the accelerating potential fixed, it is seen that that the number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation .



B. Effect of potential on photoelectric current



Keeping the anode at positive potential with respect to the cathode and illuminating it with light of fixed frequency ν and fixed intensity I_1, it is seen that the photoelectric current increases with increase in positive potential. For a certain positive potential of anode , the photoelectric current becomes maximum or saturates.

Applying a negative potential to the anode with respect to the cathode , it is seen that the photocurrent decreases rapidly until it drops to zero at a certain value of the negative potential V_0 on the anode , called the cut-off or stopping potential.

07. What is saturation current ?

This maximum value of the photoelectric current is called saturation current. Saturation current corresponds to the case when all the photoelectrons emitted by the cathode reach anode .

08. What is cut-off or stopping potential ?

For a particular frequency of incident radiation, the minimum negative (retarding) potential V_0 given to the anode for which the photocurrent becomes zero is called the cut-off or stopping potential.

09. What is the relation between stopping potential and maximum kinetic energy ?

The interpretation of the stopping potential is that ,all the photoelectrons emitted from the metal do not have the same energy.

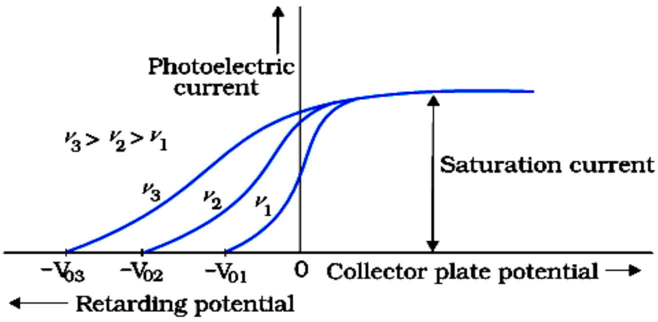
Photoelectric current is zero when the stopping potential is sufficient to repel even the most energetic photoelectrons, with the maximum kinetic energy (K_{max}), so that

$$K_{max} = e V_0$$

As for a given frequency of the incident radiation, the stopping potential is independent of its intensity.

The maximum kinetic energy of photoelectrons depends on the light source and the emitter plate material, but is independent of intensity of incident radiation.

C. Effect of frequency of incident radiation on stopping potential



Let us take the light radiation of same intensity at various frequencies $\mathbf{\nu_1}$, $\mathbf{\nu_2}$ **and** $\mathbf{\nu_3}$ such that $\nu_1 < \nu_2 < \nu_3$.

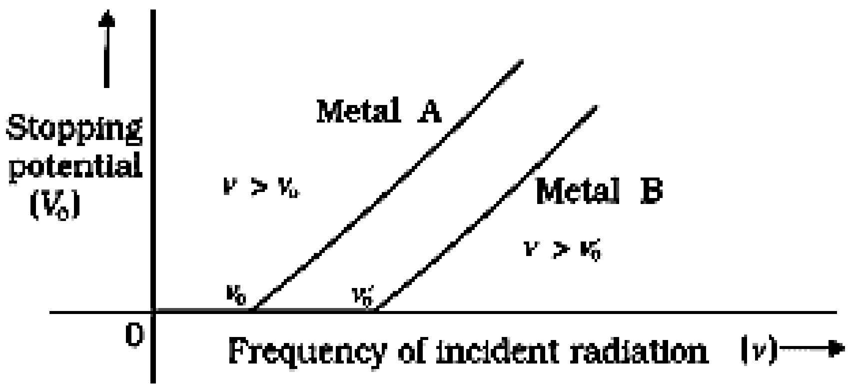
Since the kinetic energies of the emitted photo electrons , K_1 , K_2 and K_3 are directly proportional to the frequencies of the incident radiations ,

so $\mathbf{K_1 < K_2 < K_3}$.

The corresponding values of stopping potentials $\mathbf{V_{01}, V_{02}, V_{03}}$ in order to stop the photo electrons should be in the order of $\mathbf{V_{01} < V_{02} < V_{03}}$.

Graph between the frequency of incident radiation and the corresponding stopping potential

If we plot a graph between the frequency of incident radiation and the corresponding stopping potential for different metals we get a straight line, as shown in figure below



The graph shows that

(i)the stopping potential V_0 varies linearly with the frequency of incident radiation for a given photosensitive material.

(ii) there exists a certain minimum cut-off frequency ν_0 for which the stopping potential is zero.

These observations have two implications:

(i) The maximum kinetic energy of the photoelectrons varies linearly with the frequency of incident radiation, but is independent of its intensity.

(ii) For a frequency ν of incident radiation, lower than the cut-off frequency ν_0, no photoelectric emission is possible even if the intensity is large.

10. What is threshold frequency ?

This minimum, cut-off frequency ν_0, is called the threshold frequency. It is different for different metals.

IMPORTANT NOTES

1) Selenium is more sensitive than zinc or copper.

2) The ultraviolet light gives rise to photoelectric effect in copper while green or red light does not.

3) If frequency of the incident radiation exceeds the threshold frequency, the photoelectric emission starts instantaneously without any apparent time lag .

4) Even if the incident radiation is very dim , the emission starts in a time of the order of 10^{-9} s or less.

LAWS OF PHOTO-ELECTRICITY

(i)For a given photosensitive material and frequency of incident radiation (above the threshold frequency), the photoelectric current is directly proportional to the intensity of incident light .

(ii)For a given photosensitive material and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation whereas the stopping potential is independent of its intensity .

(iii) For a given photosensitive material, there exists a certain minimum cut-off frequency of the incident radiation, called the threshold frequency, below which no emission of photoelectrons takes place, no matter how intense the incident light is.

(iv) Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity

(iv) The photoelectric emission is an instantaneous process without any apparent time lag (10^{-9}s or less), even when the incident radiation is made exceedingly dim.

Einstein's photoelectric equation

In 1905, Albert Einstein, successfully applied quantum theory of radiation to photoelectric effect.

According to Einstein, the emission of photo electron is the result of the interaction between a single photon of the incident radiation and an electron in the metal.

When a photon of energy $h\nu$ is incident on a metal surface, its energy is used up in two ways :

(i) A part of the energy of the photon is used in extracting the electron from the surface of metal, since the electrons in the metal are bound to the nucleus. This energy W_0 is known as photoelectric work function of the metal.

(ii) The remaining energy of the photon is used to impart kinetic energy to the liberated electron.

If m is the mass of an electron and v, its velocity then

Energy of the incident photon =Work function + Kinetic energy of the electron

$$h\nu = W_o + \frac{1}{2} mv^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

This equation is known as **Einstein's photoelectric equation**.

When the frequency (ν) of the incident radiation is equal to the threshold frequency (ν_o) of the metal surface, kinetic energy of the electron is zero.

Then equation (2) becomes, $h\nu_o = W_o$ ………………………….(2)

Substituting the value of W in equation (1) we get, $h\nu = h\nu_o + \frac{1}{2} mv^2$

$$\Rightarrow h\nu - h\nu_o = \frac{1}{2} mv^2$$

$$\Rightarrow h(\nu - \nu_o) = \frac{1}{2} mv^2$$

This is another form of Einstein's photoelectric equation.

Experimental verification of Einstein's photoelectric equation

Einstein's photoelectric equation is,

$$\frac{1}{2} mv^2 = h(\nu - \nu_o) \quad \ldots(1)$$

If V_o is the stopping potential and e, the electronic charge, then

$$\frac{1}{2} mv^2 = eV_o \quad \ldots(2)$$

From equations (1) and (2),

$$eV_o = h(\nu - \nu_o)$$

or, $$V_o = \left(\frac{h}{e}\right)\nu - \left(\frac{h}{e}\right)\nu_o \quad \ldots\ldots(3)$$

This is an equation of a straight line. Millikan verified eq. (3) experimentally and found that it is in harmony with the observed facts .

PARTICLE NATURE OF LIGHT: THE PHOTON

Light in interaction with matter behaved as if it is made of quanta or packets of energy, each of energy h ν, called photon.

11.Is light quantum of energy be associated with a particle? According to Einstein , the light quantum can be associated with momentum (h ν/c). A definite value of energy as well as momentum is a strong sign that the light quantum can be associated with a particle.

12.What is the photon picture of electromagnetic radiation

(i)In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons.

(ii) Each photon has energy E (=hν) & momentum p (= h ν/c), and speed c, the speed of light.

(iii) All photons of light of a particular frequency ν, or wavelength λ, have the same energy E (=hν = hc/λ) and momentum p (= hν/c= h/λ),whatever the intensity of radiation may be. By increasing the intensity of light of given wavelength, there is only an increase in the number of

photons per second crossing a given area, with each photon having the same energy. Thus, photon energy is independent of intensity of radiation.

(iv) Photons are electrically neutral and are not deflected by electric and magnetic fields.

(v)In a photon-particle collision (such as photon-electron collision), the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision. The photon may be absorbed or a new photon may be created.

Matter waves

In 1924, Louis de Broglie put forward the bold hypothesis that **moving particles should possess wave properties under suitable conditions , on the basis of the fact, that nature is symmetrical and hence the basic physical entities – matter and energy should have symmetrical characters.**

If radiation shows dual aspects, so should matter.

de Broglie's wavelength of matter waves

de Broglie equated the energy equations of Planck (wave) and Einstein (particle).For a wave of frequency ν, the energy associated with each photon is given by Planck's relation,

$$\mathbf{E = h\nu} \ldots(1) \qquad [\text{ h is Planck's constant}]$$

According to Einstein's mass energy relation, a mass m is equivalent to energy,

$$\mathbf{E = mc^2} \ldots(2) \qquad [\text{c is the velocity of light}]$$

If, $\mathbf{h\nu = mc^2}$

Or, $\mathbf{hc/\lambda = mc^2}$

or, $\mathbf{\lambda = h/mc} \ldots(3)$

For a particle moving with a velocity v, if c = v

from equation (3) …$\mathbf{\lambda = h / mv = h / p}$ …(4)

Limitation of de Broglie's hypothesis

These hypothetical matter waves will have appreciable wavelength only for very light particles.

de Broglie wavelength of an electron

When an electron of mass m and charge e is accelerated through a potential difference V, then the energy eV is equal to kinetic energy of the electron.

$$\frac{1}{2} mv^2 = eV \quad \text{(or)} \quad v = \sqrt{\frac{2eV}{m}} \quad \ldots(1)$$

The de Broglie wavelength is , $\lambda = \frac{h}{mv}$

Substituting the value of v,

$$\lambda = \frac{h}{m\sqrt{\frac{2eV}{m}}} = \frac{h}{\sqrt{2meV}} \quad \ldots(2)$$

Substituting the known values in (2),

$$\lambda = \frac{12.27}{\sqrt{V}} \text{ Å}$$

If V = 100 volts, then λ = 1.227 Å

i.e., the wavelength associated with an electron accelerated by 100 volts is 1.227 Å.

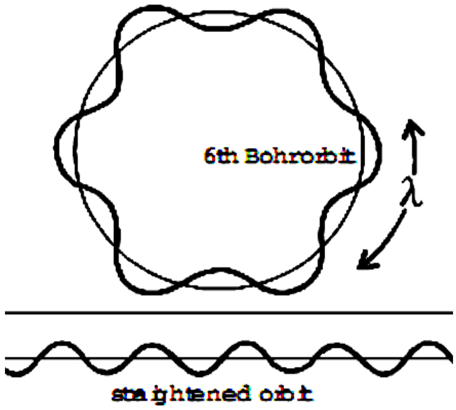
Since E = eV is kinetic energy associated with the electron, the equation (2) becomes, $\lambda = h/\sqrt{2mE}$

Wave mechanical concept of atom

According to de Broglie's hypothesis, an electron of mass m in motion with a velocity v is associated with a wave whose wavelength λ is given by

$\lambda = h/mv$ ……………………………(1) where h is Planck's constant.

On the basis of de Broglie's hypothesis, an atom model was proposed with the same stationary orbits of Bohr's model and electrons in them behaves as a wave as shown in figure below



It was suggested that stationary orbits are those in which orbital circumference ($2\pi r$) is an integral multiple of de Broglie wavelength λ, i.e., stationary orbits for an electron are those which contain the complete waves of electron.

Thus, $2\pi r = n\lambda$ …(2)

where n = 1, 2, 3 … and r is the radius of the circular orbit.

Substituting equation (1) in equation (2),

$$2\pi r = n\lambda\left(\frac{h}{mv}\right) \quad \text{(or)} \quad mv\,r = \frac{nh}{2\pi} \quad \ldots(3)$$

From equation (3), it is seen that the total angular momentum of the moving electron is an integral multiple of **h/2π .**

Thus, de Broglie's concept confirms the Bohr's postulate.

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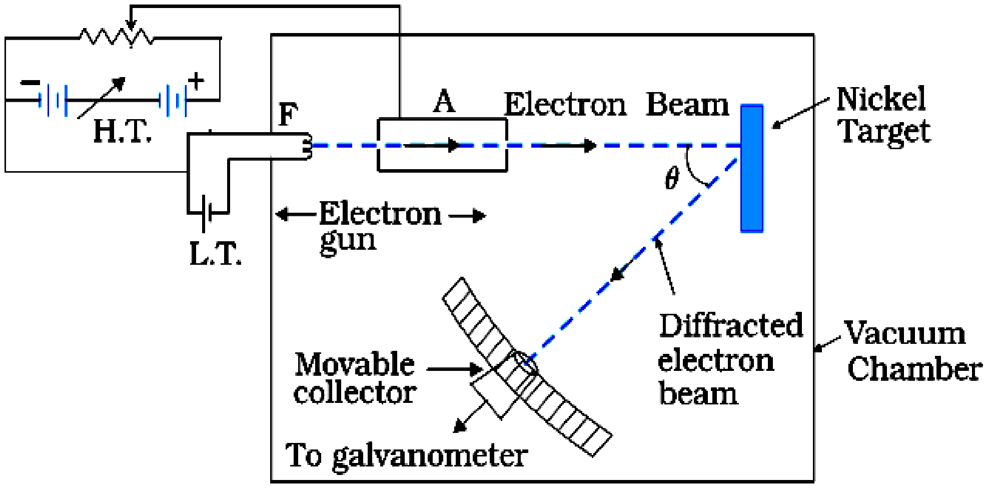
DAVISSON AND GERMER EXPERIMENT



The wave nature of electrons was first experimentally verified by C.J.Davisson and L.H. Germer in 1927.

Electrons emitted by the electron gun , are accelerated to a desired velocity by applying suitable voltage . They are passed through a cylinder along its axis, to produce a fine collimated beam, which is made to fall on the surface of a nickel crystal.

The electrons are scattered in all directions by the atoms of the crystal. The intensity of the electron beam, scattered in a given direction, is measured by the electron detector , which can be moved on a circular scale and is connected to a sensitive galvanometer, which records the current. The deflection of the galvanometer is proportional to the intensity of the electron beam entering the collector.

By moving the detector on the circular scale at different positions, the intensity of the scattered electron beam is measured for different values of angle of scattering θ which is the angle between the incident and the scattered electron beams. The variation of the intensity (I) of the scattered electrons with the angle of scattering θ is obtained for different accelerating voltages. The experiment was performed by varying the accelarating voltage from 44 V to 68 V.

It was noticed that a strong peak appeared in the intensity (I) of the scattered electron for an accelarating voltage of 54V at a scattering angle θ = 50º

The appearance of the peak in a particular direction is due to the constructive interference of electrons scattered from different layers of the regularly spaced atoms of the crystals. From the electron diffraction measurements, the wavelength of matter waves was found to be 0.165 nm.

de Broglie wavelength λ associated with electrons, for V=54 V

$$\lambda = h/p = \frac{1.227}{\sqrt{V}} \text{ nm} = \frac{1.227}{\sqrt{54}} \text{ nm} = 0.167 \text{ nm}$$

Thus, there is an excellent agreement between the theoretical value and the experimentally obtained value of de Broglie wavelength. Davisson- Germer experiment thus strikingly confirms the wave nature of electrons and the de Broglie relation.

Uses of de Broglie hypothesis

1) It has been basic to the development of modern quantum mechanics.

2) It has also led to the field of electron optics.

3) The wave properties of electrons have been utilised in the design of electron microscope which is a great improvement, with higher resolution, over the optical microscope.