DUAL NATURE OF RADIATION AND MATTER

ELECTRON EMISSION

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

One electron volt is the energy gained by an electron when it has been accelerated by a potential difference of 1 volt, so that 1 eV = 1.602 ×10–19 J.

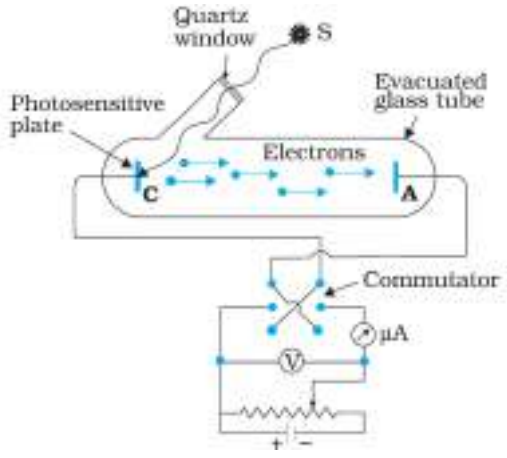
The minimum energy required for the electron emission from the metal surface can be supplied to the free electrons by any one of the following physical processes
(i) *Thermionic emission:* By suitably heating
(ii) *Field emission*: By applying a very strong electric field
(iii) *Photo-electric emission*: When light of suitable frequency illuminates a metal surface

Hertz's observations
Hertz observed that high voltage sparks across the detector loop were enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp
(After gaining sufficient energy from the incident light, the electrons escape from the surface of the metal into the surrounding space).

Hallwachs' and Lenard's observations
Lenard observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes , current flows in the circuit . As soon as the ultraviolet radiations were stopped, the current flow also stopped.
Hallwachs, observed that the negatively charged zinc plate lost its charge when it was illuminated by ultraviolet light. Further, the uncharged zinc plate became positively charged when it was irradiated by ultraviolet light. Positive charge on a positively charged zinc plate was found to be further enhanced when it was illuminated by ultraviolet light. From these observations he concluded that negatively charged particles were emitted from the zinc plate under the action of ultraviolet light.

EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT

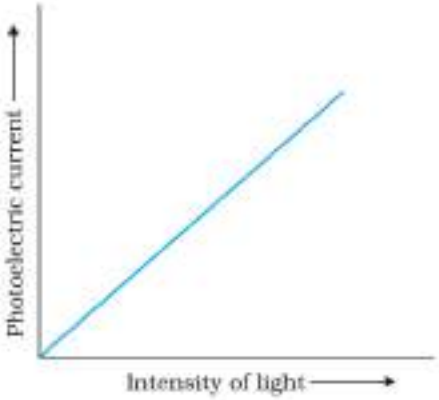
Figure depicts a schematic view of the arrangement used for the experimental study of the photoelectric effect



The potential difference between the emitter and collector plates is measured by a voltmeter (V) whereas the resulting photo current flowing in the circuit is measured by a microammeter(μA). The photoelectric current can be increased or decreased by varying the potential of collector plate A with respect to the emitter plate C. The intensity and frequency of the incident light can be varied, as can the potential difference *V* between the emitter C and the collector A.

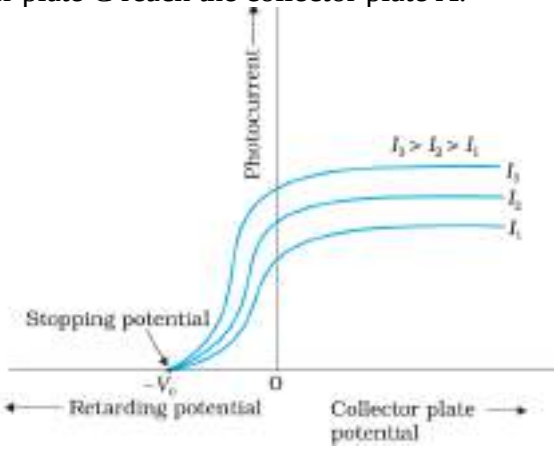
Effect of intensity of light on photocurrent

Keeping the frequency of the incident radiation and the accelerating potential fixed, the intensity of light is varied and the resulting photoelectric current is measured each time. It is found that the photocurrent increases linearly with intensity of incident light as shown graphically . The photocurrent is directly proportional to the number of photoelectrons emitted per second. This implies that *the number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation.*



Effect of potential on photoelectric current

We next vary the positive potential of plate A gradually and measure the resulting photocurrent each time. It is found that the photoelectric current increases with increase in accelerating (positive) potential. At some stage, for a certain positive potential of plate A, all the emitted electrons are collected by the plate A and the photoelectric current becomes maximum or saturates. If we increase the accelerating potential of plate A further, the photocurrent does not increase. This maximum value of the photoelectric current is called *saturation current.* Saturation current corresponds to the case when all the photoelectrons emitted by the emitter plate C reach the collector plate A.

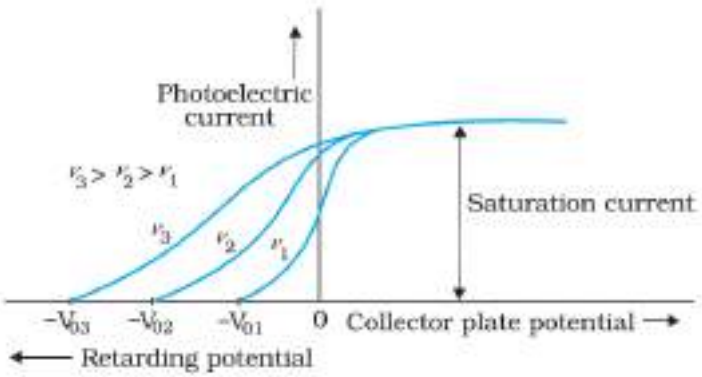


When the polarity is reversed, the electrons are repelled and only the most energetic electrons are able to reach the collector A. The photocurrent is found to decrease rapidly until it drops to zero at a certain sharply defined, critical value of the negative potential *V*0 on the plate A. For a particular frequency of incident radiation, *the minimum negative (retarding) potential V_0 given to the plate A for which the photocurrent stops or becomes zero is called the cut-off or stopping potential*.
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

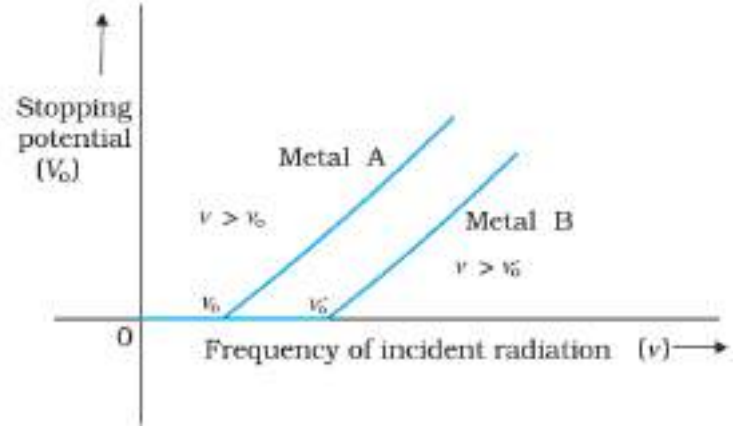
$$K\text{max} = e\,V_0$$

We can now repeat this experiment with incident radiation of the same frequency but of higher intensity *I*2 and *I*3 . *for a given frequency of the incident radiation, the stopping potential is independent of its intensity*

Effect of frequency of incident radiation on stopping potential
We now study the relation between the frequency ν of the incident radiation and the stopping potential V_0. We suitably adjust the same intensity of light radiation at various frequencies and study the variation of photocurrent with collector plate potential



We obtain different values of stopping potential but the same value of the saturation current for incident radiation of different frequencies. If we plot a graph between the frequency of incident radiation and the corresponding stopping potential for different metals we get a straight line.



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

Summary
(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

(v) The photoelectric emission is an instantaneous process without any apparent time lag .

PHOTOELECTRIC EFFECT AND WAVE THEORY OF LIGHT

According to the wave picture of light, the free electrons at the surface of the metal absorb the radiant energy continuously. The greater the intensity of radiation, the greater should be the energy absorbed by each electron. The maximum kinetic energy of the photoelectrons on the surface is then expected to increase with increase in intensity. Also, no matter what the frequency of radiation is, a sufficiently intense beam of radiation (over sufficient time) should be able to impart enough energy to the electrons, so that they exceed the minimum energy needed to escape from the metal surface . A threshold frequency, therefore, should not exist. These expectations of the wave theory directly contradict observations. In short, the wave picture is unable to explain the most basic features of photoelectric emission.

EINSTEIN'S PHOTOELECTRIC EQUATION

Radiation energy is built up of discrete units – the so called *quanta of energy of radiation*. Each quantum of radiant energy has energy $h\nu$,

the electron is emitted with maximum kinetic energy
$K_{max} = h\nu - \varphi_0$ (*Einstein's photoelectric Equation*)
More tightly bound electrons will emerge with kinetic energies less than the maximum value.

Note that the intensity of light of a given frequency is determined by the number of photons incident per second.

Increasing the intensity will increase the number of emitted electrons per second. However, the maximum kinetic energy of the emitted photoelectrons is determined by the energy of each photon.

*K*max depends linearly on ν, and is independent of intensity of radiation

photoelectric emission is possible only if $h\nu > \varphi_0$

$$e V_0 = h\nu - \phi_0; \text{ for } \nu \geq \nu_0$$

$$\text{or } V_0 = \left(\frac{h}{e}\right)\nu - \frac{\phi_0}{e}$$

This is an important result. It predicts that the V_0 versus ν curve is astraight line with slope = (*h*/*e*),

PARTICLE NATURE OF LIGHT: THE PHOTON

We can summarise the photon picture of electromagnetic radiation as follows

(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*) and momentum *p* (= *h* ν*/c*), and speed *c*.

(iii) All photons of light of a particular frequency ν, or wavelength ν, have the same energy *E* and momentum *p* , whatever the intensity of radiation may be.

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

(v) In a photon-particle collision the total energy and total momentum are conserved. However, the number

of photons may not be conserved in a collision.

WAVE NATURE OF MATTER.

De Broglie proposed that the wave length λ associated with a particle of momentum *p* is given as

$$\lambda = h/p = h/mv$$

known as the *de Broglie relation* and the wavelength λ of the *matter wave* is called *de Broglie wavelength*

Consider an electron (mass *m*, charge *e*) accelerated from rest through a potential *V*. The kinetic energy *K* of the electron equals the work done (*eV*) on it by the electric field:

$$K = e V$$

$$\text{Now, } K = \frac{1}{2} m v^2 = \frac{p^2}{2m} \text{ , so that}$$

$$p = \sqrt{2\, m\, K} = \sqrt{2\, m\, eV}$$

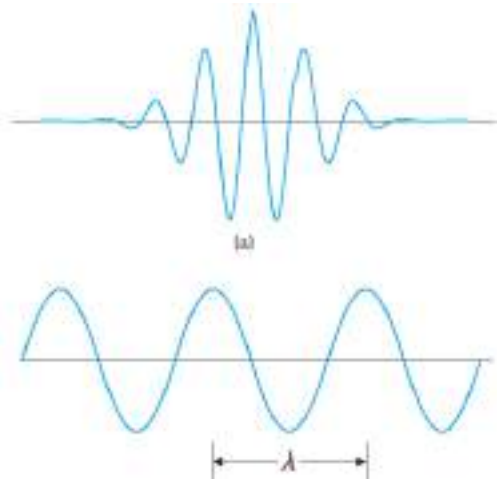
The de Broglie wavelength λ of the electron is then

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2\, mK}} = \frac{h}{\sqrt{2\, meV}}$$

Substituting the numerical values of *h*, *m*, *e*, we get

$$\lambda = \frac{1.227}{\sqrt{V}} \text{ nm}$$

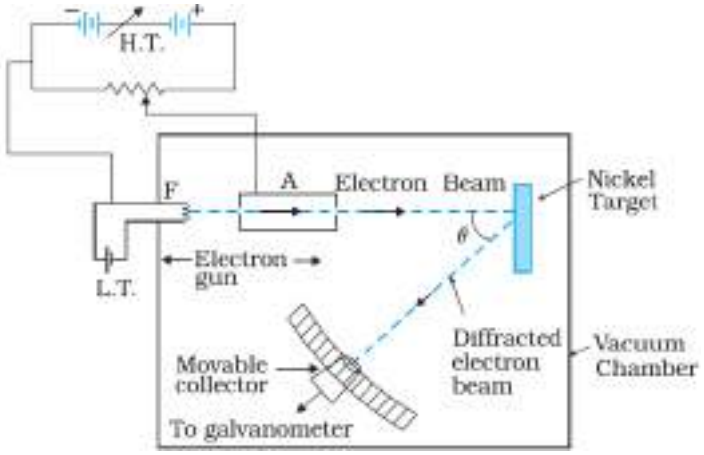
The matter–wave picture elegantly incorporated the Heisenberg's *uncertainty principle*. According to the principle, it is not possible to measure *both* the position and momentum of an electron (or any other particle) *at the same time* exactly.



(a) The wave packet description of an electron. The wave packet corresponds to a spread of wavelength around some central wavelength (and hence by de Broglie relation, a spread in momentum). Consequently, it is associated with an uncertainty in position (Δx) and an uncertainty in momentum (Δp).
(b) The matter wave corresponding to a definite momentum of an electron extends all over space. In this case, $\Delta p = 0$ and $\Delta x \rightarrow \infty$

DAVISSON AND GERMER EXPERIMENT

The wave nature of electrons was first experimentally verified by C.J. Davisson and L.H. Germer
The experimental arrangement used by Davisson and Germer is schematically shown. It consists of an electron gun which comprises of a tungsten filament F, Electrons emitted by the filament are accelerated to a desired velocity. The beam 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



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 $\theta = 50^{o}$
The de Broglie wavelength λ associated with electrons for $V = 54$ V is given by

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

$$\lambda = \frac{1.227}{\sqrt{54}} \text{ nm} = 0.167 \text{ nm}$$

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

wave properties of electrons have been utilised in the design of electron microscope.

Hareesh Kumar VK
PGT Physics
JNV Bidar.