DUAL NATURE OF MATTER AND RADIATION

LEARNING ROADMAP

- Electron emission
  - ↳ concept of work function
  - ↳ definition of electron volt
  - ↳ types of electron emission
- Photoelectric effect
  - ↳ experimental setup
  - ↳ observations
    - → effect of intensity
    - → effect of potential
    - → effect of frequency
  - ↳ laws of photoelectric emission
- Einstein's photoelectric equation
  - ↳ photon concept
  - ↳ photoelectric equation derivation
- Properties of photon
- Photocell
  - ↳ types
  - ↳ working
  - ↳ applications
- de Broglie waves or matter waves
- Davisson - Germer experiment

ELECTRON EMISSION

Metals have free electrons which are held to the atoms by the attractive forces of the ions.

Work function (ϕ_0) : 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 is called the work function of the metal.

→ denoted by ϕ_0

→ measured usually in electron volt (eV).

Electron volt (eV) : 1 electron volt (1 eV) is the energy gained by an electron when it has been accelerated by a potential difference of 1 volt.

$$1\ eV = 1.602 \times 10^{-19}\ \text{Joule}.$$

Types of electron emission :

The energy required to pull out an electron from a metal surface can be supplied in different ways. Accordingly, electron emission can be of the following types :-

1) **Thermionic emission** : When a metal is heated, its free electrons get sufficient thermal energy and is ejected from the metal surface.

2) Field emission or cold cathode emission : When a metal surface is subjected to very high electric fields of the order of 10^3 to 10^8 Vm^{-1} electrons are emitted.

3) Secondary emission : When fast moving electrons strike a metal surface, they transfer some of their energy to free electrons of the metal. As a result the excess of the free electrons becomes more than the work function of the metal and they get ejected from the metal surface.

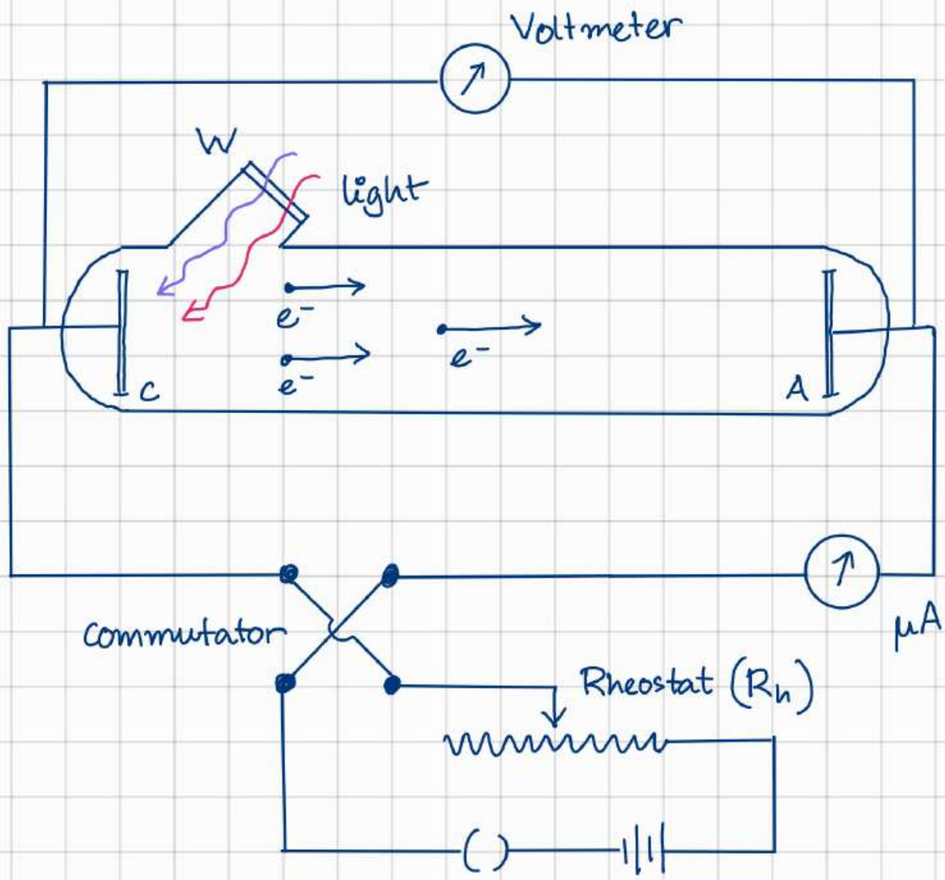
4) Photoelectric emission : Next topic

PHOTOELECTRIC EFFECT

The phenomenon of emission of electrons from a metallic surface when radiation of suitable frequency falls on it is called photoelectric effect.

The electrons ejected through this process are called photoelectrons.

Experimental Setup :



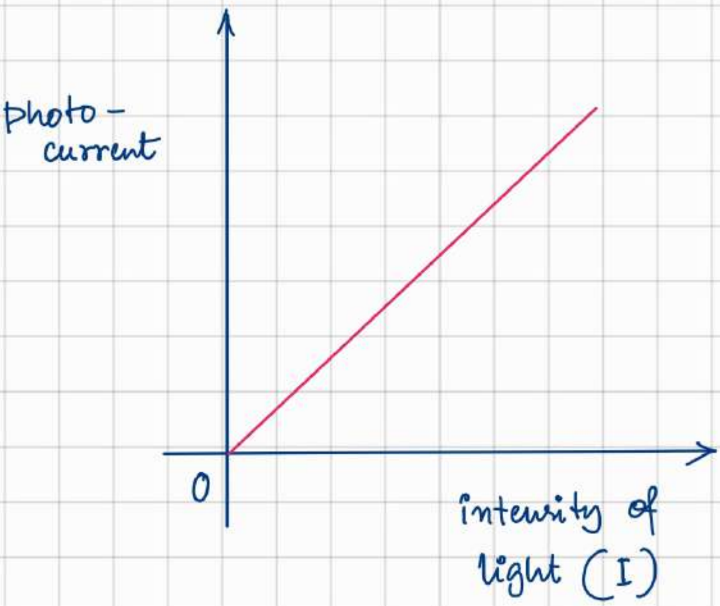
The experimental setup consists of an evacuated glass tube which encloses a photo sensitive plate C and another metal plate A.

C → cathode ; A → anode.

A glass window W permits the light to fall on the metal plate C. The electrons are emitted by the cathode C and are collected by the plate A.

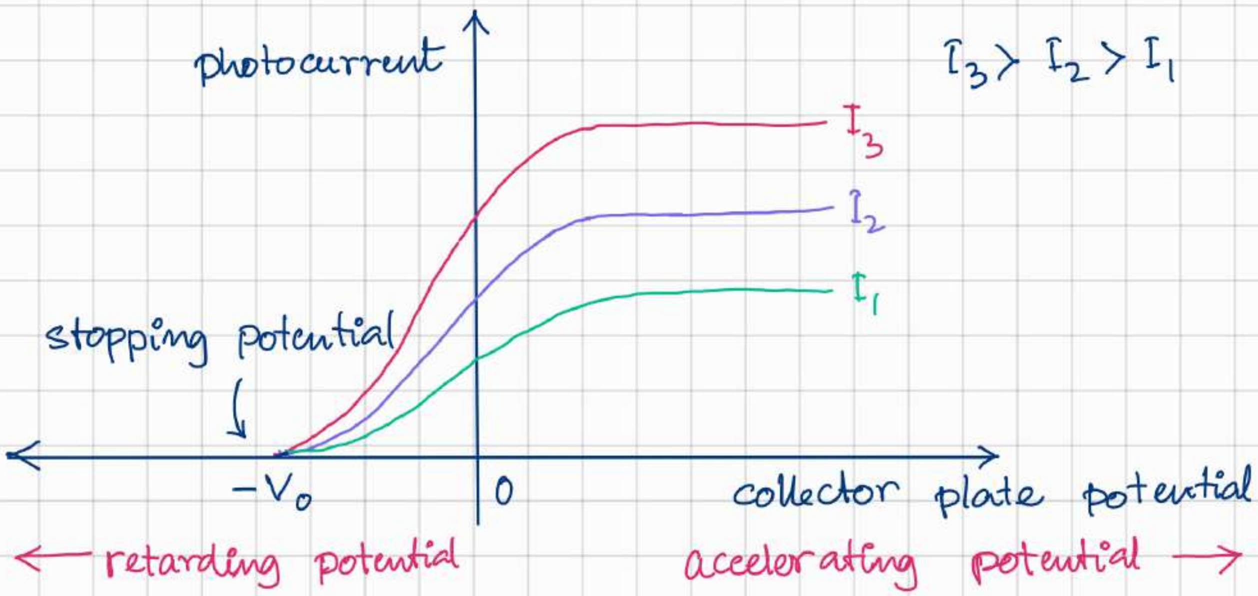
Observations from the experiment :

1. Effect of intensity on photocurrent (graph 1)



The photoelectric current is directly proportional to the intensity of light incident on the photosensitive plate.

2. Effect of anode potential (graph 2)

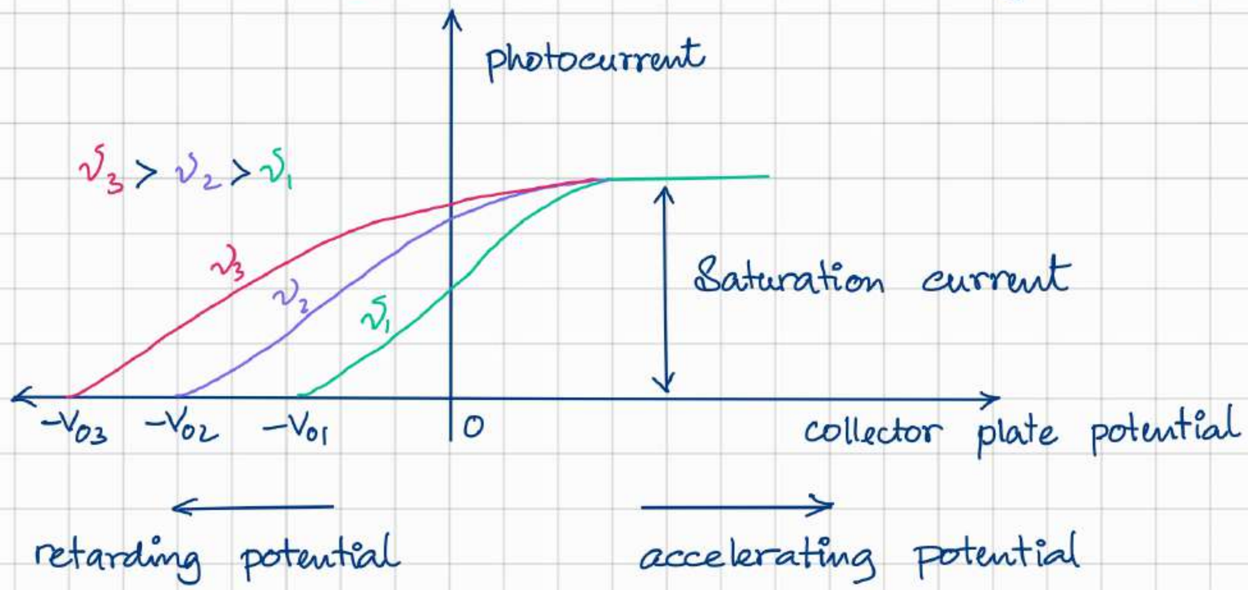


For a given frequency of incident radiation, the stopping potential is independent of intensity of incident radiation.

The photoelectric current increases with the increase in retarding potential till a stage is reached when the photoelectric current becomes maximum and doesnot increase further with the increase in the accelerating potential. This maximum current is called saturation current.

The value of the retarding potential at which the photoelectric current becomes zero is called cut-off potential or stopping potential for the given frequency of incident radiation.

3. Effect of frequency on stopping potential : (graph 3)



Greater the frequency of incident radiation greater is the maximum kinetic energy of the photoelectrons and hence greater the stopping potential.

LAWS OF PHOTOELECTRIC EMISSION

The experimental features and observations are described below :

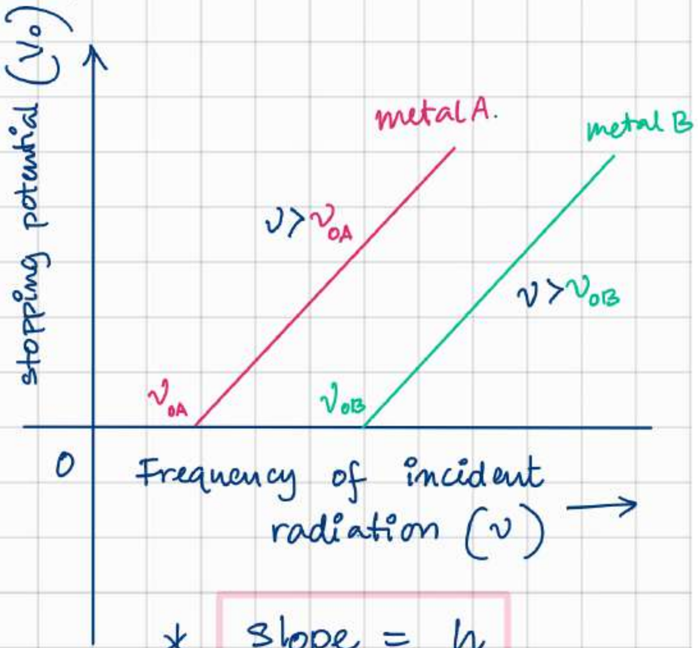
1. For a given photosensitive material and frequency of incident radiation (above the threshold frequency), the photoelectric current is directly proportional to the intensity of incident light.

(draw graph 1 here)

2. 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.

(draw graph 2 here)

3. 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 take place, no matter how intense the incident light is.



Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the emitted

* $\boxed{\text{slope} = h}$

photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity.

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

Implications of the observations :

1. The minimum kinetic energy of the photoelectrons varies linearly with the frequency of incident radiation, but is independent of its radiation.

2. 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.

EINSTEIN'S PHOTOELECTRIC EQUATION

In 1905, Albert Einstein proposed a radically new picture of electromagnetic radiation to explain the photoelectric effect.

Why wave theory of light could not explain the photoelectric effect?

1. According to wave picture of light, the free electrons at the surface of the metal absorb the radiant energy continuously. The greater the intensity of radiation, 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.

   But it was observed that kinetic energy of the electron is dependent on the frequency.

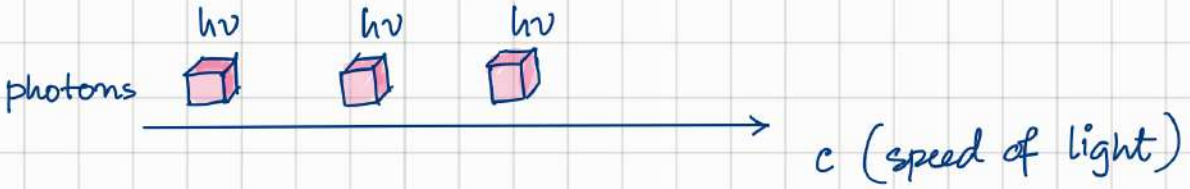
2. According to wave theory, no matter what the frequency of radiation is, a sufficiently intense beam of radiation (over sufficient time) should be able to impart enough energy to the electrons, so that they exceed the minimum energy needed to escape from the metal surface.

   But it is not observed in the photoelectric effect. A threshold frequency is observed.

Einstein's explanation of the photoelectric effect

Einstein proposed that photoelectric emission does not take place by continuous absorption of energy from radiation. Radiation energy is built up of discrete units – "quanta" of energy of radiation.

Each quantum of radiant energy of electromagnetic radiation is called a photon.



According to Einstein when a photon of suitable frequency ν (greater than the threshold frequency of the metal) is incident on the metal surface, the energy $h\nu$ of the photon is spent in two ways:

① a part of the energy is used to overcome the work function (ϕ) of the metal

② the rest of the energy of the photon appears as maximum kinetic energy of the emitted photoelectron.

Mathematically, $$\boxed{h\nu = \phi_0 + (K.E.)_{max}}$$

$$\Rightarrow \boxed{(K.E.)_{max} = h\nu - \phi_0}$$

When Kinetic energy of the electron is 0, the incident energy is equal to the work function. The frequency of the photon in such a case is the threshold frequency ν_0

$$h\nu_0 = \phi_0 + 0$$

zero K.E.

$$\Rightarrow \boxed{\phi_0 = h\nu_0}$$

This is the expression for work function in terms of the incident radiation frequency.

If $\lambda \rightarrow$ wavelength of incident radiation
$\lambda_0 \rightarrow$ threshold wavelength

$$h\nu = \phi_0 + (K.E.)_{max}$$

$$\Rightarrow h\nu = h\nu_0 + \frac{1}{2}mv^2$$

$(c = \nu\lambda)$

speed of light

$$\Rightarrow h\frac{c}{\lambda} = h\frac{c}{\lambda_0} + \frac{1}{2}mv^2$$

$$\Rightarrow \boxed{\frac{1}{2}mv^2 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)}$$

If the stopping potential is V_0 then

$$K.E. = \frac{1}{2}mv_{max}^2 = eV_0$$

($e \rightarrow$ charge of electron)

$$\therefore \boxed{h\nu = \phi_0 + eV_0}$$

PROPERTIES OF PHOTON

1. The "mass" of photon is not defined. We say that the "rest mass" of the photon is zero.

2. Photons travel at speed $c = 3 \times 10^8$ m/s in vacuum in a straight line.

3. The energy of a photon is

$$\boxed{E = h\nu = \frac{hc}{\lambda}}$$

* $\nu \rightarrow$ frequency ; $\lambda \rightarrow$ wavelength

4. The linear momentum of a photon is

$$\boxed{p = \frac{E}{c} = \frac{h}{\lambda}}$$

$h = 6.626 \times 10^{-34}$ Js

5. Photons are electrically neutral and are not deflected by electric and magnetic fields.

6. A photon may collide with a material particle. The total energy and total momentum remain conserved in such collisions. However, the photon may get absorbed or a new photon may be created, the total number of photons may not be conserved.

PHOTOCELL

A photocell is a device that converts light energy into electrical energy. It measures the intensity of light by measuring the photoelectric current.

Types :-

1. Photoemissive cell : works on the principle of photoelectric emission

2. Photoconductive cell : works on the principle that electrical conductivity of a photosensitive semiconductor increases when exposed to light

3. Photovoltaic cell : works on the principle that an emf is produced between two layers of different materials as a result of radiation.

Applications :

1. Cinematography
2. Counting devices
3. Burglar 's alarm
4. Fire alarm
5. Photographic cameras
6. Used to determine Planck's constant

de Broglie waves or matter waves

The waves associated with material particles in motion are called matter waves or de-Broglie waves.

The wavelength of such matter waves is called de-Broglie wavelength.

Derivation of expression for matter wave :

According to Einstein's theory of relativity

$$E = pc \rightarrow (1)$$

From quantum theory of radiation,

$$E = h\nu \longrightarrow (2)$$

From (1) and (2),

$$pc = h\nu$$

$$\Rightarrow pc = h\frac{c}{\lambda}$$

$$\Rightarrow \boxed{\lambda = \frac{h}{p}}$$

For a particle of mass 'm'

$$\boxed{\lambda = \frac{h}{mv}}$$

Note : if $v = 0$ then $\lambda = \frac{h}{m \times 0} = \infty$

It means that matter waves are associated with material particles only if they are in motion.

---

de-Broglie wavelength of large moving objects is very very small (quite beyond measurement) due to their large mass

$$\left(\because \lambda \propto \frac{1}{m} \right)$$

So, macroscopic objects do not show wave-like properties.

For an eletron accelerated through a potential difference V,

Kinetic energy $= eV$ ($e \rightarrow$ charge of e^-)

$$\Rightarrow \frac{mv^2}{2} = eV$$

$$\Rightarrow \frac{m^2v^2}{2m} = eV$$

$$\Rightarrow m^2v^2 = 2meV$$

$$\Rightarrow mv = \sqrt{2meV}$$

Thus, the de-Broglie wavelength of the electron accelerated by a potential difference V is

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

$$= \frac{h}{\sqrt{2meV}}$$

By putting the value of constants. h, m and e, we get the value of λ

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

DAVISSON - GERMER EXPERIMENT

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

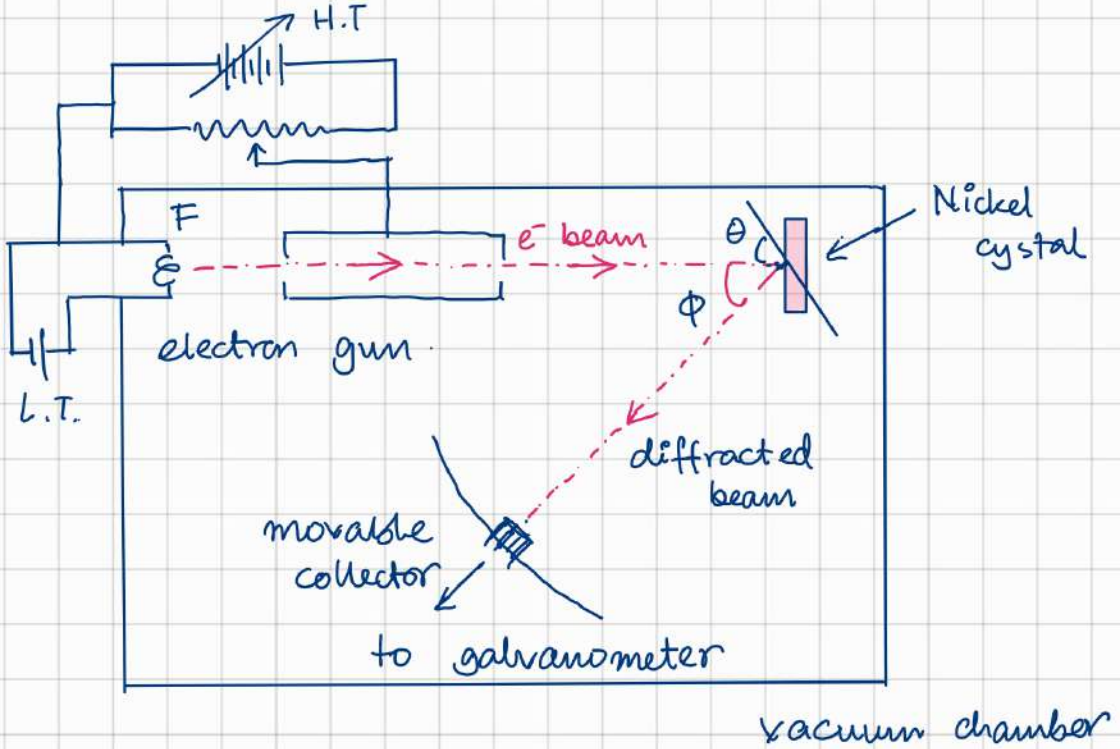


Fig: experimental setup of Davisson-Germer experiment

The experimental setup consists of an electron gun with tungsten filament F, heated by a low voltage power supply. Electrons from the filament are accelerated by applying suitable high voltage across the gun.

A beam of electrons is made to fall on the surface of a nickel crystal. The electrons are scattered in all directions by atoms of the crystal. The intensity of electron beam scattered in a given direction is measured by a detector which can be moved on a circular scale and is connected to a galvanometer.

The variation of intensity (I) of scattered electrons with scattering angle ϕ is obtained for different accelerating voltage from 44 volt to 68 volt.

It is found that when $\phi = 50°$ and $V = 54$ volts, the intensity of scattered electron beam becomes maximum.

$$\theta + \phi + \theta = 180°$$

$$\Rightarrow \theta = \frac{180° - \phi}{2}$$

$$= \frac{180° - 50°}{2}$$

$$= 65°$$

The sharp peak in a particular direction is due to constructive interference of electrons scattered from different layers of regularly spaced atoms of Nickel crystal.

According to Bragg's law, for first order diffraction maximum $(n=1)$

$$\lambda = 2d \sin\theta$$

For Ni crystal, the spacing between adjacent atomic planes = $0.91\ \mathring{A}$.

$$\therefore\ \lambda = (2 \times 0.91 \sin 65^\circ)\ \mathring{A}$$
$$= 1.65\ \mathring{A}$$

The de-Broglie wavelength of an electron accelerated through a potential difference of 54 volts is

$$\lambda = \frac{12.27}{\sqrt{V}}\ \mathring{A}$$
$$= \frac{12.27}{\sqrt{54}}\ \mathring{A}$$
$$= 1.66\ \mathring{A}$$

Thus, there is an excellent agreement between the experimental and theoretical values of de-Broglie wavelength of electron.

This proves the existence of de-Broglie wave for moving electrons.