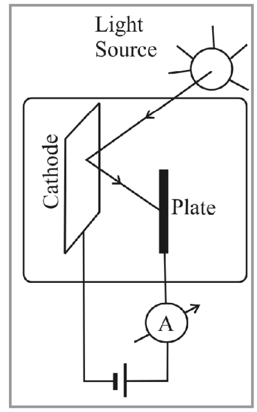
1. ELECTRON EMISSION

- Electron emission refers to the liberation of free electrons from the surface of a substance aided by the external energy transferred to the electrons.
- It tends to occur on metals because metals are rich in free electrons.
- The amount of external energy required to emit an electron from the metal surface is known as work function, which depends on the nature of the metal.
- The work function is usually expressed in electron volt (eV) unit.



Methods for obtaining electron emission from the metal surface

- **Thermionic Emission:** Filaments get heated while passing current through them and on sufficient heating electrons are emitted. Triodes, cathode ray tubes etc. are based on this principle.
- **Field Emission:** In this process, free electrons are pulled out by applying strong electric fields of the order of $10^8\ Vm^{-1}$.
- **Photoelectric Emission:** When electromagnetic radiation of sufficiently high frequency falls on a clean metal surface, free electrons are emitted from the surface. The electrons so emitted are called the photoelectrons.

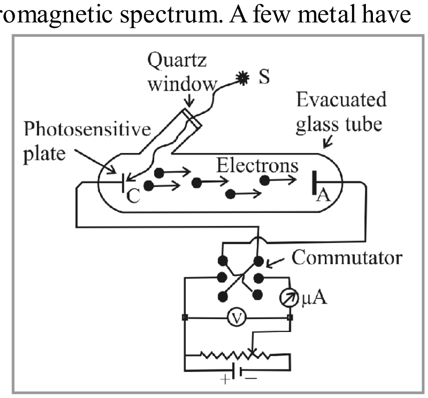
2. PHOTOELECTRIC EFFECT

- Hertz observed that if cathode is irradiated with ultraviolet radiations, spark of high voltage passes through the gap between the electrodes.
- Lenard's experiments lead to the discovery of a current between the electrodes assembled in an evacuated glass tube, when the emitter plate was illuminated using UV radiations. The current existed only when UV radiations were incident on the same.
- Hallwachs further studied this and found that when negatively charged zinc plate with an electroscope is irradiated with ultraviolet light, negative charge on the plate decreased or vanished. If neutral plate were used, it became positive and a positive plate more positive. This lead to the conclusion that negatively charged particles were emitted from the plate.
- Photoelectric effect refers to the phenomenon of emission of electrons from the surface of metals (like Zn, Cs, K etc.) when irradiated with high frequency electromagnetic radiations.
- For emission of photoelectrons, the frequency of the incident light should be more than certain minimum called threshold frequency (ν_0) whose value depends on the type of the metal.
- For most of the metals, threshold frequency lies in ultraviolet band of electromagnetic spectrum. A few metal have the same in the visible region.

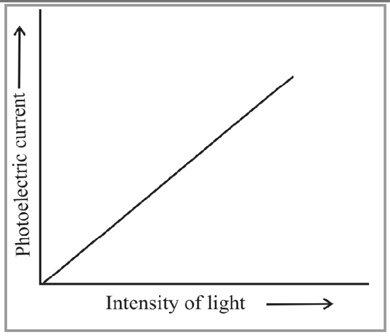
Experimental Study

The experimental arrangement to study photoelectric effect consists of an evacuated glass tube with cathode C and anode A near either ends. UV rays from the source S fall on C and electrons are emitted. A circuit can be created so that the photoelectrons initiate a current.

The potential of electrode A can be adjusted with reference to the electrode C. The following observations have been made.



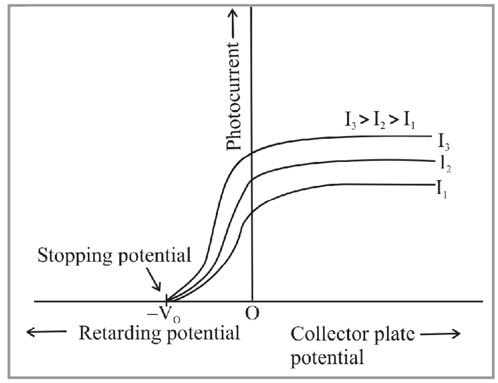
- The photoelectric current is directly proportional to the intensity of light. When the frequency of incident radiation and the accelerating potential remain the same, the number of photoelectrons emitted per second is directly proportional to the intensity of the incident radiation.



- The strength of photoelectric current increases with the increase in accelerating potential, but only upto a saturation value.

  If a negative (retarding) potential is given to anode, the electrons get repelled and as a result the photoelectric current decreases.

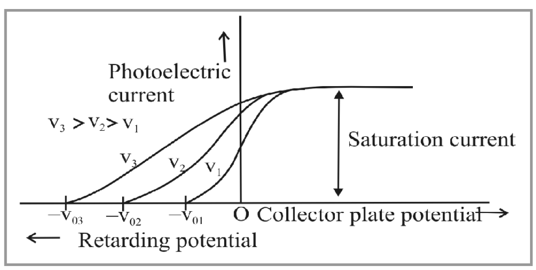
  With the increase in retarding potential of the anode, the photoelectric current rapidly decreases and becomes zero at a particular value of retarding potential called stopping potential (V_0).



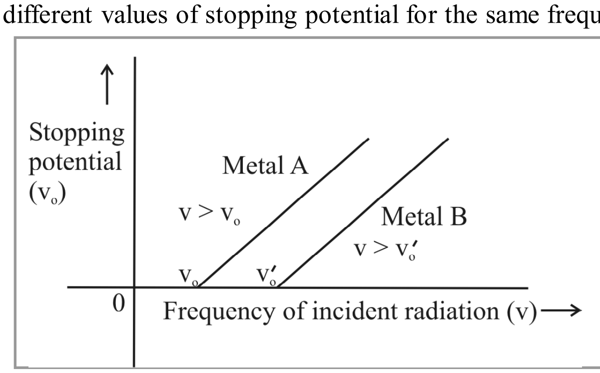
(*i*) Photoelectric current becomes zero when the retarding potential is sufficient to repel the electrons with maximum kinetic energy. $KE_{max} = eV_0$

(*ii*) For a given frequency of radiation, the value of stopping potential is independent of the intensity of radiation.

- Stopping potential depends on the frequency of the incident radiation and the nature of the metal.
- For a given metal, the value of stopping potential is more negative.



- Different metals have different values of stopping potential for the same frequency of radiations.



- There is a certain minimum cut-off frequency for each metal for which the stopping potential is zero. This cut –off frequency is referred to as threshold frequency.
- The photoelectric emission is an instantaneous process without any apparent time lag (<10^{-9} s or less), even when the intensity of incident radiation is very less.

3. EINSTEIN'S PHOTOELECTRIC EQUATION

- Failure of wave theory:
  - According to wave theory, more intense light supplies more energy and so the kinetic energy of photoelectrons should increase with the intensity of light. But experiments show that the maximum kinetic energy of photoelectrons is independent of the intensity of light.
  - According to wave theory, the photoelectric effect should take place irrespective of the frequency of light, provided the intensity is sufficient to supply required energy to the electrons. But experiments confirm a threshold frequency, below which no emission of electrons takes place.
  - If wave theory were correct, the electrons would take some time to absorb sufficient energy and leave the metal surface, *i.e.* there is a time delay between the irradiation of the surface and the emission of electrons. However, no such time delay was detected.
- Einstein modified quantum theory of light and explained photoelectric effect on the basis of that.
  - In photoelectric effect, light behaves as particles called photons.
  - Photon is a discrete unit (quantum) of light energy with no charge and zero rest mass.
  - Photon can transfer energy ($E = h\nu$) and momentum $\left(p = \frac{E}{c}\right)$.
  - When a photon undergoes a direct inelastic collision with an electron, the energy of photon ($E = h\nu$) is completely absorbed. This makes the electron more energetic.
  - If the energy absorbed by an electron at the surface is higher than the work function (ϕ), then the emission of electron takes place.
  - A part of the energy absorbed by an electron at the surface is utilised towards the work function and the rest appears as the maximum kinetic energy (KE_{max}) of the electron.
- Therefore,

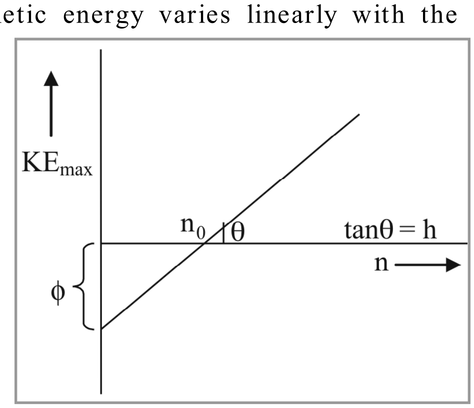
  $h\nu = \phi + KE_{max}$ Or, $KE_{max} = h\nu - \phi \; \dots (i)$

  Equation (i) is referred to as Einstein's photoelectric equation
- If the energy transferred by the photon is just sufficient to eject the electron from the surface, then the frequency of photon is threshold frequency (ν_0).

  Here, KE = 0 and $h\nu_0 = \phi \; \dots (ii)$
- From (i) and (ii), Einstein's photoelectric equation becomes,

  $KE_{max} = h(\nu - \nu_0)$
- Success of Einstein's explanation:
  - Photoelectric current depends on the number of electrons emitted per second. But this is directly proportional to the number of photons incident which in turn increases with the intensity of light. Therefore, photoelectric current increases with the intensity of light. (This is when is a constant)
  - Photoelectric equation shows that the maximum kinetic energy varies linearly with the frequency of the incident radiation and is independent of intensity.
  - Photoelectric equation also shows that when $\nu < \nu_0$, kinetic energy is negative. This is impossible. It necessitates the frequency of radiation to be equal to or greater than the threshold frequency.
  - The energy of photon is localised and the electron is knocked out as soon as the photon with sufficient energy meets the electron. There is no detectable time lag in this process.
  - The plot between KE_{max} max and is a straight line, the slope of which gives the value of the Planck's constant (h).

    This verifies Einstein's theory experimentally.



4. PARTICLE NATURE OF LIGHT - PHOTON

The particle nature of light is revealed in photoelectric effect. Light photon interacted with electron as a quantum of energy. The reverse can be seen in Compton effect, where, the X-ray photons get scattered by electrons as if they are real particles.

The properties of photons can be summarised as follows.

- Photons have no charge and zero rest mass
- They can be considered a real particle having mass $m = \frac{hv}{c^2}$ (as $E = mc^2$)
- The energy associated with a photon of frequency v is $h\,v$.
- Einstein has defined the relation between energy (E) and momentum (p) of a particle in special theory of relativity as

  $$E = \sqrt{p^2c^2 + m_0{}^2c^4}$$

  where, m_0 is the rest mass of the particle. This is applicable to photons as well.
  If the rest mass of the particle is zero, $E = pc$

∴ Momentum of photon of frequency f is $p = \frac{E}{c} = \frac{hv}{c}$

- Photon, like a real particle, interacts with other particles following the laws of conservation of momentum and energy.

5. WAVE NATURE OF MATTER

- Photoelectric effect and Compton effect can be explained by using the particle nature of light.
- Momentum (p) of a photon of wavelength (λ) is given by:

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

- Certain experiments revealed that electrons produced patterns attributed to waves. It lead to the conclusion that electron had wavelike properties.
- Louis de Broglie established a relation between the momentum and wavelength of an electron that can be given as:

  $$\text{Wave length} = \frac{\text{Planck's constant}}{\text{Momentum}}$$

  $$\lambda = \frac{h}{p} = \frac{h}{mv} \qquad \ldots(i)$$

  Equation (i) is called de Broglie relation and λ is the wavelength of matter wave called de Broglie wavelength.
- de Broglie equation is applicable to all types of matter. It shows that λ is smaller for heavier particles.
- In certain situations like electron diffraction, it is easier to measure the kinetic energy (K) of the electron than its momentum.

  $$K = \frac{1}{2}mv^2 \Rightarrow mv = \sqrt{2mK}$$

  Equation (i) becomes, $\lambda = \frac{h}{\sqrt{2mK}}$ …(ii)
- For an electron accelerated from rest through a potential difference of V volts,
  $K = eV$

  Then (ii) becomes, $\lambda = \frac{h}{\sqrt{2meV}}$ …(iii)

Putting the values of h, m and e in (iii),

$$\lambda = \frac{1.227}{\sqrt{V}}\ mm$$

- Matter waves associated with electrons could be verified by crystal diffraction experiments.
- Equation (iii) can be generalised for any charged particle with mass m and charge q accelerated through a pd of V volts:

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

- A concept of wave packet is introduced to explain the wave activity of matter waves.

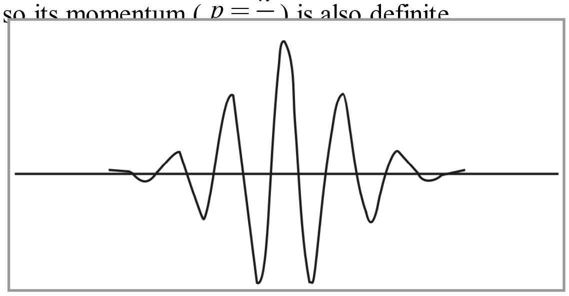
The figure shows the resultant of the superposition of many harmonic waves with continuously changing wavelengths. The non-zero displacement of the resulting wave limited to a small part of the space can represent a particle.

- The concept of matter waves led to Heisenberg's uncertainty principle.

The probability of finding a particle is greater in the region of its greater displacement.

For a single harmonic wave, such a probability is the same anywhere on its path or, the position of the particle is uncertain.

But the wavelength of the single harmonic wave is definite, so its momentum ($p = \frac{h}{\lambda}$) is also definite.



If more waves are superposed and the wave packet is made finite, the position of the particle will be more definite. But in such a wave packet, the wavelength of the wave packet and hence its momentum becomes uncertain.

- Heisenberg's uncertainty principle states that it is not possible to measure both the position and momentum of an electron (or any other particle) at the same time exactly.

If the uncertainty in the x-coordinate of the position of a particle is Δx and uncertainty in the x-component of its momentum is Δp, then $\Delta x.\Delta p \approx \frac{h}{2\pi} = \hbar$ ($\hbar$ is defined to be $\frac{h}{2\pi}$)

$\Rightarrow$ if $\Delta x \to 0$, then, $\Delta p \to \infty$ and if $\Delta p \to 0$, then, $\Delta x \to \infty$

In general, Δx and Δp are non-zero and their product is of the order.

6. DAVISSON - GERMER EXPERIMENT

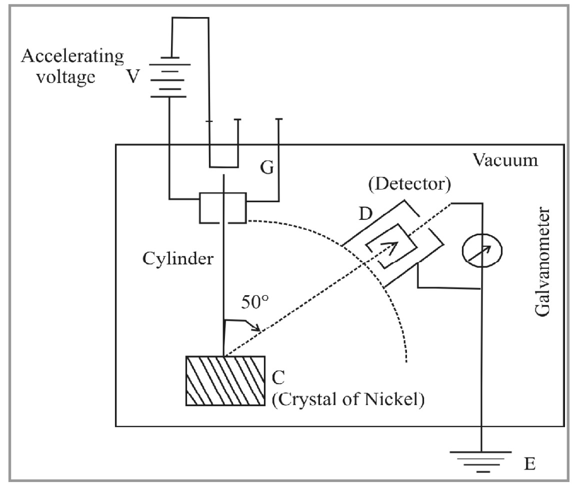
In 1927, Davisson and Germer performed experiments to study scattering of electrons by a piece of nickel placed in vacuum. The experimental set up is shown in the figure below.

G is an electron gun having tungsten filament coated with barium oxide. The electrons emitted by the filament are accelerated using high voltage (V). The electrons are made into a thin beam by a cylinder. The electron beam is made incident on a piece of nickel (C) and get scattered by the atoms of Nickel. D is a detector which can be moved in an arc. The electrons scattered in different directions are detected by D. The current through the detector is measured by the galvanometer which indicates the number of electrons scattered in that direction.

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 accelerating 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 accelerating voltage of 54V at a scattering angle $= 50^{\circ}$.

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.



V, m and e representing the accelerating voltage, mass and charge of the electron respectively, the wavelength is given by,

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

Putting V = 54 V, h = 6.62×10^{-34} Js, m = 9.1×10^{-31} kg and e = 1.6×10^{-19} C, the value of λ works out to be 1.66×10^{-10} m or 0.166 nm.

Thus, it is found that the theoretical value for the de Broglie wavelength is in agreement with the value obtained by Davisson–Germer experiment. This confirms the wave nature of electrons and the de Broglie relation.

Previous Years Questions

2012

1. Write Einstein's photoelectric equation. State clearly how this equation is obtained using the photon picture of electromagnetic radiation.

Write the three salient features observed in photoelectric effect which can be explained using this equation **(3 Marks)**

2011

1. When monochromatic light travels from one medium to another its wavelength changes but frequency remains the same. Explain. **(1 Marks)**

2. Show graphically, the variation of the de-Broglie wavelength (λ) with the potential (V) through which an electron is accelerated from rest. **(1 Marks)**

3. An electron and a photon each have a wavelength of 2 nm. Find

(i) their momenta (ii) the energy of the photon (iii) the kinetic energy of the electron.

2010

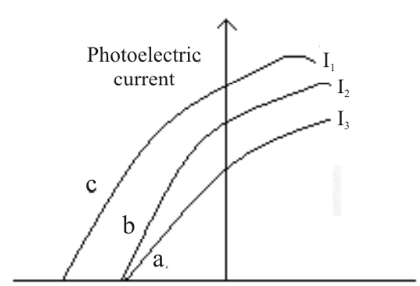
1. An electron is accelerated through a potential difference of 64 volts. What is the de-Broglie wavelength associated with it? To which part of the electromagnetic spectrum does this value of wavelength correspond? **(2 Marks)**

2. Plot a graph showing the variation of stopping potential with the frequency of incident radiation for two different photosensitive materials having work functions W1 and W2 (W1 > W2). On what factors does the (i) slope and (ii) intercept of the lines depend? **(2 Marks)**

2009

1. The figure shows a plot of three curves a, b, c showing the variation of photocurrent vs collector plate potential for three different intensities I_1, I_2 and I_3 having frequencies v_1, v_2 and v_3 respectively incident on a photosensitive surface.

Point out the two curves of which the incident radiations have same frequency but different intensities. **(1 Mark)**



2008

1. An electron and alpha particle have the same de-Broglie wavelength associated with them. How are their kinetic energies related to each other. **(1 Mark)**

2. An electromagnetic wave of wavelength λ is incident on a photosensitive surface of negligible work function. If the photoelectrons emitted from this surface have the de-Broglie wavelength λ_1, prove that $\lambda = \frac{2mc}{h}\lambda_1^2$ **(3 Marks)**

2007

1. An electron, an alpha-particle and a proton have the same kinetic energy. Which one of these particles has the largest de Broglie wavelength. **(1 Mark)**

2. Ultraviolet radiations of different frequencies v_1 and v_2 are incident on two photosensitive materials having work functions ϕ_1 and ϕ_2 respectively. The kinetic energy of the emitted electrons is same in both the cases. Which one of the two radiations will be of higher frequency. **(1 Mark)**

3. Show graphically how the stopping potential for a given photosensitive surface varies with the frequency of incident radiations. **(1 Mark)**

4. Draw a schematic diagram of the experimental arrangement used by Davisson and Germer to establish the wave nature of electrons. Explain briefly how the de-Broglie relation was experimentally verified in case of electrons. **(3 Marks)**

5. In a plot of photoelectric current versus anode potential, how does **(3 Marks)**

(*i*) The saturation current vary with anode potential for incident radiations of different frequencies but same intensity.

(*ii*) The stopping potential vary for incident radiations of different intensities but same frequency.

(*iii*) Photoelectric current vary for different intensities but same frequency of incident radiations. Justify your answer in each case.

6. An electron, α-particle and a proton have the same de Broglie wavelength. Which of these particles has: **(3 Marks)**

(*i*) minimum kinetic energy (*ii*) maximum kinetic energy.

Give reasons for your answers.

In what way has the wave nature of electron been exploited in electron microscope.

2006

1. With what purpose was famous Davisson-Germer experiment with electrons performed. **(1 Mark)**

2. How will the photoelectric current change on decreasing the wavelength of incident radiation for a given photosensitive material. **(1 Mark)**

3. de Broglie wavelength associated with an electron accelerated through a potential difference V is λ. What will be its wavelength when the accelerating potential is increased to 4V. **(1 Mark)**

4. Name the experiment which establishes the wave nature of a particle. **(1 Mark)**

5. Draw the graphs showing the variation of photoelectric current with anode potential of a photocell for **(3 Marks)**

(*i*) The same frequencies but different intensities $I_1 > I_2 > I_3$, of incident radiation,

(*ii*) The same intensity but different frequencies $V_1 > V_2 > V_3$ of incident radiation. Explain why the saturation current is independent of the anode potential.

6. Define the terms threshold frequency and stopping potential in relation to the phenomenon of photoelectric effect. How is the photoelectric current affected on increasing the:

(*i*) frequency

(*ii*) intensity of the incident radiations and why. **(3 Marks)**

7. Sketch a graph between frequency of incident radiations and stopping potential for a given photosensitive material. What information can be obtained from the value of the intercept on the potential axis. **(3 Marks)**

A source of light of frequency greater than the threshold frequency is placed at a distance of 1 m from the cathode of a photo-cell. The stopping potential is found to be V. If the distance of the light source from the cathode is reduced, explain giving reasons, what change will you observe in the

(*i*) photoelectric current, (*ii*) stopping potential.

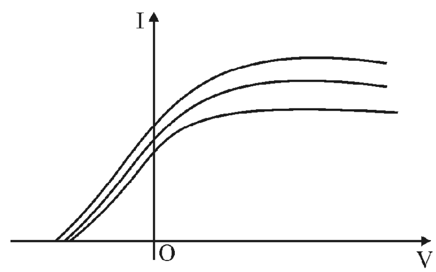
8. Sketch the graphs, showing the variation of stopping potential with frequency of incident for two photosensitive materials A and B having threshold frequencies $V_0 > V_0'$ respectively. **(3 Marks)**
(*i*) Which of the two metals, A or B has higher work function.
(*ii*) What information do you get from the slope of the graphs.
(*iii*) What does the value of the intercept of graph 'A' on the potential axis represent.

2005

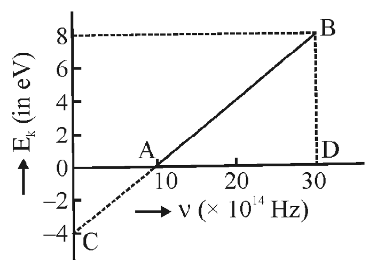
1. Electrons are emitted from a photosensitive surface when it is illuminated by green light but electron emission does not take place by yellow light. Will the electrons be emitted when the surface is illuminated by **(1 Mark)**
(*i*) red light, and
(*ii*) blue light.

2. Ultraviolet light is incident on two photosensitive materials having work functions W_1 and W_2 ($W_1 > W_2$), In which case will the kinetic energy of the emitted electrons be greater. Why. **(1 Mark)**

3. In an experiment on photoelectric effect, the following graphs were obtained between the photoelectric current (I) and the anode potential (V). Name the characteristic of the incident radiation that was kept constant in this experiment. **(1 Mark)**



4. Given below is the graph between frequency (v) of the incident light and maximum kinetic energy (E_k) of emitted photoelectrons. Find the values of **(2 Marks)**
(*i*) thresh old frequency, and (*ii*) work function from the graph.



5. An electron and a proton are moving in the same direction and possess same kinetic energy. Find the ratio of de Broglie wavelengths associated with these particles. **(2 Marks)**

6. Mention the significance of Davisson-Germer experiment. An α-particle and a proton are accelerated from rest through the same potential difference V. Find the ratio of de-Broglie wavelengths associated with them. **(3 Marks)**

7. Ultraviolet light of wavelength 2271 Å from a 100 W mercury source radiates a photo cell made of molybdenum metal. If the stopping potential is 1.3 V, estimate the work function of the metal. How would the photo cell respond to high intensity (10^5 Wm^{-2}) red light of wavelength 6328 Å produced by a He - Ne laser. Plot a graph showing the variation of photoelectric current with anode potential for two light beams of same wavelength but different intensity. **(3 Marks)**

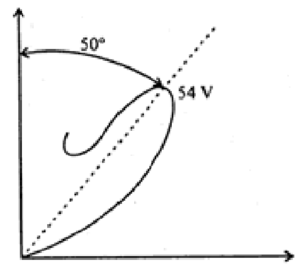
2004

1. Two metals A and B have work functions 4 eV and 10 eV respectively. Which metal has higher threshold wavelength. **(1 Mark)**

2. Two beams, one of red light and the other of blue light, of the same intensity are incident on a metallic surface to emit photoelectrons. Which one of the two beams emits electrons of greater kinetic energy. **(1 Mark)**

3. Name the experiment for which the following graph, showing the variation of intensity of scattered electrons with the angle of scattering, was obtained. Also name the important hypothesis that was confirmed by this experiment.

(1 Mark)



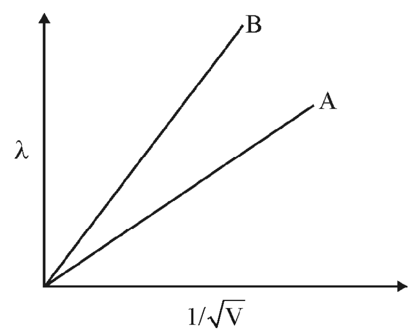
4. Define the term 'work function' of a metal. The threshold frequency of a metal is f_0. When the light of frequency $2f_0$ is incident on the metal plate, the maximum velocity of electrons emitted is v_1. When the frequency of the incident radiation is increased to $5f_0$, the maximum velocity of electrons emitted is v_2. Find the ratio of v_1 to v_2. **(3 Marks)**

5. Red light, however bright it is, cannot produce the emission of electrons from a clean zinc surface. But even weak ultraviolet radiation can do so. Why. **(3 Marks)**

X-rays of wavelength fall on photosensitive surface, emitting electrons. Assuming that the work function of the surface can be neglected, prove that the de Broglie wavelength of electrons emitted will be $\sqrt{\dfrac{h\lambda}{2mc}}$.

6. Obtain the expression for the wavelength of de Broglie wave associated with an electron accelerated from rest through a potential difference V. **(3 Marks)**

7. The two lines A and B shown in the graph plot the de Broglie wavelength λ as a function of $\dfrac{1}{\sqrt{V}}$ (V is the accelerating potential) for two particles having the same charge. Which of the two represents the particle of heavier mass.



8. Obtain Einstein's photoelectric equation. Explain how it enables us to understand the **(3 Marks)**

(*i*) linear dependence, of the maximum kinetic energy of the emitted electrons, on the frequency of the incident radiation.

(*ii*) existence of a threshold frequency for a given photo-emitter.

