Dual nature of radiation and Matter

This note is provided by the physics classes by Nayan jha in which discussed topics are

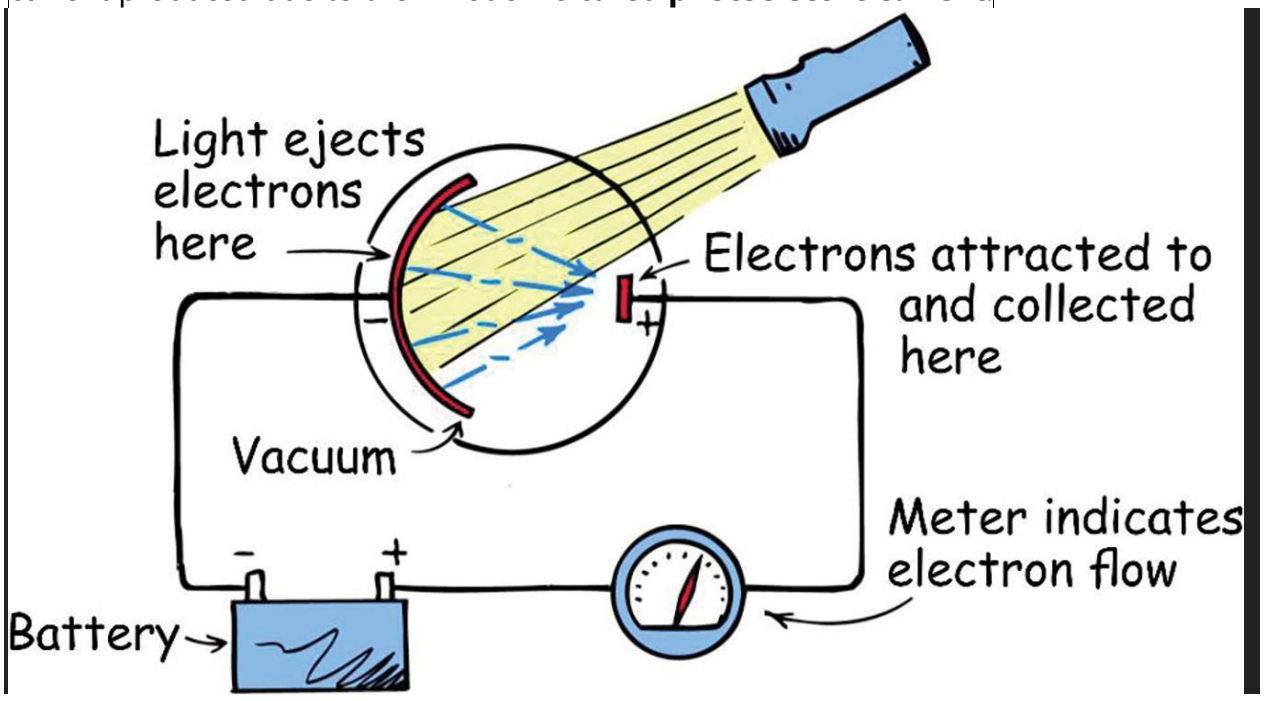
1. What is photeo electric effect and photo electric current?.
2. Hertz obseravation
3. Hallwach's and Lenards observation ,
4. Einstein's photoelectric equation (related graphs)
5 de Broglie wave nature of matter.
6 Davisson - Germer experiment

Photoelectric Effect – Class 12 Physics (CBSE)

1. What is the Photoelectric Effect?

Definition: The phenomenon of emission of electrons from the surface of a metal when light of suitable frequency falls on it is called the **photoelectric effect**.

The electrons emitted from the metal surface are called **photoelectrons**, and the current produced due to their motion is called **photoelectric current**.



Explanation:

1. When light falls on a metal surface, energy is transferred from photons to electrons.
2. If the energy received by an electron is sufficient to overcome the attraction of the metal surface, the electron gets emitted.

3. These emitted electrons are known as photoelectrons.
4. The emission of electrons takes place only when the frequency of incident light is equal to or greater than a minimum frequency called the threshold frequency.

Important terms:

- **Photoelectrons:** Electrons emitted from the metal surface.
- **Threshold frequency (ν_0):** Minimum frequency of incident light required for photoelectric emission.
- **Work function (ϕ_0):** Minimum energy required to remove an electron from the metal surface.
- **Stopping potential:** Minimum negative potential applied to stop the fastest photoelectrons.

Einstein's photoelectric equation:

$h\nu=\phi_0+K_{max}$

Or,

$h\nu=h\nu_0+\frac{1}{2}mv_{max}^2$

2. Hertz's Observation (1887)

Heinrich Hertz

Hertz discovered the photoelectric effect accidentally while performing experiments to produce electromagnetic waves.

Observations:

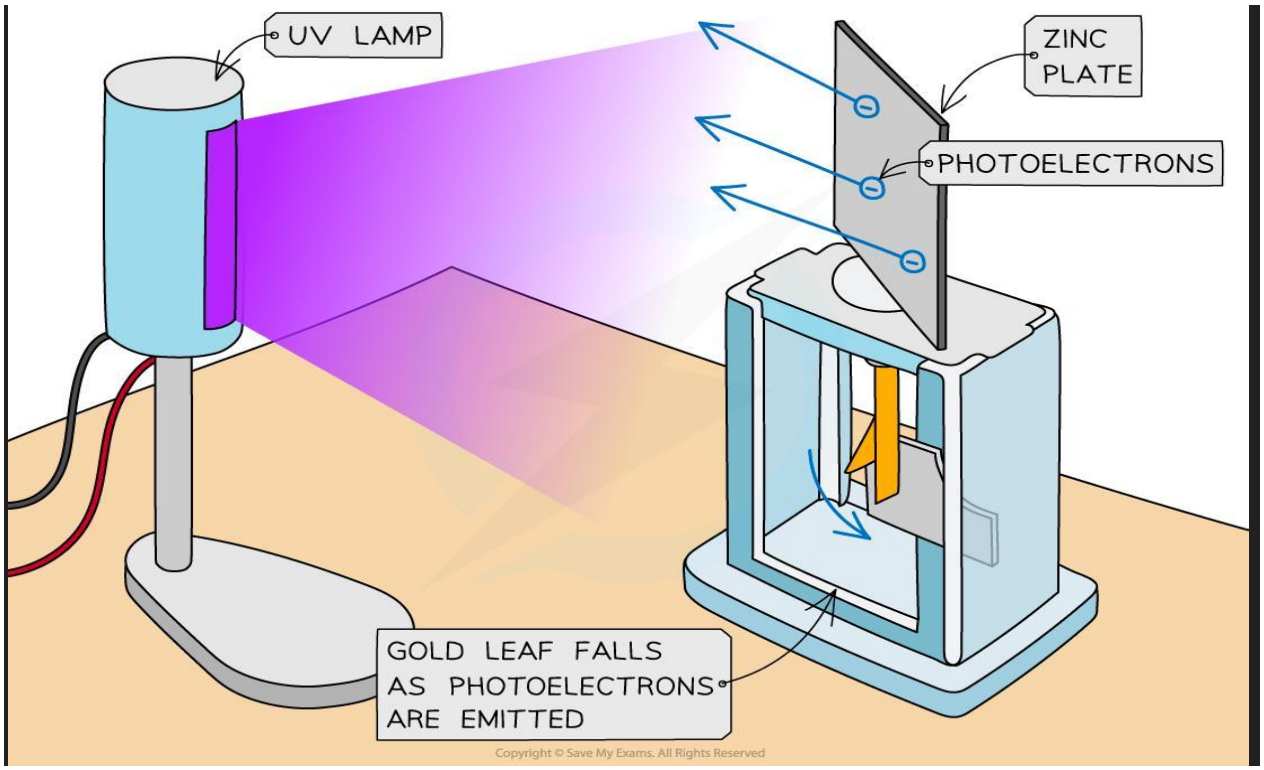
Hertz observed that when ultraviolet light was allowed to fall on a metal surface, the spark discharge between two electrodes became easier.He found that ultraviolet radiation helped in the emission of electrons from the metal surface.This showed that light can influence the emission of electrons from a metal.

Conclusion: Ultraviolet radiation helps in the emission of electrons from a metal surface.

3. Hallwachs' Observation (1888)

Wilhelm Hallwachs

Hallwachs performed an experiment using a clean zinc plate connected to an electroscope.



Observations:

When ultraviolet light was allowed to fall on a negatively charged zinc plate, the leaves of the electroscope collapsed.This happened because the zinc plate emitted negatively charged particles (electrons).When ultraviolet light was allowed to fall on a positively charged zinc plate, no discharge was observed.An uncharged zinc plate became positively charged when exposed to ultraviolet radiation.

Conclusion: Ultraviolet light causes the emission of negatively charged particles (electrons) from a metal surface.

4. Lenard's Observation (1902)

Philipp Lenard

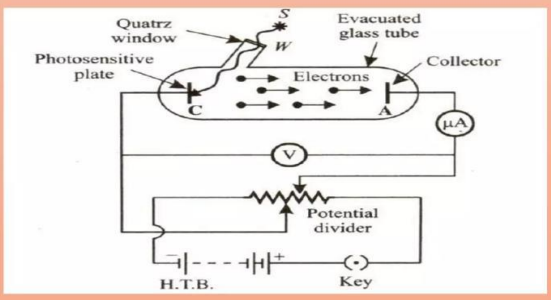
Lenard studied the photoelectric effect experimentally and investigated the behaviour of emitted electrons.

EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT :

Philipp **Lenard** studied the photoelectric effect practically.

Fig. shows his experimental setup

C – Metallic cathode
A – Metallic Anode
W – Quartz Window



When light of suitable frequency falls on the metallic cathode, photoelectrons are emitted. These photoelectrons are attracted towards the +ve anode and hence photoelectric current is constituted.

Observations:

1. Lenard observed that when ultraviolet light falls on a metal surface, electrons are emitted from it.The photoelectric current increases with an increase in the intensity of incident light, provided the frequency is above the threshold frequency.The maximum kinetic energy of photoelectrons depends on the frequency of incident light and is independent of its intensity.For a given metal, photoelectric emission takes place only when the frequency of incident light is greater than or equal to the threshold frequency.

Conclusion: The intensity of light controls the number of photoelectrons emitted, whereas the frequency of light determines their maximum kinetic energy.

5. Difference between Hertz, Hallwachs and Lenard's Observations

Scientist	Main observation
Hertz	UV light helps in producing spark discharge.
Hallwachs	UV light causes emission of electrons from a negatively charged zinc plate.
Lenard	Studied photoelectric current and the dependence of electron kinetic energy on frequency.

Einstein's Photoelectric Equation

Einstein explained the photoelectric effect in 1905 on the basis of **Planck's quantum theory of radiation**.

His explanation successfully explained the experimental observations which classical wave theory of light could not explain.

1. Einstein's explanation of the photoelectric effect

According to Einstein:

1. Light consists of small packets of energy called **photons (quanta)**.
2. Each photon carries energy proportional to the frequency of incident light.
3. The energy of each photon is given by:

$E = hv$

4. One photon transfers its energy to one electron of the metal.
5. A part of this energy is used to overcome the attraction of the metal surface. This minimum energy is called the work function.
6. The remaining energy appears as the kinetic energy of the emitted electron.

2. Einstein's Photoelectric Equation

According to the law of conservation of energy:

$$\mathbf{hv = K_{max} + \Phi_0}$$

This is called **Einstein's photoelectric equation**.

Where:

h = plank constant

Φ_0 = work function and

K_{max}=kinetic energy

We know that:

$$\mathbf{\Phi_0 = hv_0}$$

Therefore, $K_{max} = hv - hv_0$

$\frac{1}{2} mv^2 = hv - hv_0$

Since maximum kinetic energy is also related to stopping potential:

K_{max}= eVo

Therefore,

K_{max}= eVo = hv-hv_0

These are the important forms of Einstein's photoelectric equation.

3. Important features of Einstein's photoelectric equation

1. **Threshold frequency:** Photoelectric emission takes place only when the frequency of incident light is greater than or equal to the threshold frequency.

2. **Instantaneous emission:** Photoelectric emission takes place almost instantaneously because one photon transfers its energy to one electron.

3. **Effect of intensity:** Photoelectric current increases with an increase in intensity of incident light, provided frequency is above threshold frequency.

4. **Effect of frequency:** Maximum kinetic energy of photoelectrons increases with an increase in frequency of incident light.

5. **Independent of intensity:** Maximum kinetic energy of photoelectrons does not depend on the intensity of incident light.

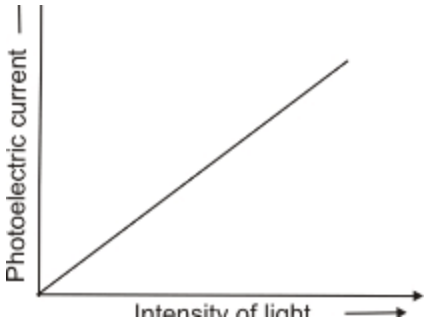
6. **Work function:** Different metals have different work functions and therefore different threshold frequencies.

Graphs based on Einstein's Photoelectric Equation

The following graphs are very important for CBSE Class 12 board examinations.

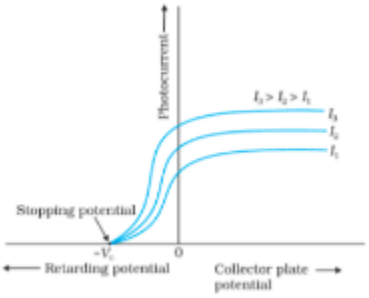
Photoelectric Current vs. Intensity of Light

Photoelectric current increases linearly with the intensity of incident light, provided the frequency is above the threshold frequency.



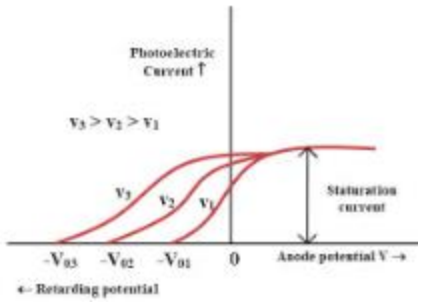
Photoelectric Current vs. Collector Plate Potential (Different Intensities)

When frequency is kept constant, increasing intensity (\(I_3 > I_2 > I_1\)) increases the saturation current, while the **stopping potential (\(-V_{0}\))** stays the same.



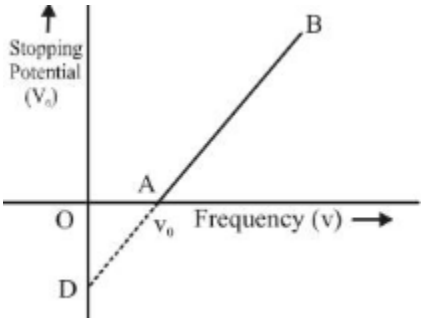
Photoelectric Current vs. Collector Plate Potential (Different Frequencies)

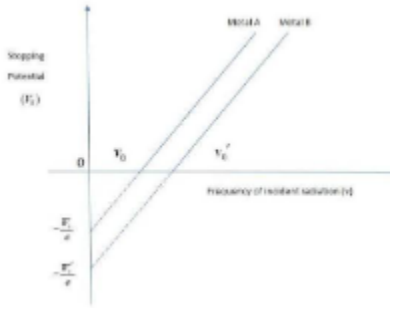
When intensity is kept constant, increasing frequency (\(\nu_3 > \nu_2 > \nu_1\)) results in a more negative **stopping potential**, while the **saturation current** remains identical.



Stopping Potential V_0 vs. Frequency of Incident Radiation

This straight-line graph intersects the frequency axis at the **threshold frequency (\(\nu _{0}\))** and has a constant slope equal to **\(h/e\)**. For different metals, the lines are parallel.





a horizontal straight line.

Increasing the intensity of incident light increases the number of photoelectrons, not their maximum kinetic energy.

Determination op Planck's constant and work function , using the graph of potential v/s frequency using Einstein's equation.

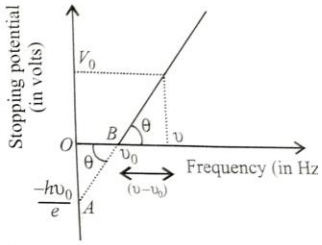
- **Determination of Planck's constant and work function**

According to Einstein's photoelectric equation, $K_{max} = h\upsilon - W_0$

$$\therefore \quad eV_0 = h\upsilon - W_0 \Rightarrow V_0 = \left(\frac{h}{e}\right)\upsilon - \frac{W_0}{e} = \left(\frac{h}{e}\right)\upsilon - \frac{h\upsilon_0}{e}$$

We compare this equation with the straight line equation, $y = mx + c$

It shows that the V_0 versus υ curve is a straight line with slope $(= h/e)$ as shown in the figure. Slope is independent of the nature of the material.



$$\text{Slope, } \tan\theta = \frac{V_0}{(\upsilon - \upsilon_0)} = \frac{eV_0}{e(\upsilon - \upsilon_0)} = \frac{\frac{1}{2}mv_{max}^2}{e(\upsilon - \upsilon_0)} = \frac{h(\upsilon - \upsilon_0)}{e(\upsilon - \upsilon_0)} = \frac{h}{e}$$

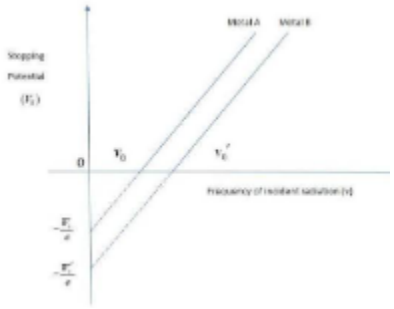
Thus, Planck's constant h can be determined.

However, the intercept of this curve on the potential axis is at $-OA = OB\tan\theta = \upsilon_0\frac{h}{e}$ or $OA = -\frac{h\upsilon_0}{e}$

$\therefore \quad W_0 = h\upsilon_0 = e \times OA$

Thus, work function W_0 can be determined.

5. Comparison of graphs for different metals



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Important observations:

1. Both lines have the same slope.
2. Different metals have different threshold frequencies.
3. Metal having a greater work function has a greater threshold frequency.
4. The graph of the metal with greater threshold frequency cuts the frequency axis farther to the right.



Observations:

- Photoelectric current increases linearly with intensity.
- Doubling the intensity approximately doubles the photoelectric current.
- The maximum kinetic energy remains unchanged.

De Broglie Wavelength –

1. Expression for de Broglie wavelength

According to de Broglie's hypothesis, every moving material particle has a wave associated with it. This wave is called a **matter wave** or **de Broglie wave**.

The wavelength associated with a moving particle is called its de Broglie wavelength.

According to de Broglie:

ʎ= h/p = h/mv

Where:

ʎ = de Broglie wavelength

h = Planck's constant

m = mass of particle

v = velocity of particle

Derivation of de Broglie's Hypothesis

de Broglie's hypothesis: According to Louis de Broglie, every moving material particle has a wave associated with it. These waves are called matter waves or de Broglie waves.

Derivation of de Broglie wavelength

De Broglie used the following two equations:

Step 1: According to Planck's quantum theory

The energy of a photon is given by:

$E=hv$

Since,

$V= c/\lambda$

Therefore,

$E=hc/\lambda$

Step 2: According to Einstein's mass-energy relation

$E=mc^2$

For a photon, momentum is:

P=mc=E/c ,

Or, E= pc….i

And $E=hc/\lambda$……ii

From eq. I and ii

Pc=hc/ʎ

P=h/ʎ

Therefor ʎ=h/p=h/mv

This is called the **de Broglie wavelength equation**.

de Broglie wavelength of an electron

If an electron is accelerated through a potential difference \(V\), then:

Electrical energy gained = Kinetic energy gained

$eV=1/2\ mv^2$ [v= velocity of electron]

$mv=\sqrt{2meV}$ [V= potential]

Using,

ʎ=h/mv

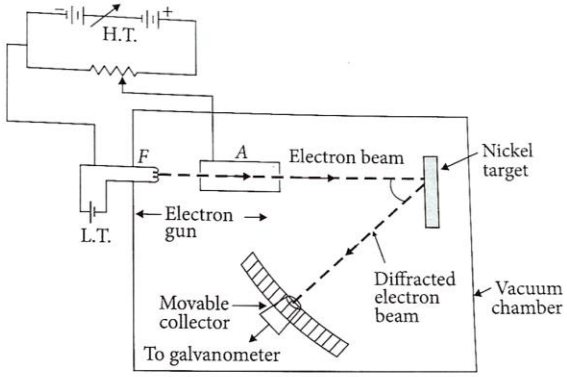
We get: ʎ=h/p=h/mv=h/√2mv

On substituting the values of constants:

ʎ=12.27/√V amstrong.

Here,V is in volts.

The apparatus used in the Davisson-Germer experiment is shown in the figure. A beam of electrons from the heated filament F is accelerated through a voltage V and strikes a target consisting of a single crystal of nickel. The scattered electrons are observed in detector which can be moved to various angles θ relative to the incident beam.



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 54 V at a scattering angle θ = 50°.

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.

The de Broglie wavelength λ associated with electrons for $V = 54$ V is given by

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

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.

3. Important points for CBSE examination

- de Broglie wavelength is inversely proportional to momentum.
- Greater momentum means smaller wavelength.
- Matter waves are associated with moving material particles.
- The wave nature of electrons was experimentally verified by the Davisson-Germer experiment.

Important for 3 Marks

Final result to remember:

Note: This is a derivation based on de Broglie's proposed extension of the photon momentum relation. It is not an independent experimental proof of the hypothesis. The experimental verification was provided by the Davisson-Germer experiment.

3. Value of de Broglie wavelength of an electron

The de Broglie wavelength depends on the accelerating potential.

Accelerating potential	de Broglie wavelength
1 V	12.27 Å
10 V	3.88 Å
100 V	1.227 Å
150 V	1.00 Å
1000 V	0.388 Å

5. Important CBSE questions

1. State de Broglie's hypothesis.
2. Derive the expression for the de Broglie wavelength of an electron accelerated through a potential difference \(V\).
3. Calculate the de Broglie wavelength of an electron accelerated through 100 V.
4. How does the de Broglie wavelength change when the accelerating potential is increased four times?

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10. Important board examination questions

1. State Einstein's photoelectric equation and explain each term.
2. Draw the graph between maximum kinetic energy and frequency of incident radiation.
3. What is the physical significance of the slope of the Kmax versus frequency graph?
4. Draw the graph between stopping potential and frequency.
5. Why are the graphs of maximum kinetic energy versus frequency parallel for different metals?
6. Draw the graph between photoelectric current and intensity of incident light.

7. Why does maximum kinetic energy remain unchanged when the intensity of incident light is increased?
8. Draw the graph between maximum kinetic energy and wavelength.

6. Important CBSE Board Examination Questions

Very Short Answer Questions (1 Mark)

1. Define the photoelectric effect.
2. What are photoelectrons?
3. Define threshold frequency.
4. What is the work function of a metal?
5. Who discovered the photoelectric effect?

Short Answer Questions (2–3 Marks)

1. Explain Hallwachs' experiment and its observations.
2. State Hertz's observations related to the photoelectric effect.
3. Explain Lenard's observations.
4. How does photoelectric current depend on the intensity of incident light?
5. How does the maximum kinetic energy of photoelectrons depend on the frequency of incident light?

Important Conceptual Question (3 Marks)

Why does increasing the intensity of incident light not increase the maximum kinetic energy of photoelectrons?

Answer: Increasing the intensity of light increases the number of incident photons and hence the number of emitted photoelectrons. However, the energy of each photon depends on its frequency $E=hv$, Therefore, at constant frequency, the maximum kinetic energy of photoelectrons remains unchanged.

Important for CBSE

Remember these three points:

Intensity of light increases → Photoelectric current increases.

Frequency of light increases → Maximum kinetic energy increases.

Frequency below threshold frequency → No photoelectric emission, irrespective of intensity.

[redacted]