Class XII Physics Notes: Chapter 11: Dual Nature of Radiation and Matter

PART 1: Dual Nature of Radiation — Photon Concept and Photoelectric Effect

1.1 Introduction

Classical physics could successfully explain many properties of light such as:

- Reflection
- Refraction
- Interference
- Diffraction
- Polarisation

These phenomena strongly support the **wave nature of light**. However, certain phenomena, especially the **photoelectric effect**, cannot be satisfactorily explained by the classical wave theory of light. This led to the development of the **quantum theory of radiation**.

According to quantum theory, light behaves as if it is made up of discrete packets of energy called **photons**.

Thus, light shows a **dual nature**:

- Wave nature → interference, diffraction, polarisation
- Particle nature → photoelectric effect, photon interactions

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1.2 Wave Nature and Particle Nature of Light

Light exhibits two apparently different behaviours.

Wave nature

The wave nature of light is demonstrated by:

1. Interference
2. Diffraction
3. Polarisation

For a wave:

$$v = f\lambda$$

Where: v = speed of wave; f = frequency; λ = wavelength

For electromagnetic radiation in vacuum:

$$c = f\lambda$$

Where:

$$c = 3 \times 10^8\, m/s$$

Particle nature

According to the quantum theory, electromagnetic radiation consists of discrete packets of energy called **photons**.

Each photon has energy:

$$E = hf$$

Using:

$$f = c/\lambda$$

We get:

$$E = hc/\lambda$$

Where: E = energy of photon; h = Planck's constant; f = frequency; c = speed of light;

λ = wavelength
Planck's constant:

$$h = 6.626 \times 10^{-34}\, J\, s$$

1.3 Photon

A **photon** is a quantum (discrete packet) of electromagnetic radiation. The energy of one photon is:

$$E = hf$$

Or

$$E = hc/\lambda$$

Important properties of photons

1. A photon has energy:
$$E = hf$$
2. A photon has momentum:
$$p = h/\lambda$$
3. A photon has zero rest mass.
4. Photons travel in vacuum with speed:
$$c = 3 \times 10^{8}\, m/s$$
5. Photon energy depends on frequency.
Higher frequency → higher photon energy.
6. Photon energy is inversely proportional to wavelength.
$$E \propto 1/\lambda$$

1.4 Photon Momentum

Although a photon has zero rest mass, it carries momentum. The momentum of a photon is:

$$p = h/\lambda$$

Since:

$$E = hc/\lambda$$

And

$$p = h/\lambda T$$

Therefore:

$$E = pc$$

Or

$$p = E/c$$

Important Formula Box

Photon energy:

$$E = hf = hc/\lambda$$

Photon momentum:

$$p = h/\lambda = E/c$$

1.5 Energy of Multiple Photons

If N photons are present, each having energy E.
Total energy:

$$\boxed{E_{total} = Nhf}$$

Therefore:

$$\boxed{E_{total} = \frac{Nhc}{\lambda}}$$

This formula is useful in numerical problems involving the number of photons.

1.6 Photon Energy in Electron Volt

The energy of a photon is often expressed in electron volt (eV).
We know:

$$1\ eV\ =\ 1.602\ \times\ 10^{-19}\ J$$

For a photon:

$$E\ =\ hc/\lambda$$

A very useful relation is:

$$E(eV) = \frac{1240}{\lambda(nm)}$$

Therefore:

Important Numerical Formula

$$\boxed{E(eV) = \frac{1240}{\lambda(nm)}}$$

This formula is extremely useful for **NEET/JEE numerical problems**.

Example

Find the energy of a photon of wavelength 620 nm.
Using:

$$E\ =\ 1240/\lambda$$

Or,

$$E\ =\ 1240/620$$

Or

$$E\ =\ 2\ eV$$

Therefore: **Energy of photon = 2 eV**

1.7 Photon Flux

- Photon emission rate = photons emitted per second.
- Photon flux = photons incident per unit area per unit time.

The number of photons incident per second is called **photon flux**. If a source emits power P and each photon has energy E:
Number of photons emitted per second:

$$N\ =\ P/E$$

Since:

$$E\ =\ hf$$

Therefore:

$$N\ =\ P/hf$$

Or:

$$\boxed{N = \frac{P\lambda}{hc}}$$

For a uniform beam of cross-sectional area A:

$$\boxed{Photon\ Flux = \frac{P}{Ahf}}$$

Where: P = power of radiation, N = number of photons emitted per second

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1.8 Photoelectric Effect

The **photoelectric effect** is the phenomenon of emission of electrons from a metal surface when electromagnetic radiation of suitable frequency falls on it. The emitted electrons are called **photoelectrons**.

The current produced due to these electrons is called **photoelectric current**.

Basic terminology

- Incident radiation → incoming light
- Photocathode → photosensitive metal surface
- Photoelectrons → emitted electrons
- Photoelectric current → current due to photoelectrons
- Anode → collects emitted electrons

1.9 Experimental Observation of Photoelectric Effect

When light falls on a suitable metal surface, electrons may be emitted.

The important experimental observations are:

Observation 1: Threshold Frequency

For every metal, there exists a minimum frequency of incident radiation below which photoelectric emission does not occur.

This minimum frequency is called the **threshold frequency**. It is represented by f_0.

Therefore, If $f < f_0$ → No photoelectric emission.

If $f \geq f_0$ → Photoelectric emission is possible.

1.10 Threshold Wavelength

Corresponding to threshold frequency f_0, there is a maximum wavelength capable of producing photoelectric emission.

It is called the **threshold wavelength**.

It is represented by λ_0.

Since:

$$c = f_0\lambda_0;$$

Therefore:

$$\boxed{\lambda_0 = \frac{c}{f_0}}$$

Important Result

Photoelectric emission occurs when:

$$f \geq f_0$$

Equivalently:

$$\lambda \leq \lambda_0$$

1.11 Work Function

The minimum energy required to remove an electron from the surface of a metal is called its **work function**. It is represented by φ_0.

The work function is related to threshold frequency by:

$$\varphi_0 = hf_0$$

Therefore:

$$f_0 = \varphi_0 h$$

Using:

$$f_0 = \frac{c}{\lambda_0}$$

We get:

$$\boxed{\varphi_0 = \frac{hc}{\lambda_0}}$$

1.12 Work Function in Electron Volt

Work function is commonly expressed in electron volt (eV).

For example: Φ_0 = 2.5 eV means that a minimum energy of 2.5 eV is required to liberate an electron from the metal surface.

Conversion:

$$1\ eV\ =\ 1.602\ \times\ 10^{-19}\ J$$

Therefore:

$$\boxed{\varphi_0(J) = \varphi_0(eV) \times 1.6 \times 10^{-19}}$$

1.13 Einstein's Explanation of Photoelectric Effect

Albert Einstein explained the photoelectric effect using Planck's quantum hypothesis.

According to Einstein, light energy is absorbed by matter in discrete packets called photons.

A single photon transfers its energy to a single electron.

Energy of incident photon:

$$E = hf$$

Part of this energy is used to overcome the work function of the metal.

The remaining energy appears as the maximum kinetic energy of the emitted photoelectron.

Therefore:

$$hf = \varphi_0 + K_{max}$$

Hence:

Einstein's Photoelectric Equation

$$K_{max} = hf - \varphi_0$$

Since:

$$\varphi_0 = hf_0$$

We get:

$$K_{max} = hf - hf_0$$

Therefore:

$$\boxed{K_{max} = h(f - f_0)}$$

1.14 Einstein's Equation in Terms of Stopping Potential

The maximum kinetic energy of a photoelectron is related to the stopping potential V_0 by:

$$K_{max} = eV_0$$

Therefore:

$$eV_0 = hf - \varphi_0$$

Or:

$$eV0 \quad = h(f - f_0)$$

Hence:

Important Formula

$$\boxed{V_0 = \left(\frac{h}{e}\right)(f - f_0)}$$

This equation is extremely important for **NEET and JEE numerical problems**.

1.15 Meaning of Stopping Potential

The minimum negative potential applied to the collector that just stops the fastest photoelectrons from reaching it is called the **stopping potential**.

It is represented by: V_0

At stopping potential:

$$K_{max} = eV_0$$

Therefore:

$$\boxed{eV_0 = hf - \varphi_0}$$

1.16 Saturation Current

When all the photoelectrons emitted by the photosensitive surface are collected by the anode, the photoelectric current reaches a maximum value.

This maximum current is called the **saturation current**.

At saturation:

- Increasing the positive collector potential further does not significantly increase the current.
- All emitted photoelectrons are effectively collected.

1.17 Effect of Intensity of Incident Light

For a fixed frequency above threshold:

Increasing intensity → increases number of emitted photoelectrons.

Therefore: Intensity ↑ → Number of photoelectrons ↑ → Photoelectric current ↑

However:

Maximum kinetic energy does not depend on intensity.

Thus: Kmax is independent of intensity.

Similarly: V_0 is independent of intensity.

Very Important Exam Point

Intensity controls the number of photoelectrons, whereas frequency controls their maximum kinetic energy.

1.18 Effect of Frequency

For a fixed intensity, if the frequency of incident radiation is increased: Photon energy increases, because: E = hf
Therefore: Kmax increases.
From Einstein's equation:

$$Kmax = h(f - f_0)$$

Hence:

$$\boxed{f \uparrow \rightarrow Kmax \uparrow and: V_0 \uparrow}$$

1.19 Instantaneous Nature of Photoelectric Effect

When the frequency of incident radiation is above the threshold frequency, photoelectric emission occurs practically without measurable time delay.
This is one of the important observations supporting the photon picture of light.

Classical wave theory difficulty

According to classical wave theory, an electron should gradually absorb energy from a weak wave. But experimentally, photoemission can occur essentially immediately when suitable-frequency radiation falls on the surface.
Einstein's photon model explains this naturally:
One photon transfers its energy to one electron in a single interaction.

1.20 Important Experimental Observations — Quick Table

Quantity	Effect
Intensity increased	Photoelectric current increases
Frequency increased	Maximum kinetic energy increases
Frequency below f_0	No photoelectric emission
Frequency = f_0	Maximum kinetic energy = 0
Frequency above f_0	Photoelectric emission occurs
Intensity increased	Kmax unchanged
Frequency increased	Stopping potential increases

Solved Example 1 — Photon Energy

Question
Calculate the energy of a photon having wavelength 400 nm.
Solution
Use:

$$E\ (eV) = 1240/\lambda(nm)$$

Therefore:

$$E = 1240/400\ Or, E = 3.10\ eV$$

Answer: E = 3.10 eV

Solved Example 2 — Maximum Kinetic Energy

A metal has work function 2 eV. Light of photon energy 5 eV falls on its surface. Find the maximum kinetic energy of photoelectrons.

Solution

Einstein's equation:

$$Kmax = E - \varphi_0$$

Therefore:

$$Kmax = 5 - 2$$

Or,

$$Kmax = 3\,eV$$

Answer: Kmax = 3 eV

Solved Example 3 — Stopping Potential

If the maximum kinetic energy of photoelectrons is 2.5 eV, find the stopping potential.

We know:

$$Kmax = eV_0$$

When energy is expressed in eV:

$$V_0\,numerically = Kmax\,in\,eV/e.$$

Therefore:

$$V_0 = 2.5\,V$$

Answer: Stopping potential = 2.5 V

NEET Shortcut

If all energies are given in eV:

$$Kmax(eV) = Photon\,energy(eV) - Work\,function(eV)$$

And:

$$V_0(in\,volts) = Kmax(in\,eV)\,/e$$

1.21 JEE Insight

For JEE-level problems, students should understand the physical meaning behind the equations.

Important conceptual relation

Einstein's equation:

$$Kmax = hf - \varphi 0$$

can be written as:

$$Kmax = h(f - f_0)$$

Therefore:

$$\boxed{Kmax \propto (f - f_0)}$$

This means the maximum kinetic energy varies **linearly with frequency** above threshold.

Similarly:

$$V_0 = (h/e)f - \varphi_0/e$$

Therefore, a graph of V_0 versus f is a straight line.

Its slope is:

$$\boxed{Slope = h/e}$$

This provides an experimental method of determining Planck's constant.

PART 2: Einstein's Photoelectric Equation, Experimental Laws and Graphical Analysis

2.1 Introduction

In Part 1, we studied:

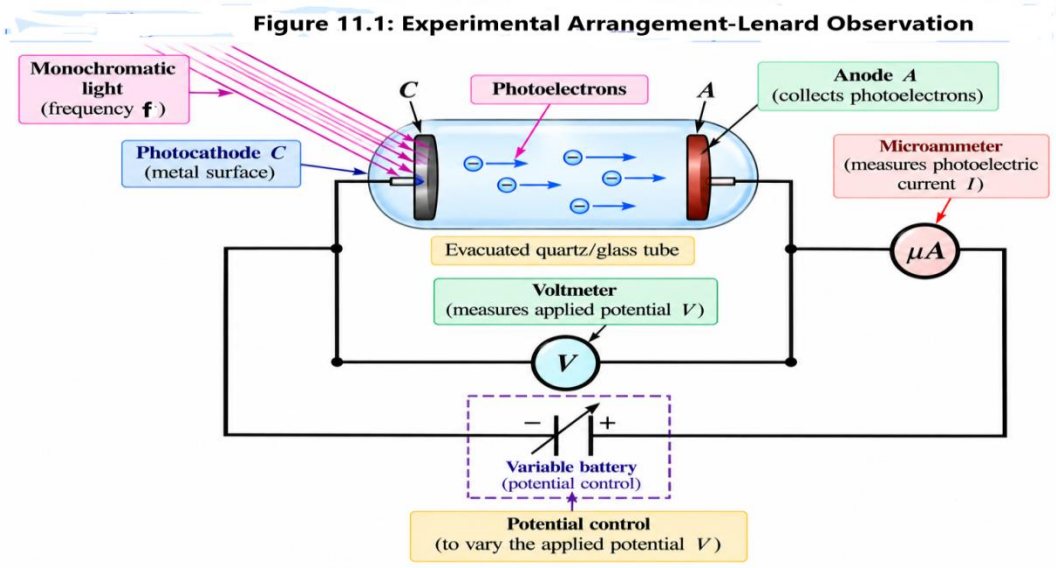
- Photon concept
- Photon energy
- Photon momentum
- Work function
- Threshold frequency
- Threshold wavelength
- Photoelectric effect
- Einstein's photoelectric equation
- Stopping potential
- Saturation current

In this part, we will study the experimental laws and important graphs in greater depth.
These concepts are extremely useful for: 1) CBSE Board theory and numerical; 2) NEET conceptual MCQs; 3) JEE Main numerical problems; 4) JEE Advanced graph-based and multi-step problems

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2.2 Experimental Arrangement for Photoelectric Effect

A typical photoelectric experiment consists of a photosensitive metal plate placed inside an evacuated tube.
The main components are: 1) Photocathode; 2) Anode; 3) Light source; 4) Battery; 5) Variable potential arrangement; 6) Microammeter
When suitable light falls on the photocathode, photoelectrons are emitted.
The applied potential controls the motion of these electrons towards the anode.



2.3 Photoelectric Current

The photoelectric current is due to the flow of photoelectrons from the photocathode to the anode.

Therefore, photoelectric current is directly proportional to number of photoelectrons reaching the anode per second.

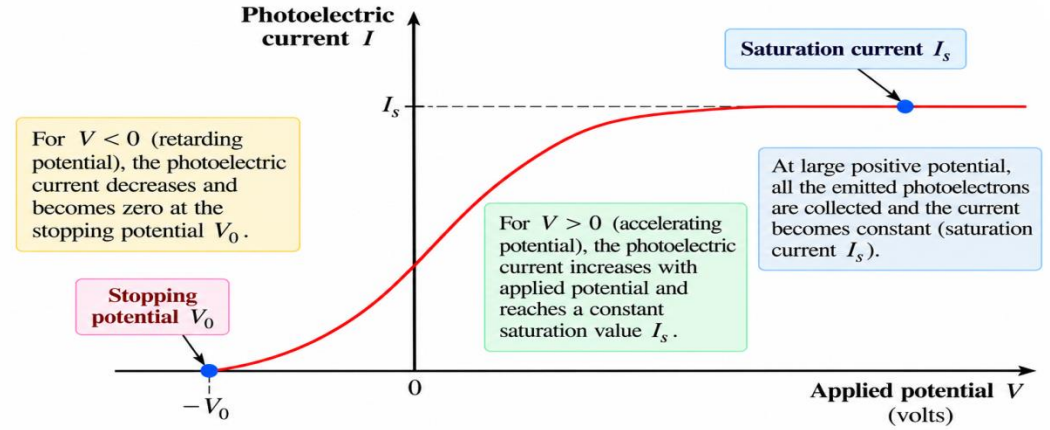
If more electrons are emitted and collected: → photoelectric current increases.

2.4 Effect of Applied Potential

Suppose light of frequency $f > f_0$ falls on a metal surface. Initially, a positive potential is applied to the anode. The positive anode attracts the emitted electrons. As the positive potential increases, photoelectric current increases.

After a certain potential, all emitted photoelectrons are collected. The current then becomes constant. This maximum current is called the **Saturation current**

Figure 11.2: Variation of Photoelectric Current with Applied Potential



2.5 Saturation Current

The maximum photoelectric current obtained when all emitted photoelectrons are collected is called the **saturation current**.

It is represented by: Is.

Important point

Saturation current depends mainly on:

- Intensity of incident radiation
- Number of emitted photoelectrons

For a fixed frequency above threshold: Intensity ↑ → Number of photons ↑ → Number of emitted electrons ↑ → Saturation current ↑

2.6 Effect of Intensity on Saturation Current

Consider two beams of the same frequency:

- Beam 1: lower intensity
- Beam 2: higher intensity

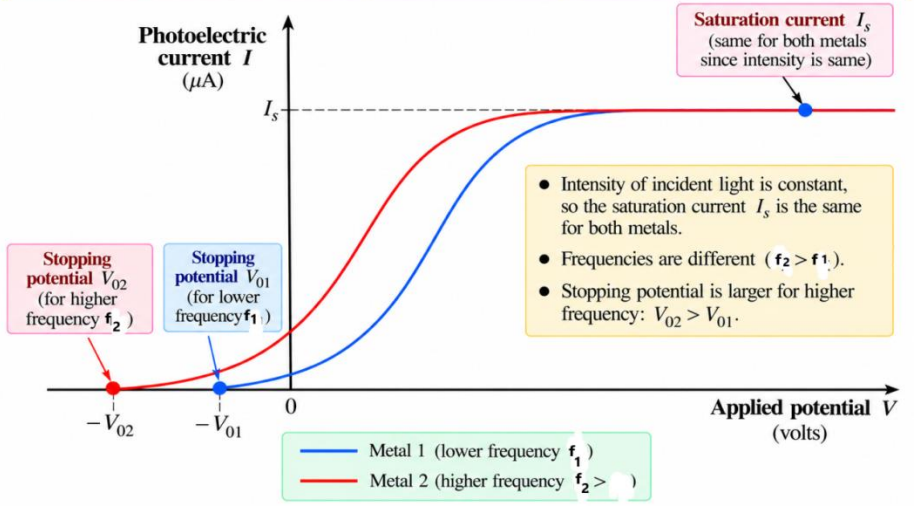
Since higher intensity means more photons incident per unit time:

Higher intensity → more photoelectrons
Therefore: Higher intensity → greater saturation current.
But the maximum kinetic energy of photoelectrons remains unchanged.
Hence: **Intensity affects photoelectric current, but not maximum kinetic energy.**

(i)Different Stopping Potentials at the Same Intensity (same saturation current)

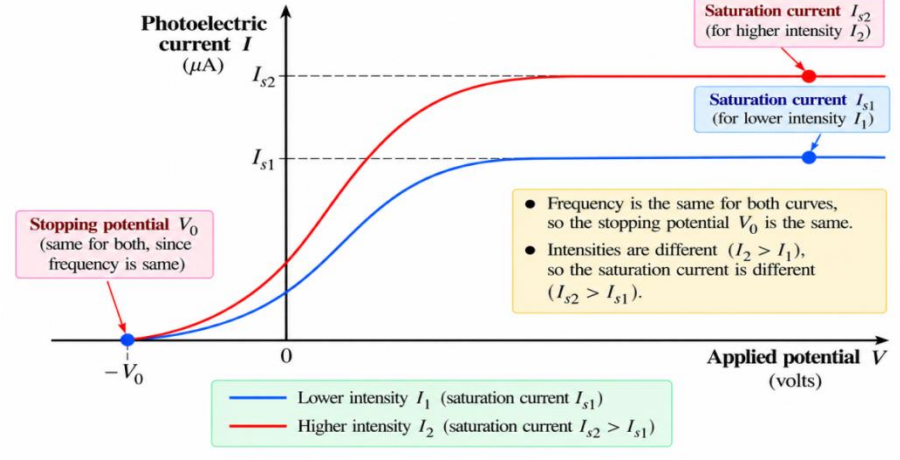
Two different metals are illuminated by radiation of the same intensity but different frequencies. Their stopping potentials may differ because their work functions and incident frequencies are different.

Figure 11.2-1 : Variation of Photoelectric Current with Applied Potential for Two Different Metals (Constant Intensity, Different Frequencies)



(ii)Same Stopping Potential but different Intensities (different saturation current)

Figure 11.2-2 : Variation of Photoelectric Current with Applied Potential for Same Frequency (Same Stopping Potential) but Different Intensity



2.7 Stopping Potential

Now reverse the polarity of the battery. The anode becomes negative relative to the cathode. The emitted electrons are now repelled by the anode. As the negative potential increases: Photoelectric current decreases. At a particular negative potential, even the fastest photoelectrons are unable to reach the anode. The current becomes zero. This potential is called the **Stopping potential.** It is represented by V_0.

Important Relation

At stopping potential: Kmax = eV_0

Therefore:

$$eV_0 = hf - \varphi_0$$

2.8 Effect of Frequency on Stopping Potential

Suppose the intensity is kept constant and the frequency of incident radiation is increased.

Photon energy:

$$E = hf$$

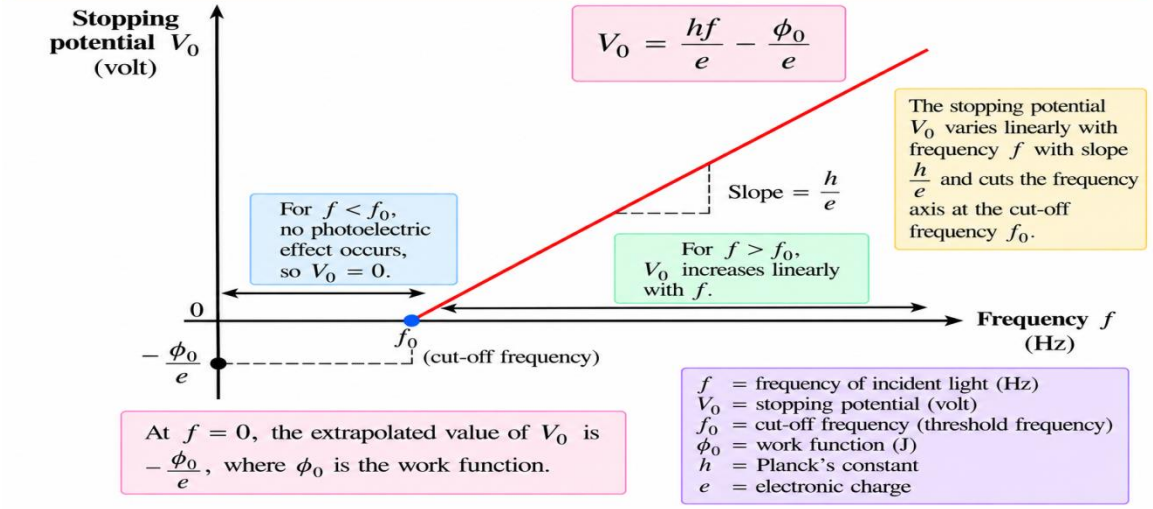
Therefore:

$$\boxed{Frequency \uparrow, Photon\ energy \uparrow, Kmax \uparrow, Stopping\ potential \uparrow}$$

Thus:

Stopping potential increases linearly with frequency.

Figure 11.3 : Variation of Stopping Potential with Frequency



2.9 Slope of V_0–f Graph

From:

$$eV_0 = hf - \varphi_0$$

Or,

$$V_0 = (h/e)\, f - \varphi_0/e$$

Compare with straight-line equation: y = mx + c

Therefore:

$$Slope = h/e$$

Hence:

Important Formula

Slope of V_0 versus f graph:

$$m = h/e$$

Therefore:

$$\boxed{h = e \times slope}$$

This is an important experimental method for determining **Planck's constant**.

2.10 Intercept of V_0–f Graph

Equation:

$$V_0 = (h/e)f - \varphi_0/e$$

At $V_0 = 0$:

$$0 = (h/e)f_0 - \varphi_0/e$$

Therefore:

$$hf_0 = \varphi_0$$

which is the work-function relation

Thus:

$$\boxed{\boldsymbol{x - intercept = threshold\ frequency\ f_0}}$$

2.11 Einstein's Photoelectric Equation — Detailed Derivation

Consider a photon of frequency f incident on a metal surface. Energy of incident photon:

$$E = hf$$

According to Einstein, this energy is used in two ways:

1. A part of the energy is used to overcome the work function.
2. The remaining energy becomes kinetic energy of the emitted electron.

Therefore: Energy of photon = Work function + Maximum kinetic energy

Hence:

$$hf = \varphi_0 + Kmax$$

Therefore:

$$Kmax = hf - \varphi_0$$

Since:

$$\varphi_0 = hf_0$$

We obtain:

$$Kmax = h(f - f_0)$$

This is the most important equation of the photoelectric effect.

2.12 Einstein Equation Using Stopping Potential

Maximum kinetic energy is:

$$Kmax = eV_0$$

Substituting into Einstein's equation:

$$eV_0 = hf - \varphi_0$$

Therefore:

$$V_0 = hf/e - \varphi_0/e$$

or:

$$V_0 = (h/e)f - \varphi_0/e$$

This is a straight-line equation.

2.13 Physical Meaning of Einstein's Equation

The equation:

$$hf = \varphi_0 + Kmax$$

has a direct physical interpretation.

Incident photon energy hf → **Energy required to liberate electron** φ_0 → **Remaining energy** Kmax

Thus:

Photon energy = Energy used for liberation + kinetic energy of photoelectron

This is simply conservation of energy applied to the photoelectric effect.

2.14 Special Case: Threshold Frequency

At threshold frequency:

$$f = f_0$$

The emitted electron has zero maximum kinetic energy.

Therefore:

$$Kmax = 0$$

Einstein equation becomes: $hf_0 = \varphi_0$

Thus:

Important Result:

$$\boxed{\varphi_0 = hf_0}$$

2.15 Special Case: Incident Frequency Below Threshold

If:

$$f < f_0$$

Then:

$$hf < hf_0$$

Therefore:

Photon energy < Work function

The electron cannot escape from the metal surface.

Hence:

No photoelectric emission occurs.

Increasing intensity cannot compensate for a frequency below threshold in the ideal photoelectric-effect model.

2.16 Special Case: Incident Frequency above Threshold

If:

$$f > f_0$$

then:

$$hf > \varphi_0$$

Therefore:

$$Kmax > 0$$

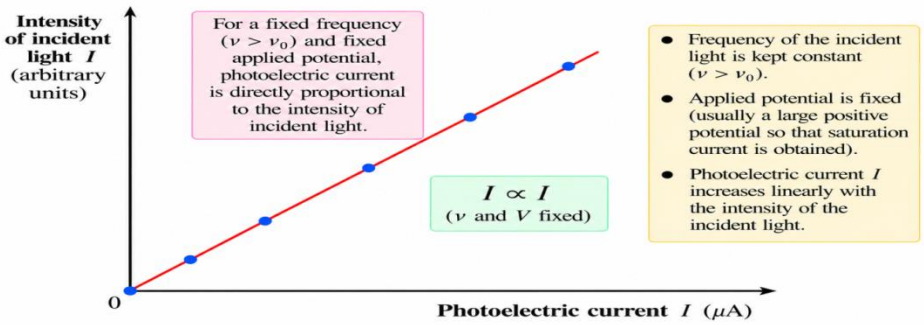
Photoelectric emission occurs.
The excess photon energy becomes kinetic energy:

$$Kmax = h(f - f_0)$$

2.17 Photoelectric Effect and Intensity

It is important to understand exactly what intensity means.
For monochromatic light:
Intensity is related to the amount of radiant energy incident per unit area per unit time.
Increasing intensity generally means more photons arriving per unit time, provided frequency remains unchanged.
Therefore:
Intensity ↑→ Number of photons ↑→ Number of emitted electrons ↑→ Photoelectric current ↑
But Photon energy = hf. Since f has not changed: Photon energy remains unchanged.
Therefore: Kmax remains unchanged.

Figure 11.4 : Effect of Intensity on Photoelectric Current



2.18 Photoelectric Effect and Frequency

Frequency determines the energy of each photon.
Since:

$$E = hf$$

higher frequency means higher photon energy.
Therefore:

$$\boxed{f \uparrow \rightarrow Ephoton \uparrow \rightarrow Kmax \uparrow \rightarrow V_0 \uparrow}$$

This is one of the most important conceptual chains in this chapter.

2.19 Intensity vs Frequency — Important Comparison

Intensity	Frequency
Determines number of photons per unit time for a given setup	Determines energy of each photon
Increasing intensity increases photoelectric current	Increasing frequency increases K_max
Increases saturation current	Increases stopping potential
Does not change K_max for fixed frequency	Does not simply mean more electrons; it changes photon energy
Cannot produce emission when $f < f_0$	Must be at least f_0 for emission

2.20 Laws of Photoelectric Emission

The important experimental laws can be summarized as follows.

Law 1: Threshold Frequency

For each metal there is a minimum frequency f_0 below which photoelectric emission does not occur.

Law 2: Dependence of Kinetic Energy on Frequency

For radiation above threshold: Kmax increases with frequency.
Mathematically:

$$\boxed{Kmax = h(f - f_0)}$$

Law 3: Dependence of Photoelectric Current on Intensity

For fixed frequency above threshold: Photoelectric current increases with intensity.

Law 4: Instantaneous Emission

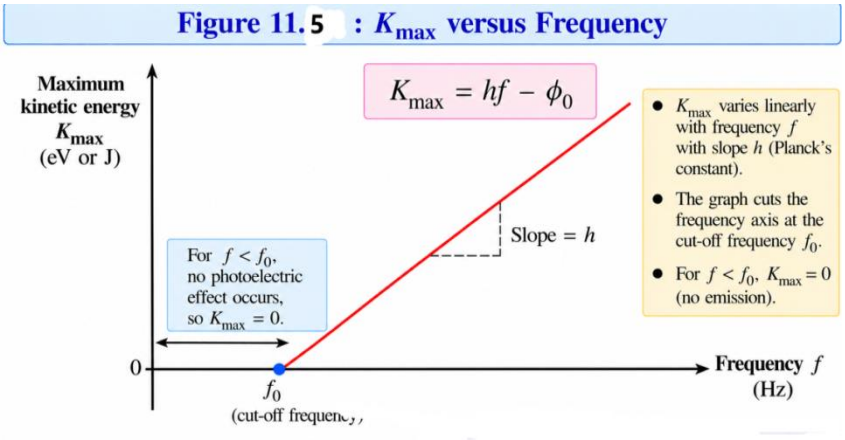
Photoelectric emission occurs without appreciable time delay when suitable radiation falls on the surface.

2.21 Photoelectric Current vs Intensity

For a fixed frequency above threshold, and under unchanged experimental conditions:

$$\boxed{Is \propto I_{rad}}$$

Where, I_s is saturation current, I_{rad} is incident light intensity.
Thus:
Intensity doubled → saturation current approximately doubles, under otherwise identical experimental conditions.



Example 4

Question

A metal has threshold frequency:

$$f_0 = 5 \times 10^{14}\, Hz;$$

Incident light has frequency:

$$f = 8 \times 10^{14}\, Hz$$

Find the maximum kinetic energy of emitted photoelectrons.

Take:

$$h = 6.626 \times 10^{-34}\, J\, s$$

Solution

Using:

$$Kmax = h(f - f_0)$$

Therefore:

$$Kmax = 6.626 \times 10^{-34} \times (8 \times 10^{14} - 5 \times 10^{14})$$

Or,

$$Kmax = 6.626 \times 10^{-34} \times 3 \times 10^{14}$$

Or,

$$Kmax \approx 1.99 \times 10^{-19}\, J$$

In eV:

$$Kmax \approx 1.24\, eV$$

Answer: Kmax ≈ 1.24 eV

Example 5

Question

The work function of a metal is 2.0 eV. Light of wavelength 400 nm falls on it. Find the maximum kinetic energy of emitted electrons.

Solution

Photon energy:

$$E = 1240/\lambda(nm)$$

Or,

$$E = 1240/400$$

Or,

$$E = 3.10\ eV$$

Work function: $\varphi_0 = 2.0$ eV

Therefore:

$$Kmax = E - \varphi_0$$

Or,

$$Kmax = 3.10 - 2.0$$

Or,

$$Kmax = 1.10\ eV$$

Hence:

Maximum kinetic energy = 1.10 eV

Stopping potential: $V_0 = 1.10$ V

Answer: Kmax = 1.10 eV; V_0 = 1.10 V

Example 6

Question

A metal has work function 2.5 eV. Find its threshold wavelength.

Solution

Using:

$$\lambda_0(nm) = \frac{1240}{\varphi_0}(eV)$$

Therefore:

$$\lambda_0 = 1240/2.5$$

Or

$$\lambda_0 = 496\ nm$$

Answer: Threshold wavelength = 496 nm

Therefore, photoelectric emission is possible for: $\lambda \leq 496$ nm

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2.22 Board Exam Focus

Why does increasing intensity increase photoelectric current but not maximum kinetic energy?

Model Answer

Increasing intensity at fixed frequency increases the number of incident photons per unit time. Hence, more photoelectrons are emitted and the photoelectric current increases.

However, the energy of each photon is: E = hf

Since frequency is unchanged, the energy of each photon remains unchanged. Therefore, the maximum kinetic energy of photoelectrons remains unchanged.

2.23 NEET Quick Concept

If two light beams have the same frequency but different intensities:

Higher intensity beam produces: **greater photoelectric current;** but: **same stopping potential**

This is a very common conceptual situation.

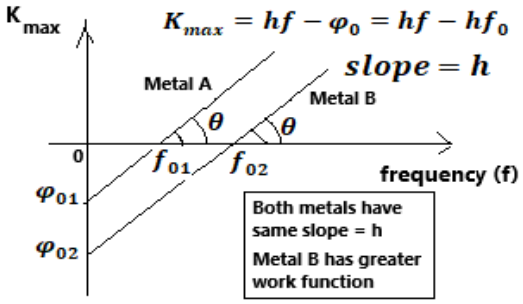
2.24 JEE Insight — Graph Interpretation

Suppose two metals A and B have different work functions. Their Kmax versus frequency graphs are:

$$Kmax = hf - \varphi_0$$

Both graphs have: **same slope = h**
if plotted against frequency using the same units.
But they have different intercepts because: φ_0 differs.
The metal having larger work function has a larger threshold frequency:

$$f_0 = \varphi_0/h$$



2.25 Common Conceptual Traps

Trap 1: "Higher intensity means higher photon energy." **Incorrect**
Photon energy depends on frequency: E = hf

Trap 2: "Any sufficiently intense light can eject electrons." **Incorrect**
The frequency must satisfy: $f \geq f_0$

Trap 3: "Stopping potential depends on intensity."
For fixed frequency, ideal photoelectric theory predicts: **Stopping potential is independent of intensity.**

Trap 4: "Threshold wavelength is the minimum wavelength."
It is actually the **maximum wavelength capable of producing photoelectric emission**.
Condition: $\lambda \leq \lambda_0$

2.26 Quick Revision — Part 2

Remember these chains:

Intensity Chain

Intensity ↑ → Number of photons ↑ → Number of photoelectrons ↑ → Photoelectric current ↑ → Saturation current ↑ But: Kmax unchanged

Frequency Chain

Frequency ↑ → Photon energy ↑ → Kmax ↑ → stopping potential ↑

Core Equation Chain

$E = hf \rightarrow hf = \varphi_0 + Kmax \rightarrow Kmax = hf - \varphi_0 \rightarrow Kmax = eV_0$

Therefore: $eV_0 = hf - \varphi_0$

Part 2 — Master Takeaway

The most important relationships to remember are:

$$\boldsymbol{E = hf}$$

$$\boldsymbol{\varphi_0 = hf_0}$$

$$\boldsymbol{Kmax = hf - \varphi_0}$$

$$\boldsymbol{Kmax = h(f - f_0)}$$

$$\boldsymbol{Kmax = eV_0}$$

And:

$$\boldsymbol{V_0 = (h/e)(f - f_0)}$$

The central conceptual distinction is:

Intensity determines how many photons are available, while frequency determines the energy carried by each photon.

PART 3: Matter Waves and de Broglie Hypothesis

3.1 Introduction

In the previous parts, we studied the **particle nature of light** through the photon concept and photoelectric effect.
We learned that light, which was traditionally considered a wave, can also behave like a stream of particles called photons.
This raised an important question:
If radiation can show both wave and particle nature, can matter particles also exhibit wave nature?
In 1924, Louis de Broglie proposed that matter particles also exhibit wave nature.
According to de Broglie:
Every moving material particle is associated with a wave called a matter wave or de Broglie wave.
This idea is called the **de Broglie hypothesis**.

3.2 de Broglie Hypothesis

According to de Broglie's hypothesis:
A moving particle has both particle and wave characteristics.
The wave associated with a moving particle is called its: **Matter wave** or **de Broglie wave**
The wavelength associated with the particle is called the: **de Broglie wavelength** and is represented by: λ

3.3 de Broglie Wavelength

For a particle with momentum p, the de Broglie wavelength is:

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

Where: λ = de Broglie wavelength; h = Planck's constant; p = momentum of particle
Since:

$$\boxed{p = mv}$$

for a non-relativistic particle,
We obtain:

Important Formula

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

Therefore:
de Broglie wavelength is inversely proportional to momentum. $\lambda \propto 1/p$

3.4 Derivation of de Broglie Relation

For a photon:

$$E = hf$$

Also:

$$E = pc$$

Therefore:

$$pc = hf$$

Since:

$$c = f\lambda$$

We get:

$$pc = hc/\lambda$$

Therefore:

$$p = h/\lambda$$

Or:

$$\boldsymbol{\lambda = h/p}$$

de Broglie extended this relation to material particles.
Thus, for a particle of momentum p:

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

For a particle of mass m moving with velocity v: p = mv
Therefore:

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

This is the fundamental de Broglie equation.

3.5 Matter Wave and Momentum

From:

$$\lambda = h/p$$

We can write:

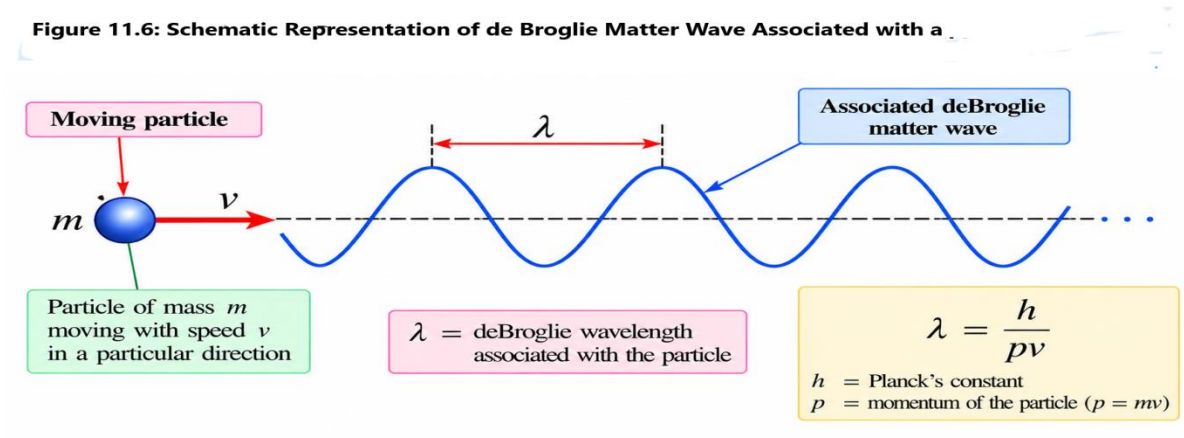
$$p = h/\lambda$$

Therefore:

- Greater momentum → smaller wavelength
- Smaller momentum → larger wavelength

This relation is important in understanding why wave effects of microscopic particles are observable, while those of ordinary macroscopic objects are generally negligible.

Figure 11.6: Schematic Representation of de Broglie Matter Wave Associated with a



3.6 de Broglie Wavelength in Terms of Kinetic Energy

For a non-relativistic particle:

$$K = 1/2\, mv^2$$

Momentum:

$$p = mv$$

Squaring:

$$p^2 = m^2v^2$$

From:

$$2K = mv^2$$

Multiplying by m:

$$2mK = m^2v^2$$

Therefore:

$$p^2 = 2mK$$

Hence:

$$p = \sqrt{(2mK)}$$

Using:

$$\lambda = h/p$$

We obtain:

Important Formula

$$\boxed{\lambda = \frac{h}{\sqrt{2mK}}}$$

Therefore: **de Broglie wavelength of a non-relativistic particle:**

$$\lambda = h/\sqrt{(2mK)}$$

3.7 Relation between de Broglie Wavelength and Kinetic Energy

From:

$$\lambda = h/\sqrt{(2mK)}$$

For a particle of fixed mass:

$$\lambda \propto 1/\sqrt{K}$$

Therefore:

$$K \uparrow \rightarrow \lambda \downarrow \; and: K \downarrow \rightarrow \lambda \uparrow$$

Important Result

If kinetic energy becomes four times:

$$K' = 4K;\; then: \lambda' = \lambda/2$$

3.8 de Broglie Wavelength in Terms of Velocity

We already have:

$$\lambda = h/(mv)$$

Therefore, for constant mass:

$$\lambda \propto 1/v$$

Thus:

Velocity ↑ → de Broglie wavelength ↓

Velocity ↓ → de Broglie wavelength ↑

3.9 de Broglie Wavelength of an Electron Accelerated through Potential Difference

This is one of the **most important formulas for NEET and JEE numerical problems**.
Suppose an electron is initially at rest and is accelerated through a potential difference V.
The electric field gives kinetic energy to the electron.
Energy gained by electron:

$$K = eV$$

Where:

- e = magnitude of electronic charge
- V = accelerating potential

For an electron:

$$K = 1/2\, mv^2$$

Therefore:

$$eV = 1/2\, mv^2$$

Hence:

$$v = \sqrt{(2eV/m)}$$

Momentum:

$$p = mv$$

Therefore:

$$p = \sqrt{(2meV)}$$

Using:

$$\lambda = h/p$$

We get**: Important Formula**

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

This is the de Broglie wavelength of an electron accelerated through potential V.

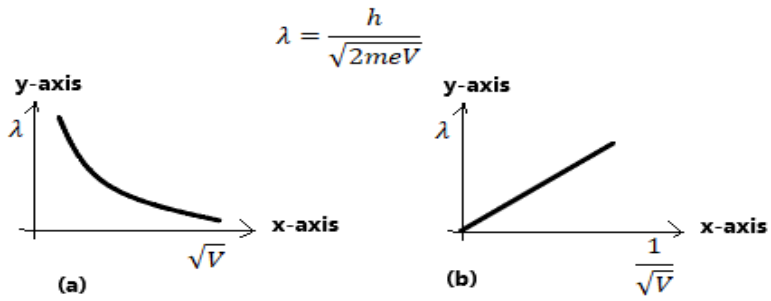


Figure 11.7-1: Graph between de-Broglie wavelength and accelerating potential

In Figure 11.7-1 (a) above,

$$\lambda \propto \frac{1}{\sqrt{V}}$$

3.10 Numerical Form of Electron de Broglie Wavelength

For an electron accelerated through potential V:

$$\lambda = h/\sqrt{(2meV)}$$

When V is expressed in volts, a very useful approximate relation is:

$$\boldsymbol{\lambda(nm) \approx \frac{1.227}{\sqrt{V}}}$$

Or:

$$\boxed{\boldsymbol{\lambda(\text{Å}) \approx \frac{12.27}{\sqrt{V}}}}$$

Where:

$$1\,\text{Å} = 10^{-10}\,m$$

These forms are extremely useful for quick numerical calculations.

Example-6

An electron is accelerated through 100 V. Find its wavelength.

Using:

$$\lambda\,(in\,nm) = 1.227/\sqrt{V}$$

We get:

$$\lambda = 1.227/\sqrt{100}$$

Or,

$$\lambda = 1.227/10$$

Or,

$$\lambda \approx 0.123\,nm$$

Therefore:

$$\boxed{\boldsymbol{\lambda \approx 0.123\,nm}}$$

3.11 General Relation for a Particle Charged Through Potential Difference

For a particle of charge magnitude q accelerated through potential difference V:

$$K = qV$$

Therefore:

$$p = \sqrt{(2mqV)}$$

Hence:

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

For an electron: q = e

Therefore:

$$\lambda = h/\sqrt{(2meV)}$$

3.12 Dependence on Accelerating Potential

From:

$$\lambda = h/\sqrt{(2meV)}$$

For an electron:

$$\lambda \propto 1/\sqrt{V}$$

Therefore:
If accelerating potential increases: V ↑ → λ ↓
If accelerating potential decreases: V ↓ → λ ↑

Important Numerical Result

If: $V_2 = 4V_1$; then: $\lambda_2 = \lambda_1/2$
Similarly, if:

$$V_2 = 9V_1$$

Then:

$$\lambda_2 = \lambda_1/3$$

3.13 de Broglie Wavelength of Proton

For a proton moving with momentum p:

$$\lambda = h/p$$

If kinetic energy is K:

$$\lambda = h/\sqrt{(2mpK)}$$

Since proton mass is much greater than electron mass:

$$mp \gg me$$

For the same kinetic energy:

$$\lambda proton < \lambda electron$$

This is an important comparison.

3.14 Electron vs Proton — Same Kinetic Energy

Suppose an electron and proton have the same kinetic energy K.
For each particle:

$$\lambda = h/\sqrt{(2mK)}$$

Therefore:

$$\lambda \propto 1/\sqrt{m}$$

Hence:

$$\boxed{\frac{\lambda_e}{\lambda_p} = \sqrt{\frac{m_p}{m_e}}}$$

Since: mp ≈ 1836me
We get:

$$\boxed{\lambda e \,/\, \lambda p \approx \sqrt{1836} \approx 42.8}$$

Therefore:
For the same kinetic energy, an electron has a much larger de Broglie wavelength than a proton.

3.15 Electron vs Proton — Same Momentum

If electron and proton have the same momentum:

$$p_e = p_p$$

Then:

$$\lambda = h/p$$

Therefore: $\boldsymbol{\lambda_e = \lambda_p}$

So: **Particles having the same momentum have the same de Broglie wavelength, irrespective of their masses.** This is an important JEE conceptual point.

3.16 Electron vs Proton — Same Velocity

If electron and proton have the same velocity:

$$\lambda = h/(mv)$$

Therefore:

$$\lambda \propto 1/m$$

Since:

$$m_p \gg m_e$$

We get:

$$\lambda e \gg \lambda p$$

Thus, at the same velocity, the electron has a much larger de Broglie wavelength.

3.17 Comparison of Different Conditions

Condition	Important Result
Same momentum	Same de Broglie wavelength
Same kinetic energy	$\lambda \propto 1/\sqrt{m}$
Same velocity	$\lambda \propto 1/m$
Same accelerating potential for singly charged particles	$\lambda \propto 1/\sqrt{m}$
Same mass	$\lambda \propto 1/v$
Same mass and kinetic energy	$\lambda \propto 1/\sqrt{K}$

3.18 Matter Waves of Macroscopic Objects

According to: λ = h/(mv); every moving object has a de Broglie wavelength.
However, for ordinary macroscopic objects:

- mass is large
- momentum is large
- wavelength becomes extremely small

Therefore, wave effects are practically unobservable.
For microscopic particles such as:

- electrons
- protons
- neutrons
- atoms

The de Broglie wavelength can become comparable to atomic dimensions.
Hence, quantum wave effects become significant.

3.19 Why are Matter Waves not Easily Observed for Large Objects?

Consider:

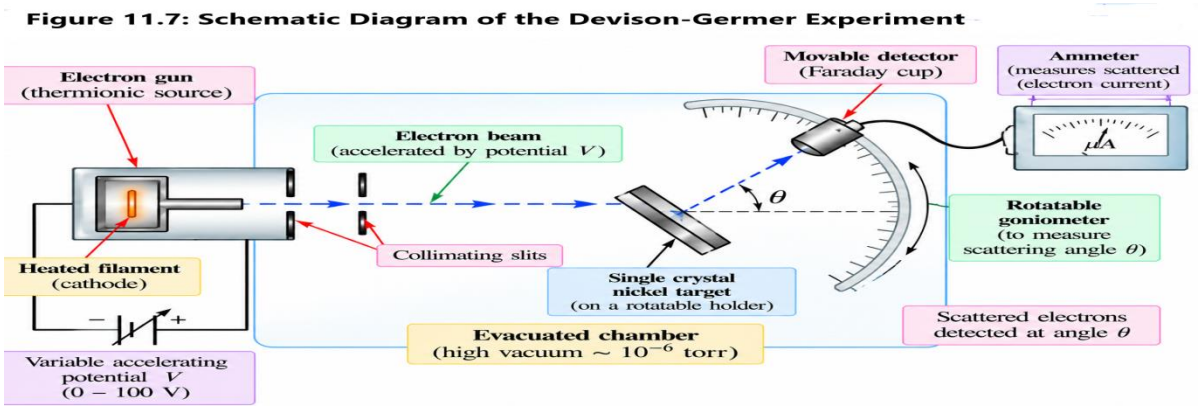
$$\lambda = h/(mv)$$

For a large object: m is large.
Therefore: λ is extremely small.
Such a tiny wavelength makes diffraction and interference effects difficult to observe under ordinary conditions.
This is why macroscopic objects appear to behave predominantly according to classical mechanics.

3.20 Experimental Verification of Matter Waves

de Broglie's hypothesis was experimentally supported by experiments showing diffraction of electrons.
The most famous evidence came from the: **Davisson–Germer experiment**
This experiment demonstrated that electrons can undergo diffraction from a crystal surface.
This provided strong experimental evidence for the wave nature of matter.

Figure 11.7: Schematic Diagram of the Devison-Germer Experiment



3.21 Davisson–Germer Experiment — Basic Idea (NEET/JEE enrichment)

In the experiment:

1. Electrons are produced by an electron gun.
2. They are accelerated through a potential difference.
3. The electron beam falls on a nickel crystal.
4. Electrons are scattered by the crystal.
5. The intensity of scattered electrons is measured at different angles.

A pronounced maximum in the scattered intensity is observed at particular conditions.
This behaviour is characteristic of **diffraction**.
Since diffraction is a wave phenomenon, the experiment supports the wave nature of electrons.

3.22 de Broglie Wavelength from Diffraction

The experimentally observed diffraction pattern can be used to determine the wavelength of electrons.
The wavelength calculated from the diffraction condition agrees with the de Broglie prediction:

$$\lambda = h/p$$

This agreement provided strong experimental support for de Broglie's hypothesis.

3.23 Bragg's Law (NEET/JEE Enrichment)

The diffraction condition for waves incident on crystal planes is described by:

$$\boxed{2d \sin\theta = n\lambda}$$

Where:

- d = separation between crystal planes,
- θ = angle between the incident electron beam and the crystal planes (Bragg angle).
- n = order of diffraction ;
- λ = wavelength

For first-order diffraction: n = 1

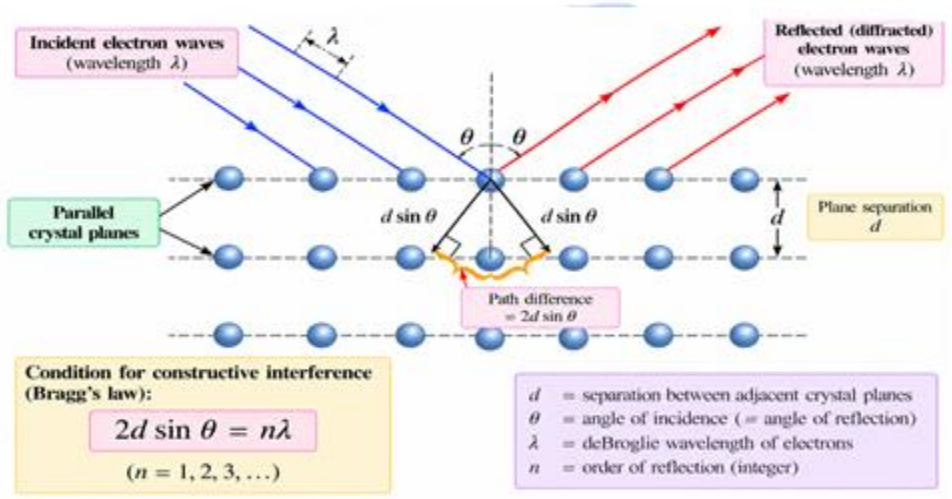
Therefore:

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

The experimentally obtained wavelength can be compared with: λ = h/p

Agreement between the two supports the de Broglie hypothesis.

Figure 11.8: Bragg Reflection from Crystal Planes



3.24 Important Concept: Matter Wave Is Not an Electromagnetic Wave

A common misconception is that matter waves are electromagnetic waves.

They are not.

Electromagnetic wave Associated with:

- Electric field
- Magnetic field
- Electromagnetic radiation

Matter wave Associated with:

- Moving material particle

- Quantum mechanical description of matter

Therefore:

Matter wave ≠ electromagnetic wave

Example 7 — de Broglie Wavelength

Question

Find the de Broglie wavelength of a particle of mass m moving with velocity v.

Solution

Momentum:

$$p = mv$$

de Broglie relation:

$$\lambda = h/p$$

Therefore:

$$\boldsymbol{\lambda = h/(mv)}$$

Example 8 — Effect of Kinetic Energy

Question

The kinetic energy of an electron is increased four times. How does its de Broglie wavelength change?

Solution

For a fixed particle:

$$\lambda \propto 1/\sqrt{K}$$

Therefore:

$$\lambda_2/\lambda_1 = \sqrt{(K_1/K_2)}$$

Given: $K_2 = 4K_1$

Hence:

$$\lambda_2/\lambda_1 = 1/2$$

Therefore:

$$\boxed{\boldsymbol{\lambda_2 = \lambda_1/2}}$$

So the wavelength becomes half.

Example 9 — Electron Accelerated Through Potential

Question

An electron is accelerated through a potential difference of 150 V. Find its approximate de Broglie wavelength.

Solution

Using:

$$\lambda = 1.227/\sqrt{V}\ (nm)$$

Or:

$$\lambda = 1.227/\sqrt{150}$$

Since:

$$\sqrt{150} \approx 12.25$$

Therefore:

$$\lambda \approx 1.227/12.25 \; or \; \lambda \approx 0.100\, nm$$

Answer:

$$\boxed{\boldsymbol{\lambda \approx 0.100\, nm}}$$

Example 10 — Same Momentum

Question

An electron and a proton have the same momentum. Compare their de Broglie wavelengths.

Solution

de Broglie relation:

$$\lambda = h/p$$

Since:

$$p_e = p_p$$

Therefore:

$$\lambda e = \lambda p$$

Answer: Their de Broglie wavelengths are equal.

Example 11 — Same Kinetic Energy

Question

An electron and proton have the same kinetic energy. Which has the larger de Broglie wavelength?

Solution

$$\lambda = h/\sqrt{(2mK)}$$

For the same K:

$$\lambda \propto 1/\sqrt{m}$$

Since:

$$m_e < m_p$$

Therefore:

$$\boxed{\lambda e > \lambda p}$$

Answer: Electron has the larger de Broglie wavelength.

Example 12

The ratio of momenta of two particles is:

$$p_1 : p_2 = 1 : 2$$

Find their ratio of wavelength.

Solution

Since:

$$\lambda = h/p$$

Therefore:

$$\lambda_1/\lambda_2 = p_2/p_1$$

Hence:

$$\lambda_1/\lambda_2 = 2/1$$

Therefore:

$$\boxed{\boldsymbol{\lambda_1 : \lambda_2 = 2 : 1}}$$

Example 13

The kinetic energy of an electron becomes 9 times its initial value. Find the ratio of its new de Broglie wavelength to its initial wavelength.

Solution

Given: $K_2 = 9K_1$

Using:

$$\lambda_2/\lambda_1 = \sqrt{(K_1/K_2)}$$

Therefore:

$$\lambda_2/\lambda_1 = \sqrt{(1/9)}\ or\ \lambda_2/\lambda_1 = 1/3$$

Answer:

$$\boxed{\boldsymbol{\lambda_2 = \lambda_1/3}}$$

Example 14

The velocity of an electron is doubled. What happens to its de Broglie wavelength?

Solution

Since:

$$\lambda \propto 1/v$$

Therefore:

$$\lambda_2/\lambda_1 = v_1/v_2 = 1/2$$

Hence:

$$\boldsymbol{\lambda_2 = \lambda_1/2}$$

Example 15

An electron is accelerated through 100 V. Find its approximate de Broglie wavelength.

Using:

$$\lambda = 1.227/\sqrt{V}\ nm$$

$$\lambda = 1.227/10 = 0.1227\ nm$$

Answer:

$$\boxed{\boldsymbol{\lambda \approx 0.123\ nm}}$$

Example 16 — Electron Wavelength

Question

An electron is accelerated through 400 V. Calculate its de Broglie wavelength.

Solution

Using:

$$\lambda = 1.227/\sqrt{V}\ nm$$

Or

$$\lambda = 1.227/\sqrt{400} = 1.227/20 = 0.06135\ nm$$

Therefore:

Answer:

$$\boxed{\boldsymbol{\lambda \approx 0.061\,nm}}$$

Example 17 — Potential Ratio

Question

Two electrons are accelerated through potentials V and 4V. Find the ratio of their de Broglie wavelengths.

Solution

For electrons:

$$\lambda \propto 1/\sqrt{V}$$

Therefore:

$$\lambda_1/\lambda_2 = \sqrt{(V_2/V_1)} = \sqrt{4} = 2$$

Hence:

$$\boldsymbol{\lambda_1 : \lambda_2 = 2 : 1}$$

Example 18 — Same Momentum

Question

An electron and a proton have equal momenta. Compare their wavelengths.

Solution

$$\lambda = h/p$$

Since: $p_e = p_p$

Therefore:

$$\boldsymbol{\lambda e = \lambda p}$$

Example 19 — Same Velocity

Question

An electron and a proton move with equal velocities. Find the ratio of their de Broglie wavelengths.

Solution

$$\lambda = h/(mv)$$

Therefore:

$$\lambda e/\lambda p = m_p/m_e$$

Since, $m_p/m_e \approx 1836$

Hence:

$$\boldsymbol{\lambda e : \lambda p \approx 1836 : 1}$$

Example 20 — Same Kinetic Energy

Question

An electron and proton have the same kinetic energy. Find the ratio of their de Broglie wavelengths.

Solution

$$\lambda = h/\sqrt{(2mK)}$$

For same K:

$$\lambda \propto 1/\sqrt{m}$$

Therefore:

$$\frac{\lambda_e}{\lambda_p} = \sqrt{\frac{m_p}{m_e}} \approx \sqrt{1836} \approx 42.8$$

Hence:

$$\boldsymbol{\lambda e : \lambda p \approx 42.8 : 1}$$

3.25 JEE Insight

Many JEE problems are designed around **ratios** rather than direct calculation.
Suppose:

$$V_2 = 9V_1$$

For electrons:

$$\lambda_2/\lambda_1 = \sqrt{(V_1/V_2)}$$

Therefore:

$$\lambda_2/\lambda_1 = 1/3$$

No numerical constants are required.

Strategy

Before substituting values:

1. Write
$$\lambda \propto 1/p.$$
2. Express p in terms of the given quantity.
3. Form a ratio.
4. Cancel common constants.
5. Calculate only what is necessary.

This makes many multi-step questions considerably easier.

3.26 Important Comparison Table

Condition	Relation
Same momentum	$\lambda_e = \lambda_p$
Same kinetic energy	$\lambda_e/\lambda_p \approx 42.8$
Same velocity	$\lambda_e/\lambda_p \approx 1836$
Same potential for singly charged particles	$\lambda_e/\lambda_p \approx 42.8$

This table is especially useful for **NEET/JEE MCQs**.

PART 4: Photon–Matter Interaction, Numerical Applications and Conceptual Mastery

4.1 Introduction

So far we have learned:

- Photon and its energy
- Photoelectric effect
- Einstein's photoelectric equation
- Work function
- Threshold frequency and wavelength
- Stopping potential
- de Broglie matter waves
- Electron wavelength
- Davisson–Germer experiment

Now, we will connect these concepts and examine how photon energy, work function, kinetic energy, stopping potential and de Broglie wavelength are interrelated.

The following concepts are particularly useful for:

- CBSE numerical questions
- NEET conceptual MCQs
- JEE Main numerical questions
- JEE Advanced multi-step problems

4.2 Photon Energy and Work Function

When a photon is incident on a metal surface, its energy is:

$$E = hf$$

The minimum energy required to eject an electron from a metal surface is called the work function.

If:

$$hf < \varphi_0$$

Then, electron cannot eject outside.

It:

$$hf = \varphi_0$$

Then, electron just comes out,

But:

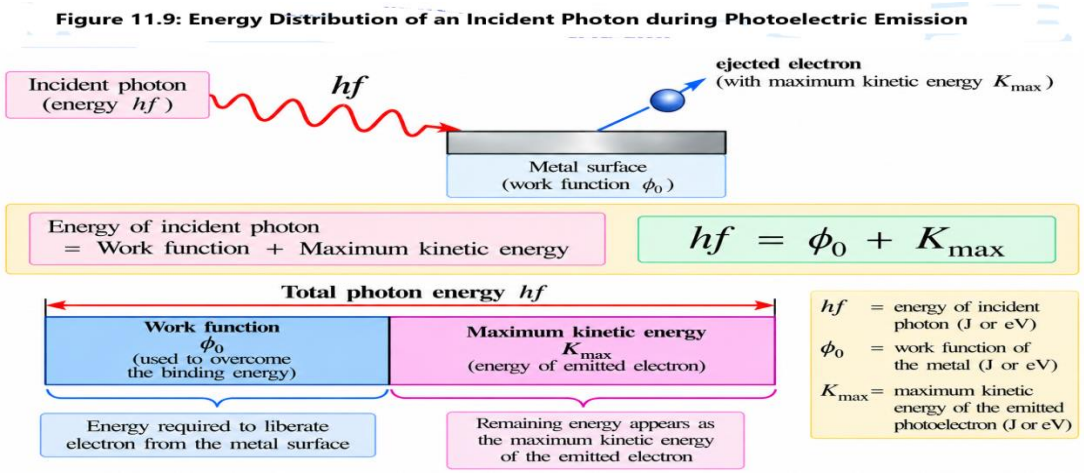
$$K_{max} = 0$$

If:

$$hf > \varphi_0$$

The excess energy appears as the maximum kinetic energy of the emitted photoelectron.

$$K_{max} = hf - \varphi_0$$



4.3 Three Important Energy Conditions

Case 1:

$$hf < \varphi_0$$

No photoelectric emission.

Case 2:

$$hf = \varphi_0$$

Photoelectron just escapes.

$$K_{max} = 0$$

Case 3:

$$hf > \varphi_0$$

Photoelectric emission occurs.

$$K_{max} = hf - \varphi_0$$

4.4 Threshold Frequency and Threshold Wavelength

Threshold frequency:

$$f_0 = \varphi_0/h$$

Threshold wavelength:

$$\lambda_0 = c/f_0$$

Therefore:

$$\lambda_0 = hc/\varphi_0$$

Remember:

Frequency condition:

$$\boxed{f \geq f_0}$$

Wavelength condition:

$$\boxed{\lambda \leq \lambda_0}$$

4.5 Frequency and Wavelength Conditions — Important Comparison

Because:

$$c = f\lambda$$

frequency and wavelength are inversely related.
Therefore:
Higher frequency → shorter wavelength and Lower frequency → longer wavelength
For photoelectric emission:
Frequency must be at least threshold frequency.
Equivalently:
Wavelength must not exceed threshold wavelength.

4.6 Maximum Kinetic Energy

Einstein equation:

$$K_{max} = hf - \varphi_0$$

Using:

$$\varphi_0 = hf_0$$

We get:

$$K_{max} = h(f - f_0)$$

Therefore:
Kmax is directly proportional to: $(f - f_0)$
This relation is useful for graph-based problems.

4.7 Determination of Planck's Constant

From:

$$V_0 = (h/e)f - \varphi_0/e$$

The slope of the graph is:

$$m = h/e$$

Therefore:

$$\boldsymbol{h = em}$$

Thus, by measuring the slope of the V_0 versus f graph, Planck's constant can be determined experimentally.

4.8 Determination of Work Function from Graph

From:

$$V_0 = (h/e)f - \varphi_0/e$$

At: f = 0, the extrapolated intercept is:

$$V - intercept = -\varphi_0/e$$

Therefore:

$$\varphi_0 = -e \times (V - intercept)$$

Alternatively, determine threshold frequency f_0 from the x-intercept and use: $\boldsymbol{\varphi_0 = hf_0}$

4.9 Relation between Stopping Potential and Frequency

Suppose two radiations have frequencies: f_1 and f_2
The corresponding stopping potentials are: V_{01} and V_{02}.
Using:

$$eV_0 = hf - \varphi_0$$

For the same metal:

$$e(V_{02} - V_{01}) = h(f_2 - f_1)$$

Therefore:

$$V_{02} - V_{01} = (h/e)(f_2 - f_1)$$

This is an important numerical relation.

Example 21 — Difference in Stopping Potential

Question

Two radiations differ in frequency by 2×10^{14} Hz. Find the difference in their stopping potentials.

Take:

$$h = 6.626 \times 10^{-34}\, J\, s$$
$$e = 1.602 \times 10^{-19}\, C$$

Solution

Using:

$$\Delta V_0 = (h/e)\, \Delta f$$

Therefore:

$$\Delta V_0 = (6.626 \times 10^{-34} / 1.602 \times 10^{-19}) \times 2 \times 10^{14}$$

Hence:

$$\Delta V_0 \approx 0.827\, V$$

Answer: Difference in stopping potential ≈ 0.83 V

4.10 Photon Number and Intensity

Suppose monochromatic radiation has power P.

Energy of one photon:

$$E = hf$$

Therefore:

Number of photons emitted per second:

$$N = P/hf$$

Or:

$$N = P\lambda/hc$$

Thus, for the same power:

$$\boxed{N \propto 1/f \; or: N \propto \lambda}$$

This relation is useful when comparing photon numbers for different frequencies.

4.11 Same Power — Different Frequencies

Suppose two monochromatic sources have the same power:

$$P_1 = P_2$$

But:

$$f_2 > f_1$$

Since:

$$N = P/hf$$

We get:

$$N \propto 1/f$$

Therefore:

$$N_2 < N_1$$

Thus:

At the same power, higher-frequency radiation contains fewer photons per second.

But each high-frequency photon has more energy.

4.12 Photon Number and Photoelectric Current

The number of emitted photoelectrons need not be equal to the number of incident photons."

Therefore:

Photon flux ↑ → Photoelectron number ↑ → Photoelectric current ↑

This gives a useful conceptual connection between photon theory and photoelectric current.

4.13 Photoelectric Efficiency

The number of emitted photoelectrons need not equal the number of incident photons.

A useful conceptual quantity is the **quantum efficiency**:

$$\eta = \frac{\text{Number of emitted photoelectrons}}{\text{Number of incident photons}}$$

It is generally less than or equal to 1 in a simple one-photon-one-electron picture.

For an idealized 100% efficient process: $\eta = 1$

For the ideal one-photon–one-electron process, the quantum efficiency cannot exceed 1.

This concept is useful for understanding why incident photon number and emitted electron number are not always identical.

4.14 Photoelectric Current and Electron Rate

If n electrons reach the collector per second, current is: I = ne

Where:

- I = current
- n = number of electrons reaching per second
- e = electronic charge

Therefore: n = I/e

This relation can be used to calculate the rate at which electrons reach the collector.

Example 22

A photoelectric current of 1.6 μA is produced. Find the number of electrons reaching the collector per second.

Solution

Using:

$$n = I/e$$

Given:

$$I = 1.6 \times 10^{-6}\, A$$
$$e = 1.602 \times 10^{-19}\, C$$

Therefore:

$$n \approx 1.0 \times 10^{13}\, electrons/s$$

Answer:
Approximately 1.0×10^{13} electrons per second

4.15 Energy of Photoelectrons

The maximum kinetic energy is:

$$K_{max} = hf - \varphi_0$$

Not all emitted photoelectrons necessarily have the maximum kinetic energy.
Therefore:

- Kmax → maximum kinetic energy
- Other photoelectrons → may have lower kinetic energy

The stopping potential is determined by the **fastest photoelectrons**.

4.16 Why Stopping Potential Measures Maximum Kinetic Energy

At stopping potential:
The fastest photoelectrons are just prevented from reaching the collector.
Their maximum kinetic energy is completely balanced by the electrical potential energy:

$$K_{max} = eV_0$$

Therefore:
V_0 provides a direct measure of the maximum kinetic energy.

4.17 de Broglie Connection

Now consider the emitted photoelectron. If its maximum kinetic energy is Kmax:

$$K_{max} = \frac{p^2}{2m_e}$$

Therefore:

$$p = \sqrt{2m_e K_{max}}$$

Its de Broglie wavelength is:
$\lambda = h/p$
Hence:

$$\lambda = \frac{h}{\sqrt{2m_e K_{max}}}$$

Using:

$$K_{max} = hf - \varphi_0$$

We can write:

$$\boxed{\lambda = \frac{h}{\sqrt{2m_e(hf - \varphi_0)}}}$$

This connects:
Photoelectric effect + de Broglie matter waves
This is particularly useful for higher-level problems.

4.18 de Broglie Wavelength of Photoelectron

For the fastest photoelectron:

$$\lambda_{min} = \frac{h}{\sqrt{2m_e K_{max}}}$$

Why is it called λmin?
Because: Kmax is maximum momentum.
Since:

$$\lambda = h/p$$

maximum momentum corresponds to minimum wavelength.
Therefore:

Maximum kinetic energy → maximum momentum → minimum wavelength

This is a useful JEE conceptual relation.

4.19 Stopping Potential and Photoelectron Wavelength

Since:

$$Kmax = eV_0$$

We obtain:

$$\lambda_{min} = \frac{h}{\sqrt{2m_e(eV_0)}}$$

Thus, if stopping potential is known, the minimum de Broglie wavelength of the emitted photoelectrons can be calculated.

Example 23

A photoelectron is stopped by a potential of 4 V. Find its maximum kinetic energy.

Solution

$$K_{max} = eV_0$$

Since
$V_0 = 4$ V:

$$K_{max} = 4\ eV$$

Answer: Kmax = 4 eV

Example 24 — Minimum de Broglie Wavelength

Question

Photoelectrons are emitted with a maximum kinetic energy of 3.0 eV. Find their minimum de Broglie wavelength approximately.

Solution

Using:

$$\lambda = \frac{h}{\sqrt{2m_e K}}$$

Converting:

$$K = 3.0 \times 1.602 \times 10^{-19}\ J$$

Using:

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

$m_e = 9.11 \times 10^{-31}$ kg

We obtain approximately:

$$\boxed{\lambda \approx 0.71\ nm}$$

Answer:

Minimum de Broglie wavelength ≈ 0.71 nm

4.20 Important Concept: Wave–Particle Duality

The chapter now gives us a complete picture.

Light

Wave nature:

- Interference
- Diffraction
- Polarisation

Particle nature:

- Photon
- Photoelectric effect

Matter

Particle nature:

- Mass
- Momentum
- Kinetic energy

Wave nature:

- de Broglie wavelength
- Electron diffraction

Thus:

Radiation → wave + particle nature

Matter → particle + wave nature

4.21 Important Comparison

Radiation	Matter
Photon energy E = hf	Particle momentum p = mv
Photon momentum p = h/λ	Matter wavelength λ = h/p
Interference demonstrates wave nature	Electron diffraction demonstrates wave nature
Photoelectric effect demonstrates particle nature	Particle has mass and momentum
Photon rest mass = 0	Material particle has rest mass

Example 25 — Complete Concept

Question

A metal has work function 2 eV and is illuminated by radiation of wavelength 310 nm. Find:

1. Photon energy
2. Maximum kinetic energy

3. Stopping potential

Solution

Step 1: Photon energy

$$E = 1240/\lambda$$

Or

$$E = 1240/310 = 4\,eV$$

Step 2: Maximum kinetic energy

$$Kmax = E - \varphi_0$$

Or,

$$Kmax = 4 - 2$$

Or,

$$Kmax = 2\,eV$$

Step 3: Stopping potential

$$Kmax = eV_0$$

Therefore:

$$V_0 = 2\,V$$

Answers

1. Photon energy = **4 eV**
2. Maximum kinetic energy = **2 eV**
3. Stopping potential = **2 V**