FREE NOTES · NCERT + JEE/NEET LEVEL

Dual Nature of Radiation & Matter

Electron emission, the photoelectric effect experiments and graphs, Einstein's equation, the photon, de Broglie wavelength and the Davisson-Germer experiment.

01 Electron emission
02 Photoelectric effect
03 Experimental results (graphs)
04 Why wave theory failed
05 Einstein's photoelectric equation
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01 Electron emission

Removing a free electron from a metal needs a minimum energy: the **work function φ_0** (in eV). It depends on the metal (Cs lowest ≈ 2.1 eV, Pt high ≈ 5.6 eV).

Method	Energy from
Thermionic emission	Heat (a bulb's filament)
Field emission	A very strong electric field (~10^8 V/m)
Photoelectric emission	Light (of suitable frequency)

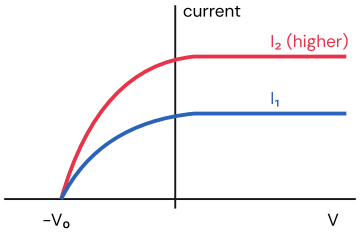
02 Photoelectric effect

Light of suitable frequency falling on a metal ejects electrons (observed by Hertz, Hallwachs, Lenard). Zinc needs UV; alkali metals (Cs, K) respond even to visible light.

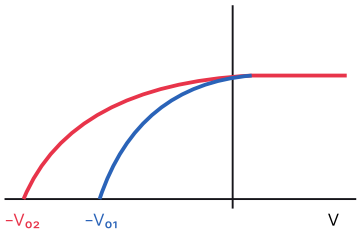
TERMS

- **Threshold frequency ν_0:** below it no electrons are emitted, however intense the light.
- **Stopping potential V_0:** the negative voltage that stops even the fastest electron: $eV_0 = K_{max}$.
- **Saturation current:** when all emitted electrons are collected.

03 Experimental results (graphs)



Higher intensity: larger saturation current, same V_o



Higher frequency ($\nu_2 > \nu_1$): larger V_o, same saturation

Observation	Result
Photocurrent vs intensity	Current ∝ intensity (more photons, more electrons)
Stopping potential vs intensity	No effect
K_{max} / V_o vs frequency	Straight line, rising above ν_o
Time lag	None ($< 10^{-9}$ s), instantaneous

04 Why wave theory failed

- Wave theory: brighter light ⇒ more energy ⇒ K_{max} should rise. In fact only the current rises.
- Wave theory: any frequency should work after enough waiting, as energy accumulates. In fact never below ν_o.
- Wave theory: dim light should take time. In fact emission is instant.

So Einstein proposed that light comes in **photons** (packets of energy).

05 Einstein's photoelectric equation

$$K_{max} = h\nu - \varphi_0 = eV_0$$

$$\varphi_0 = h\nu_0 = hc/\lambda_0$$

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

One photon gives all its energy to one electron. Slope of the V_0–ν graph = h/e (the same for every metal). x-intercept = ν_0.



Two metals: parallel lines (slope h/e)

SHORTCUT

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

hc = 1240 eV·nm. For quick calculation.

06 Photon

Property	Value
Energy	$E = h\nu = hc/\lambda$
Momentum	$p = h/\lambda = E/c$
Rest mass	0
Speed	c (in vacuum)
Charge	0 (not deflected by fields)

Increasing intensity increases the **number** of photons, not the energy of each. In collisions the number of photons can change (they can be created or absorbed), but energy and momentum are conserved.

07 de Broglie wavelength

de Broglie reasoned: if light (a wave) behaves like particles, then particles (electrons) should also behave like waves.

$$\lambda = h / p = h / (m\,v)$$

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

Charge q accelerated through V: $\lambda = h/\sqrt{(2mqV)}$

For an electron: $\lambda = 1.227/\sqrt{V}$ nm

WHY DON'T EVERYDAY OBJECTS SHOW WAVES?

A cricket ball's mass is huge ⇒ $\lambda \approx 10^{-34}$ m, impossible to measure. An electron is light ⇒ λ is about the size of an atom (~Å) ⇒ it diffracts from crystals.

Same KE: $\lambda \propto 1/\sqrt{m}$ (lighter particle, longer λ). Same V: $\lambda \propto 1/\sqrt{(mq)}$.

08 Davisson-Germer experiment

Electrons accelerated through 54 V were directed at a nickel crystal. A peak in intensity appeared at 50° (diffraction) ⇒ electrons behave like waves.

Experiment: $\lambda \approx 0.165$ nm. de Broglie: $\lambda = 1.227/\sqrt{54} \approx 0.167$ nm. They match ⇒ **matter waves proven**.

The **electron microscope** uses this idea: an electron's λ is far shorter than light's ⇒ far better resolution.

09 JEE Extra + Tricks

JEE LEVEL

- Photon: $E = hc/\lambda$; trick $E(eV) = 1240/\lambda(nm)$. Momentum $p = h/\lambda$.
- Einstein: $K_{max} = h\nu - \varphi = eV_o$; V_o vs ν graph slope = h/e (same for all metals), intercept gives threshold frequency.
- Intensity ↑ ⇒ photocurrent ↑ (not K_{max}); frequency ↑ ⇒ K_{max} ↑.
- de Broglie $\lambda = h/p = h/\sqrt{(2mK)} = h/\sqrt{(2mqV)}$; electron $\lambda = 12.27/\sqrt{V}$ Å.
- For same K, $\lambda \propto 1/\sqrt{m}$ (electron has longer λ than proton).

10 Solved numericals ($h = 6.6 \times 10^{-34}$, $hc = 1240$ eV·nm)

Q1. Energy of a photon of 500 nm light?
E = 1240/500 = 2.48 eV ≈ 3.97×10^{-19} J. **Ans: 2.48 eV**

Q2. A metal has φ_o = 2 eV and the light is 4 eV. K_{max} and V_o?
K_{max} = 2 eV, V_o = 2 V. **Ans: 2 eV, 2 V**

Q3. φ_o = 2.48 eV. Threshold wavelength?
λ_o = 1240/2.48 = 500 nm. **Ans: 500 nm**

Q4. λ of an electron accelerated through 100 V?
λ = 1.227/10 = 0.1227 nm. **Ans: ≈ 0.123 nm**

Q5. A proton and an electron have the same KE. Ratio λ_p/λ_e?
$\lambda \propto 1/\sqrt{m} \Rightarrow \sqrt{(m_e/m_p)} = \sqrt{(1/1836)} \approx 1/43$. **Ans: ≈ 1 : 43**

Q6. How many photons per second does a 1 mW laser (λ = 663 nm) emit?
$E = hc/\lambda = 6.6 \times 10^{-34} \times 3 \times 10^{8}/6.63 \times 10^{-7} \approx 3 \times 10^{-19}$ J. $n = 10^{-3}/3 \times 10^{-19} \approx 3.3 \times 10^{15}$. **Ans: ≈ 3.3×10^{15} per s**

11 Common mistakes

- Thinking higher intensity raises K_{max} (only the current rises).
- Mixing eV and J (1 eV = 1.6×10^{-19} J).
- Putting KE or V directly in place of v in de Broglie's formula.
- Thinking the slope of the V_o–ν graph depends on the metal (it is h/e for all).
- Assuming emission below ν_o happens "after a while".

12 Formula sheet

Photon	$E = h\nu = hc/\lambda,\ p = h/\lambda$
Shortcut	$E(\text{eV}) = 1240/\lambda(\text{nm})$
Einstein	$K_{max} = h\nu - \varphi_0 = eV_0$
Work function	$\varphi_0 = h\nu_0 = hc/\lambda_0$
de Broglie	$\lambda = h/mv = h/\sqrt{(2mK)} = h/\sqrt{(2mqV)}$
Electron	$\lambda = 1.227/\sqrt{V}$ nm
Photons per second	$n = P/(h\nu)$

13 Practice questions

1. Frequency is doubled. Does K_{max} double?
2. An electron's accelerating voltage is made 4 times. λ?
3. Slope of the V_o–ν graph?
4. A photon has momentum 3.3×10^{-27} kg·m/s. λ?

ANSWERS

1) No, more than double ($2h\nu - \varphi_o$) · 2) Halves · 3) h/e · 4) $\lambda = h/p = 200$ nm

14 Quick revision: 5 minutes before the exam

PHOTOELECTRIC

- $K_{max} = h\nu - \varphi_o = eV_o$.
- Intensity ⇒ current; frequency ⇒ K_{max}.
- $\nu < \nu_o$ ⇒ nothing; no time lag.

PHOTON

- $E = 1240/\lambda(nm)$ eV.
- $p = h/\lambda$; rest mass 0.

DE BROGLIE

- $\lambda = h/p = h/\sqrt{(2mK)}$.
- Electron: $1.227/\sqrt{V}$ nm.
- Same K: $\lambda \propto 1/\sqrt{m}$.

PROOF

- Davisson-Germer: 54 V, 50°, Ni.
- Electron microscope.

Have a doubt? Ask the AI Doubt Solver at padhaiadda.netlify.app, or take the mock test on this chapter.