KSQUARE CAREER INSTITUTE

DUAL NATURE OF MATTER & RADIATION

Class 12 Physics • Photon Theory & Photoelectric Effect • NEET / JEE Notes

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Topics Covered

1. History — theories of light (Newton → de Broglie)
2. Electron volt & particle theory of light — properties of a photon
3. Energy of a photon; energy, power and intensity of light; mass of a photon
4. Electron emission — thermionic, field, photoelectric
5. Work function, threshold frequency & wavelength
6. 35 practice questions solved • Added: Einstein's equation & stopping potential, graphs, photon momentum, de Broglie waves, Davisson–Germer — formula sheet

HISTORY — THEORIES OF LIGHT

Scientist / Year	Theory	Key idea
Newton, 1672	Corpuscular theory	Light is made of particles called **corpuscles**; explains **reflection & refraction**
Huygens, 1690	Wave theory	Light is a **mechanical wave** travelling through **ether**; explains **interference, diffraction, polarisation**
Maxwell, 1865	Electromagnetic theory ("A Dynamical Theory of the EM Field")	Light is a **non-mechanical (EM) wave** — needs **no medium**
Max Planck, 1900	Quantum theory (Nobel 1918)	Light is made of **photons**, E = hf; energy is **quantised**; explained **black-body radiation**
de Broglie, 1924	Dual nature	Radiation (and matter) shows **both wave and particle** nature

- **Davisson & Germer (1927)** and **G. P. Thomson** proved that the **electron behaves as a wave** — Nobel Prize 1937.

Wave relation

$$\lambda f = \text{speed} \Rightarrow \text{for light in vacuum: } \lambda f = c, \quad f = c/\lambda$$

*Note: de Broglie's 1924 hypothesis was that **matter** (e.g. electrons) also has a wave nature; the dual nature of light had already been shown by Planck/Einstein (particle) and Young/Maxwell (wave).*

ELECTRON VOLT (EV)

1 eV

Energy gained by **one electron accelerated through a potential difference of 1 V**.

Energy from potential difference

$$\Delta E = qV \text{ (joule)}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}; \quad 1 \text{ J} = 1/(1.6 \times 10^{-19}) \text{ eV}$$

- Electron moving from 5 V → 6 V (towards higher potential) gains **1 eV**; from –6 V → –5 V also **1 eV**; from 50 V → 51 V also **1 eV** — only the **difference** matters.

PARTICLE THEORY OF LIGHT — PHOTON

Light is a form of energy made up of tiny packets called **photons**.

Property	Value
Speed in vacuum	$c = 3 \times 10^8$ m/s
Speed in a medium	c/μ (μ = refractive index)
Rest mass	**Zero**
Charge	**Zero** — so photons are **not deflected** by electric or magnetic fields
Energy	$E = hf$ ($h = 6.626 \times 10^{-34}$ J s)

NEET Point / PYQ Alert

Frequency depends only on the source — not on distance or medium. As long as the source is unchanged, f is unchanged (λ and speed change in a medium).

Energy of One Photon

Photon energy

$$E = hf = hc/\lambda \quad \Rightarrow \quad E \propto f \text{ and } E \propto 1/\lambda$$

$$\text{Shortcut: } E(\text{eV}) = 1240 / \lambda(\text{nm}) = 12400 / \lambda(\text{Å}) \qquad (hc \approx 1240 \text{ eV nm})$$

$$1 \text{ Å} = 10^{-10} \text{ m}; \quad 1 \text{ nm} = 10^{-9} \text{ m}$$

Energy, Power & Intensity of Light

Quantity	Formula
Energy (N photons)	$E = Nhf = Nhc/\lambda \Rightarrow N = E/hf = E\lambda/hc$
Power (n = photons per second)	$P = E/t = nhf = nhc/\lambda \Rightarrow n = P\lambda/hc$

Quantity	Formula
Intensity (flux)	$I = E/(At) = P/A = nhf/A \Rightarrow$ Power $= I \times A$

Mass of a Photon (dynamic)

Using $E = mc^2$

$$m = E/c^2 = hf/c^2 = h/(\lambda c) \Rightarrow m \propto 1/\lambda$$

VIBGYOR: violet has the **maximum** photon mass/energy, red the **least**

NEET Point / PYQ Alert

Frequency decides **how much energy each photon (and photo-electron) gets**; **intensity** decides **how many photons / electrons**.

Practice — Photon Energy & Number

Q1. What is the effect on the number of photons if intensity becomes double?

Answer: Number of photons becomes 2 times — $n = IA/hf \propto I$.

Q2. What is the effect on the number of photons if intensity and frequency both become double?

Answer: No effect — $n \propto I/f = 2/2 = 1$.

Q3. The wavelength of a photon is 2000 Å. Find its energy in eV.

Answer: 6.2 eV ($\approx 9.9 \times 10^{-19}$ J) — $E = 12400/2000$.

Q4. The wavelength of a photon is 496 nm. Find its energy in eV.

Answer: 2.5 eV ($= 4 \times 10^{-19}$ J) — $E = 1240/496 = 2.5$ eV.

Q5. Find the energy (in joule) if the frequency of light is 60×10^{30} Hz.

Answer: $\approx 4 \times 10^{-2}$ J — $E = 6.6 \times 10^{-34} \times 6 \times 10^{31} = 3.96 \times 10^{-2}$ J.

Q6. Find the energy (in eV) if the frequency of light is 3 lakh Hz.

Answer: $\approx 1.24 \times 10^{-9}$ eV — $E = 6.6 \times 10^{-34} \times 3 \times 10^{5} = 1.98 \times 10^{-28}$ J $\div 1.6 \times 10^{-19}$.

Note: in the class working of Q6 the joule value is written with exponent 10^{-23}; correct value is 1.98×10^{-28} J (the final eV value is right).

Q7. Find the energy (J) if the wavelength of light is 10×10^{-10} m.

Answer: $\approx 2 \times 10^{-16}$ J (= 1240 eV) — $\lambda = 1$ nm $\Rightarrow E = 1240$ eV.

Q8. Find the energy (eV & joule) if the wavelength of light is 40 nm.

Answer: 31 eV $\approx 4.96 \times 10^{-18}$ J — 1240/40.

Q9. Find the energy (eV) if the wavelength of light is 8×10^{-8} m.

Answer: 15.5 eV — $\lambda = 80$ nm $\Rightarrow$ 1240/80.

Q10. A photon has energy 124 eV. Find its wavelength.

Answer: 100 Å = 10 nm — $\lambda = 12400/124$ Å.

Q11. A beam of light of 200 eV contains photons of energy 5 eV each. Number of photons?

Answer: 40 — $N = 200/5$.

Q12. What is the energy of a beam containing 10 photons each of wavelength 30 Å?

Answer: ≈ 4133 eV ≈ 6.6×10^{-16} J — One photon = 12400/30 = 413.3 eV; × 10.

Q13. A 2 mW laser operates at 500 nm. Number of photons emitted per second ($h = 6.6 \times 10^{-34}$ J s)?

(A) 2×10^{6}
(B) 1.5×10^{16}
(C) 5×10^{15}
(D) 1×10^{16}

Answer: (C) — $n = P\lambda/hc = (2 \times 10^{-3} \times 5 \times 10^{-7})/(1.98 \times 10^{-25}) \approx 5 \times 10^{15}$.

Q14. Number of electrons emitted per second by a 24 W source of 6600 Å with 3% photoelectric efficiency?

(a) 48×10^{19}
(b) 48×10^{17}
(c) 8×10^{19}
(d) 24×10^{17}

Answer: (d) — Useful P = 0.72 W; $n = P\lambda/hc = 0.72 \times 6.6 \times 10^{-7}/1.98 \times 10^{-25} = 2.4 \times 10^{18}$.

Note: Q15 is missing in the lecture PDF (numbering jumps from Q14 to Q16).

Q16. Light of 3000 Å falls on a 4 cm^2 surface with intensity 150 mW/m^2. Rate at which photons strike?

Answer: ≈ 9×10^{13} photons/s — $P = IA = 0.15 \times 4 \times 10^{-4} = 6 \times 10^{-5}$ W; $n = P\lambda/hc = 1.8 \times 10^{-11}/1.98 \times 10^{-25}$.

Q17. A point source at distance d ejects photoelectrons at rate n with max KE E. Brought to d/2, the rate and max KE become

(a) 2n and 2E
(b) 4n and 4E
(c) 4n and E
(d) n and 4E

Answer: (c) — $I \propto 1/d^2 \Rightarrow 4\times$ electrons; KE depends only on frequency.

Q18. The energy of a photon of wavelength λ is

(a) hλ
(b) chλ
(c) λ/hc
(d) hc/λ

Answer: (d)

Q19. The approximate wavelength of a photon of energy 2.48 eV is

(a) 500 Å
(b) 5000 Å
(c) 2000 Å
(d) 1000 Å

Answer: (b) — 12400/2.48 = 5000 Å.

Q20. Wavelength of a 1 keV photon is 1.24×10^{-9} m. Frequency of a 1 MeV photon?

Answer: ≈ 2.4×10^{20} Hz — $\lambda \propto 1/E \Rightarrow \lambda = 1.24 \times 10^{-12}$ m; $f = c/\lambda = 2.42 \times 10^{20}$ Hz.

ELECTRON EMISSION

Electrons are emitted when they get enough energy to overcome the pull of the nuclei and leave the metal surface:

- **Thermionic emission** — metal is **heated**; emitted electrons are called **thermions**.

- **Field emission** — a **very strong electric field** is applied across the metal.
- **Photoelectric emission** — **light of suitable frequency** falls on the metal; discovered by **Heinrich Hertz (1887)**, explained by **Einstein**. Emitted electrons = **photoelectrons**.
- Photoelectric emission is **instantaneous** — **no time lag** between incidence of light and emission.

*Note: the PDF says Einstein explained it in 1920. Einstein gave the explanation in **1905** (Nobel Prize 1921).*

Work Function, Threshold Frequency & Wavelength

Work function (ϕ)

Minimum energy a free electron needs to escape from the metal surface. It is a **property of the metal** only.

Threshold frequency (f_o)

Minimum frequency of radiation just enough to liberate an electron: $\phi = hf_o$.

Threshold wavelength (λ_o)

Wavelength corresponding to the work function — the **maximum wavelength** that can cause emission: $\phi = hc/\lambda_o$.

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Emission occurs only if $\mathbf{f \geq f_o}$ ($\lambda \leq \lambda_o$) — however high the intensity.

Even with energy > ϕ, a particular electron **may or may not** eject (it can lose energy in collisions inside the metal).

Einstein's photoelectric equation

$$hf = \varphi + K_{max} \Rightarrow K_{max} = hf - hf_0 = \tfrac{1}{2} m v_{max}^2$$

Electrons come out with KE from **0 to K_{max}**

Practice — Photoelectric Effect

Q21. Photoelectric emission occurs only when the incident light has more than a certain minimum of

(a) Power
(b) Wavelength
(c) Intensity
(d) Frequency

Answer: (d)

Q22. Ultraviolet rays do not cause photoelectric effect on a metal plate. It may occur with

(a) Infrared rays
(b) X-rays
(c) Radio waves

(d) Microwaves

Answer: (b) — Only X-rays have higher frequency than UV.

Q23. A photon of 8 eV hits a metal of work function 5 eV. Range of energy of electrons released?

Answer: 0 to 3 eV

Q24. Same as above — maximum energy of electrons released?

Answer: 3 eV

Q25. A photon of 5 eV hits a metal of work function 8 eV. Range of energy?

Answer: No electrons are emitted (E < ϕ)

Q26. Photons of 3.8 eV fall on a surface of work function 2.8 eV. The KE of emitted electrons is

(a) 1 eV
(b) 6.6 eV
(c) 0 to 1 eV
(d) 2.8 eV

Answer: (c) — Range 0 to K_{max} = 1 eV (if "maximum KE" is asked, answer 1 eV).

Q27. When incident energy increases by 20%, max KE rises from 0.5 eV to 0.8 eV. Work function?

(a) 0.65 eV
(b) 1.0 eV
(c) 1.3 eV
(d) 1.5 eV

Answer: (b) — $E - \phi = 0.5$; $1.2E - \phi = 0.8 \Rightarrow E = 1.5$ eV, $\phi = 1.0$ eV.

Q28. The photoelectric work function

(a) is different for different materials
(b) is same for all metals
(c) depends on frequency of light
(d) depends on intensity of light

Answer: (a)

Q29. The photoelectric effect was first explained by

(a) Hallwachs
(b) Einstein
(c) Planck
(d) Bohr

Answer: (b)

Q30. The energy of the most energetic photoelectrons depends upon

(a) Threshold frequency
(b) Work function
(c) Wavelength of incident radiation
(d) All of these

Answer: (d) — $K_{max} = hc/\lambda - hf_o$.

Q31. Threshold wavelength of sodium is 6×10^{-7} m. Photoemission occurs if

(a) $\lambda > 6 \times 10^{-7}$ m
(b) $\lambda < 6 \times 10^{-7}$ m
(c) $\lambda = 5 \times 10^{14}$ m
(d) frequency $\leq 5 \times 10^{14}$ Hz

Answer: (b) — λ_o is the maximum wavelength; $f_o = c/\lambda_o = 5 \times 10^{14}$ Hz, so emission needs $f \geq 5 \times 10^{14}$ Hz.

Q32. With photon energy E the max KE is 2K; with 5E it is 12K. Work function in terms of E?

Answer: $\phi = E/5$ — $E = 2K + \phi$; $5E = 12K + \phi \Rightarrow 4E = 10K \Rightarrow K = 0.4E \Rightarrow \phi = 0.2E$.

Note: the class working writes $E = 2K - \varphi$; the correct form is $E = 2K + \varphi$ (the final answer E/5 is unchanged).

Q33. Photons of 1 eV and 2.5 eV illuminate a surface of work function 0.5 eV. Ratio of maximum speeds?

(a) 1:4
(b) 1:2
(c) 1:1
(d) 1:5

Answer: (b) — $v \propto \sqrt{K}$: $\sqrt{(0.5/2)} = 1/2$.

Q34. Light of $2f_o$ gives max speed v_1; $5f_o$ gives v_2. $v_1 : v_2$ =

(a) 1:2
(b) 1:4
(c) 4:1
(d) 2:1

Answer: (a) — $K_1 = hf_o$, $K_2 = 4hf_o \Rightarrow v_1/v_2 = 1/2$.

Q35. Work function is 4.0 eV. Threshold wavelength & maximum wavelength (nm)?

Answer: Both = 310 nm — $\lambda_o = 1240/4 = 310$ nm — the threshold wavelength is itself the maximum wavelength.

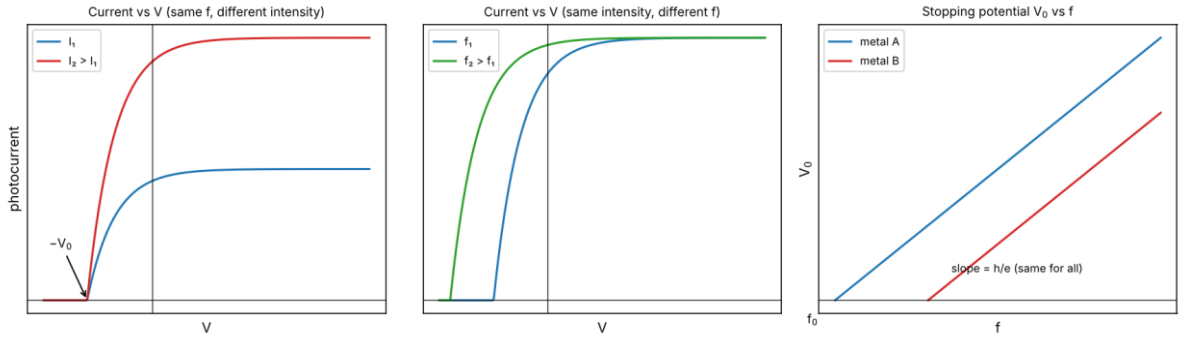
BEYOND THE LECTURE (ADDITIONAL TOPIC)

▸ Stopping Potential & Graphs

Stopping potential (V_0)

$$eV_0 = K_{max} = hf - \varphi \quad \Rightarrow \quad V_0 = (h/e)\, f - \varphi/e$$

Saturation current $\propto$ intensity; V_0 independent of intensity



- **I–V graph:** higher intensity → higher **saturation current**, same stopping potential; higher frequency → **more negative** stopping potential, same saturation current.
- **V_0 vs f:** straight line, **slope = h/e** (same for all metals), x-intercept = **f_0**, y-intercept = $-\phi/e$.
- **Photocurrent vs intensity:** straight line through origin. **K_{max} vs f:** straight line with slope h.

Photon Momentum & Matter Waves

Quantity	Formula
Photon momentum	$p = E/c = h/\lambda = hf/c$
Radiation force	Perfect absorber $F = P/c$; perfect reflector $F = 2P/c$
de Broglie wavelength	$\lambda = h/p = h/mv = h/\sqrt{(2mK)} = h/\sqrt{(2mqV)}$
Electron through V volts	$\lambda = 12.27/\sqrt{V}$ Å ($\approx 1.227/\sqrt{V}$ nm)
Proton / α through V volts	$\lambda_p = 0.286/\sqrt{V}$ Å; $\lambda_\alpha = 0.101/\sqrt{V}$ Å
Thermal particle	$\lambda = h/\sqrt{(3mkT)}$
Same KE	$\lambda \propto 1/\sqrt{m}$; **same V:** $\lambda \propto 1/\sqrt{(mq)}$

Davisson–Germer Experiment

- Electrons accelerated through **54 V** scattered from a **nickel crystal**; a strong peak was seen at **θ = 50°**.
- Measured λ = **1.65 Å** vs de Broglie $\lambda = 12.27/\sqrt{54}$ = **1.67 Å** — confirmed the **wave nature of electrons**.

Laws of Photoelectric Effect (Summary)

1. Emission is **instantaneous** (no time lag).
2. Photocurrent ∝ **intensity** (for $f > f_o$).
3. K_{max} and V_o depend on **frequency**, not intensity.
4. No emission below $\mathbf{f_o}$, however intense the light.
5. Wave theory fails to explain these — **photon theory** explains them.

FORMULA SHEET

1. $E = hf = hc/\lambda$; $E(eV) = 1240/\lambda(nm) = 12400/\lambda(Å)$
2. $1\ eV = 1.6 \times 10^{-19}\ J$; $\Delta E = qV$
3. $n = P\lambda/hc$; $I = P/A = nhf/A$
4. $m = h/\lambda c$; $p = h/\lambda$
5. $\phi = hf_o = hc/\lambda_o$; $K_{max} = hf - \phi = eV_o$
6. $\lambda_{electron} = 12.27/\sqrt{V}$ Å

Frequency gives the energy, intensity gives the number — remember this and half the chapter is done!