

1. FUNDAMENTAL CONSTANTS

Constant	Value
Planck's const h	6.626×10^{-34} J·s
h in eV·s	4.136×10^{-15} eV·s
Speed of light c	3×10^8 m/s
Electron mass m_e	9.11×10^{-31} kg
Electron charge e	1.6×10^{-19} C
hc	1240 eV·nm
hc (in J·m)	1.989×10^{-25} J·m
1 eV	1.6×10^{-19} J
h/e	4.136×10^{-15} V·s

$$E [\text{eV}] = \frac{1240}{\lambda [\text{nm}]} \quad (\text{Most used shortcut!})$$

*** Common Pitfall**

- ▶ $h = 6.626 \times 10^{-34}$ J·s (SI), but 4.136×10^{-15} eV·s for atomic-scale problems — use the right unit set!
- ▶ $hc = 1240$ eV·nm only when λ is in **nanometres**

2. PHOTON PROPERTIES

$$E = hf = \frac{hc}{\lambda} \quad p = \frac{h}{\lambda} = \frac{E}{c}$$

Rest mass of photon: $m_0 = 0$ (always)

Relativistic mass (effective): $m_{\text{eff}} = \frac{h}{c\lambda} = \frac{E}{c^2}$

Number of photons: $n = \frac{P}{hf} = \frac{P\lambda}{hc}$

(P = power of source [W])

Intensity at distance r : $I = \frac{P}{4\pi r^2}$ [W/m²]

Radiation pressure (absorbed surface): $P_{\text{rad}} = \frac{I}{c}$

Radiation pressure (reflected surface): $P_{\text{rad}} = \frac{2I}{c}$

*** Common Pitfall**

- ▶ Photon has zero **rest** mass — it does NOT mean zero momentum
- ▶ Intensity depends on *number* of photons per second; energy of each photon depends on *frequency* only
- ▶ Doubling intensity \neq doubling frequency

3. PHOTOELECTRIC EFFECT

Einstein's equation:

$$KE_{\text{max}} = hf - \phi = h(f - f_0)$$

- ▶ $\phi = hf_0$ = work function [eV or J]
- ▶ f_0 = threshold frequency [Hz]
- ▶ $\lambda_0 = c/f_0$ = threshold wavelength

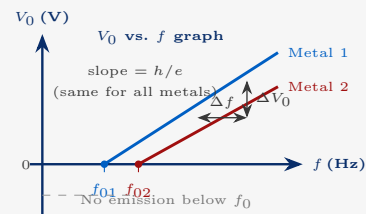
Stopping potential V_0 :

$$eV_0 = KE_{\text{max}} = hf - \phi$$

$$V_0 = \frac{h}{e}f - \frac{\phi}{e}$$

Key observations table:

Parameter changed	Effect
↑ Intensity	↑ current, no change in V_0
↑ Frequency	↑ V_0 , no change in saturation current
Change material	↑ or ↓ ϕ , changes f_0
$f < f_0$	No emission (regardless of intensity)



*** Common Pitfall**

- ▶ **Slope** of V_0 - f graph = h/e for *all* metals (same slope, different intercept)
- ▶ Stopping potential is **independent of intensity**
- ▶ **y-intercept** = $-\phi/e$ (negative); x-intercept = f_0
- ▶ Saturation current (not V_0) increases with intensity
- ▶ Emission is **instantaneous** — no time delay (classical wave theory was wrong here)

4. WORK FUNCTION & THRESHOLD

Metal	ϕ (eV)	f_0 (Hz)	λ_0 (nm)
Caesium	2.0	4.84×10^{14}	620
Potassium	2.3	5.56×10^{14}	540
Sodium	2.75	6.65×10^{14}	451
Copper	4.5	1.09×10^{15}	275
Silver	4.7	1.14×10^{15}	263
Platinum	5.65	1.37×10^{15}	219

Quick formula: $\lambda_0 [\text{nm}] = 1240 / \phi [\text{eV}]$

*** Common Pitfall**

- ▶ Higher $\phi \Rightarrow$ lower λ_0 (need higher frequency, shorter wavelength)
- ▶ Visible light (≈ 400 – 700 nm) can eject electrons only from metals with $\phi < 3.1$ eV (e.g., Cs, Na, K)

5. de BROGLIE MATTER WAVES

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

For particle of KE = K :

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

Accelerated through pd V : $K = qV$, so

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

For electron ($m_e = 9.11 \times 10^{-31}$ kg):

$$\lambda_e = \frac{1.227}{\sqrt{V}} \text{ nm} \quad (V \text{ in volts})$$

Temperature (thermal de Broglie):

$$K = \frac{3}{2}k_B T \Rightarrow \lambda = \frac{h}{\sqrt{3mk_B T}}$$

$$k_B = 1.38 \times 10^{-23} \text{ J/K}$$

Comparison at same KE:

$$\lambda \propto \frac{1}{\sqrt{m}} \Rightarrow \lambda_p < \lambda_e \text{ (proton heavier)}$$

Comparison at same p : λ same (since $\lambda = h/p$)

★ Common Pitfall

- ▶ $\lambda = h/mv$ uses *particle* momentum, not photon momentum formula
- ▶ Heavier particle \Rightarrow smaller λ at same KE
- ▶ de Broglie wavelength depends on *momentum*, not speed alone
- ▶ For relativistic particles use $p = \gamma m_0 v$, not $m_0 v$

6. DAVISSON-GERMER EXPERIMENT

Confirmed: wave nature of electrons

Setup: Electrons accelerated through $V = 54$ V, scattered by Nickel crystal

Bragg's condition for diffraction:

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

d = interplanar spacing, θ = glancing angle, n = order

Observed maximum at $\phi = 50$ (scattering angle)

Lattice spacing of Ni ≈ 0.91 Å

Calculated λ : $\lambda = h/\sqrt{2m_e eV} = \frac{1.227}{\sqrt{54}} \approx 0.167 \text{ nm} \approx 1.67 \text{ Å}$

Experimental λ from Bragg's condition: ≈ 1.65 Å

Conclusion: de Broglie hypothesis verified experimentally

★ Common Pitfall

- ▶ Glancing angle θ in Bragg's law \neq angle of incidence from normal
- ▶ Diffraction maximum \neq reflection maximum; Bragg gives *constructive interference*
- ▶ Davisson-Germer used *reflection*, G.P. Thomson used *transmission* geometry

7. HEISENBERG UNCERTAINTY PRINCIPLE

$$\Delta x \cdot \Delta p \geq \frac{h}{4\pi} = \frac{\hbar}{2}$$

$$\Delta E \cdot \Delta t \geq \frac{h}{4\pi}$$

where $\hbar = h/2\pi = 1.055 \times 10^{-34}$ J·s

Position-momentum: Cannot simultaneously know exact x and p_x

Energy-time: Energy of state with lifetime Δt has uncertainty ΔE

Minimum uncertainty form (often used in JEE):

$$\Delta x \cdot \Delta p \approx h \quad (\text{order-of-magnitude estimates})$$

★ Common Pitfall

- ▶ Use $\Delta x \cdot \Delta p \geq h/4\pi$ (exact) vs $\approx h$ (approximate)—JEE usually accepts either for estimates
- ▶ Uncertainty is **fundamental**, not due to measurement imperfection
- ▶ Δp in one direction only; Δx in same direction

8. COMPTON EFFECT

X-ray photon scattered by free electron \Rightarrow wavelength increases

$$\Delta \lambda = \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \phi)$$

ϕ = scattering angle of photon

Compton wavelength: $\lambda_c = \frac{h}{m_e c} = 2.426 \times 10^{-12} \text{ m} = 0.02426 \text{ Å}$

Special cases:

$\phi = 0 \quad \Delta \lambda = 0 \quad \text{No change}$

$\phi = 90 \quad \Delta \lambda = \lambda_c = 0.0243 \text{ Å}$

$\phi = 180 \quad \Delta \lambda = 2\lambda_c \quad \text{Maximum shift}$

Recoil electron KE: $K_e = hf - hf' = h(f - f')$

★ Common Pitfall

- ▶ $\Delta \lambda$ depends on **scattering angle only**, not on original wavelength
- ▶ Compton effect proves photon has *momentum* ($p = h/\lambda$)
- ▶ Not observed for visible light (effect too small; $\lambda_c \ll \lambda_{\text{visible}}$)
- ▶ Conserve *both* energy and momentum in Compton scattering

9. WAVE-PARTICLE DUALITY

Phenomenon	Wave	Particle
Photoelectric effect		✓
Compton effect		✓
Pair production		✓
Interference	✓	
Diffraction	✓	
Polarization	✓	
Davisson-Germer	✓	

Bohr's complementarity: Wave and particle natures are complementary — only one manifests at a time

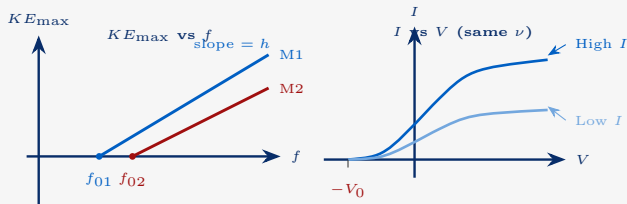
Pair production: $\gamma \rightarrow e^- + e^+$ threshold: $E_\gamma \geq 2m_e c^2 = 1.022 \text{ MeV}$

Pair annihilation: $e^- + e^+ \rightarrow 2\gamma$ each γ has $E = 0.511 \text{ MeV}$

★ Common Pitfall

- ▶ Wave nature does **not** mean the particle is literally spread out
- ▶ Electron *diffraction* (wave) and *photoelectric effect* (particle) are shown by the same electron
- ▶ Pair production needs a nucleus nearby (to conserve momentum)

10. KEY GRAPHS



★ Common Pitfall

- ▶ Both high and low intensity curves reach $-V_0$ at *same* stopping potential (same frequency)
- ▶ Saturation current \propto intensity; V_0 independent of intensity
- ▶ Slope of $KE_{\text{max}}-f$ graph = h (not h/e)
- ▶ Slope of V_0-f graph = h/e (not h)

11. COMPARISON: PHOTON vs. PARTICLE

Property	Photon	Particle
Energy E	$hf = hc/\lambda$	$\frac{1}{2}mv^2$ or qV
Momentum p	$h/\lambda = E/c$	$mv = \sqrt{2mK}$
Wavelength λ	c/f	h/p
Rest mass	0	$m \neq 0$
Speed	Always c	$v < c$
Charge	0	q

de Broglie wavelengths at same KE (K):

$$\lambda_e > \lambda_p > \lambda_\alpha \quad (\text{since } m_e < m_p < m_\alpha)$$

At same p : λ same for all particles

★ Common Pitfall

- ▶ $\lambda = h/p$ works for *both* photons and particles, but $p = E/c$ for photons, $p = mv$ for particles
- ▶ At same KE : heavier particle has smaller λ
- ▶ At same speed: heavier particle has smaller λ (larger p)

12. JEE SHORTCUTS & MASTER TIPS

One-line golden shortcuts:

1. $E [\text{eV}] = 1240 / \lambda [\text{nm}]$
2. $\lambda_e [\text{nm}] = 1.227 / \sqrt{V}$ (V in volts)
3. $KE_{\text{max}} = hf - \phi$; $V_0 = KE_{\text{max}}/e$
4. Slope of $V_0-f = h/e = 4.14 \times 10^{-15} \text{ V}\cdot\text{s}$
5. Compton max shift ($\phi = 180$): $\Delta\lambda = 2\lambda_c = 0.0486 \text{ \AA}$
6. $\lambda \propto 1/\sqrt{m}$ at same KE; λ same at same p

7. Pair production threshold: $2 \times 0.511 \text{ MeV} = 1.022 \text{ MeV}$

Dimensional analysis check:

$$[h] = \text{J} \cdot \text{s} = \text{kg} \cdot \text{m}^2/\text{s} \quad (\text{same as angular momentum})$$

$$[\lambda = h/p]: \frac{\text{kg} \cdot \text{m}^2/\text{s}}{\text{kg} \cdot \text{m}/\text{s}} = \text{m} \quad \checkmark$$

★ Master Confusion List

1. **Stopping potential vs. work function:** $V_0 = KE_{\text{max}}/e \neq \phi/e$
2. **Which slope?** $KE-f$: slope = h ; V_0-f : slope = h/e
3. **Intensity increase:** more photons/s, NOT higher energy per photon
4. **de Broglie for same KE:** $\lambda \propto 1/\sqrt{m}$; for same p : $\lambda = h/p$ (independent of mass!)
5. **Photon momentum:** $p = h/\lambda \neq 0$ even though $m_0 = 0$
6. **Threshold:** even one photon of $f > f_0$ can eject electron; no matter how bright $f < f_0$ light is, no emission