Topic E.2

QUANTUM PHYSICS

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

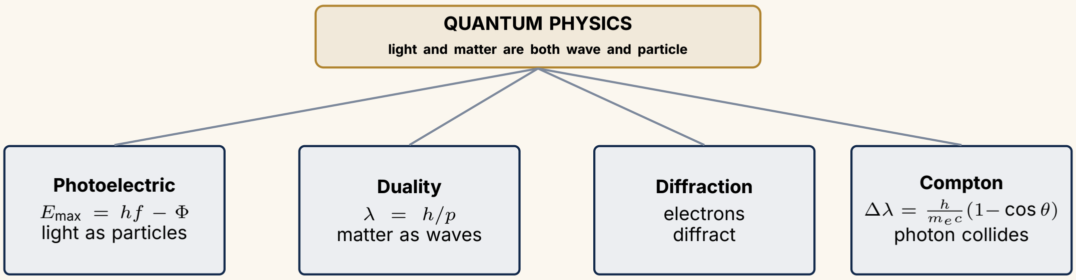
Topics Covered

The photoelectric effect
Einstein's equation & E–f graph
Wave–particle duality
de Broglie wavelength
Compton scattering

Exam Relevance

HL only — P1 & P2
$E_{\text{max}} = hf - \Phi$
Diffraction vs particle evidence
$\lambda = h/p$
$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$

The Big Picture — How E.2 Fits Together



§1 — Photoelectric Effect

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Key Concepts

Classical theory fails: Below f_0, no emission regardless of intensity. Emission is instantaneous. KE depends on frequency, not intensity.
Photon model (Einstein): Light consists of photons, each with energy $E = hf$. One photon ejects one electron. Φ = minimum energy to escape the surface.

Photon energy: $E = hf = \dfrac{hc}{\lambda}$

Work function & threshold: $\Phi = hf_0$

Einstein's photoelectric equation: $E_{\text{max}} = hf - \Phi$

Stopping voltage: $E_{\text{max}} = eV_s \implies V_s = \dfrac{hf - \Phi}{e}$

Max electron speed: $v_{\text{max}} = \sqrt{\dfrac{2E_{\text{max}}}{m_e}} = \sqrt{\dfrac{2eV_s}{m_e}}$

TRICK On a E_{max} vs f graph: **gradient** = h (same for all metals); **x-intercept** = f_0 (metal-specific); **y-intercept** (extrapolated) = $-\Phi$. A V_s vs f plot has gradient h/e (i.e. f vs V_s gives e/h) — the standard route to Planck's constant. Changing *intensity* changes current, NOT this graph.

TRAP Maximum KE depends on **frequency** only, not intensity. Intensity controls the **number** of electrons (i.e. the photocurrent). Never say "more intense = faster electrons."

NOTE $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8$ m/s, $e = 1.60 \times 10^{-19}$ C

Classical Theory vs Photon Theory — IB Comparison Table

Property	Classical predicts	Observed (photon)
Effect of intensity	KE increases	More electrons, KE unchanged
Threshold freq. f_0	None	Sharp threshold exists
Time delay	Yes (energy builds up)	Instantaneous
Effect of frequency	No effect on KE	KE $= hf - \Phi$

NOTE **I–V graph:** for one frequency, higher intensity ⇒ higher **saturation current** but the **same** stopping potential V_s (same E_{max}).

FROM THE PHOTON QUESTION BANK

Doubling f *more than* doubles E_{max} (since Φ is fixed) — a classic "show that" trap. Keep frequency (sets E_{max}, V_s) apart from intensity (sets current only), and use $\frac{1}{2}mv^2 = eV_s$ for the fastest-electron speed.

§2 — Wave–Particle Duality & de Broglie Wavelength

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de Broglie wavelength: $\lambda = \frac{h}{p} = \frac{h}{mv}$

For particle accelerated through V: $\lambda = \frac{h}{\sqrt{2mqV}}$

Photon momentum: $p = \frac{h}{\lambda} = \frac{E}{c}$

Photon wavelength (same rule): $\lambda = \frac{h}{p} = \frac{hc}{E}$

Wave–Particle Duality Summary

Entity	**Wave evidence**	**Particle evidence**
Light	Diffraction, interference, polarisation	Photoelectric effect, Compton scattering
Electrons	Electron diffraction (Davisson–Germer)	Definite mass, momentum, charge

TRICK To compare wavelengths at equal KE: $\lambda = h/\sqrt{2mE_k}$, so heavier particle $\Rightarrow$ shorter λ. At equal momentum: $\lambda = h/p$, same formula applies directly.

TRICK **Two ways to see $\lambda = h/p$:** a particle with momentum $p = mv$ (heavier/faster $\Rightarrow$ shorter λ); *and* a real wave that diffracts off crystals. Big objects: huge p, tiny λ, no visible diffraction.

TRAP For electron diffraction, **increasing** the accelerating voltage **decreases** λ (more momentum) $\Rightarrow$ rings on diffraction pattern move **inward** (less spreading).

NOTE Electron diffraction rings: bright rings = constructive interference; dark rings = **minimum intensity** (destructive). First minimum defines edge of central maximum, as in light diffraction.

FROM THE PHOTON QUESTION BANK

From a KE, get momentum via $p = \sqrt{2mE_k}$ — *not* $p = mv$ with an unknown v. Electron *diffraction* $=$ matter's wave nature; photoelectric $+$ Compton $=$ light's particle nature.

§3 — Compton Scattering

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Compton shift: $\Delta\lambda = \lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$

Compton wavelength: $\frac{h}{m_e c} = 2.43 \times 10^{-12}$ m

Compton Shift at Key Angles

Angle θ	$\cos\theta$	$(1-\cos\theta)$	$\Delta\lambda$
$0°$	1	0	0
$90°$	0	1	$h/m_e c = 2.43 \times 10^{-12}$ m
$180°$	-1	2	$2h/m_e c = 4.86 \times 10^{-12}$ m (max)

TRICK $\Delta\lambda$ depends **only on** θ, not on the incident wavelength λ_i. Scattered photon **always** has longer wavelength (lower energy). Shift is tiny ($\sim$pm), so Compton effect is significant only for X-rays/gamma rays, not visible light.

TRICK **Two ways to see the Compton shift:** photon as a billiard ball loses energy in the collision (lower f, longer λ); and classical waves *cannot* shift λ at all — so the shift itself proves light is particulate.

TRAP Do NOT confuse Compton scattering with the photoelectric effect. In Compton: photon survives with changed wavelength, electron recoils. In photoelectric: photon is **absorbed**, electron is **ejected** from the surface.

NOTE Derivation of Compton formula is NOT required by IB. The formula is given. Know how to apply it and explain why it proves photons have momentum.

FROM THE PHOTON QUESTION BANK

You may be given the shift and asked to work θ back out. Recoil-electron KE $= hc/\lambda_i - hc/\lambda_f$ (energy conservation). Compton: photon *survives*, longer λ; photoelectric: photon *absorbed*, electron ejected.

§4 — Constants & Formula Summary

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All Formulae at a Glance

$E = hf = hc/\lambda$ (photon energy)
$\Phi = hf_0$ (work function)
$E_{\text{max}} = hf - \Phi$ (Einstein's eq.)
$E_{\text{max}} = eV_s$ (stopping voltage)
$v_{\text{max}} = \sqrt{2eV_s/m_e}$ (max speed)
$\lambda = h/p = h/mv$ (de Broglie)
$\lambda = hc/E$ (photon)

$\lambda = h/\sqrt{2mqV}$ (accelerated particle)
$p = h/\lambda$ (photon momentum)
$\Delta\lambda = (h/m_e c)(1 - \cos\theta)$ (Compton)
$h = 6.63 \times 10^{-34}$ J s
$m_e = 9.11 \times 10^{-31}$ kg
$e = 1.60 \times 10^{-19}$ C
1 eV $= 1.60 \times 10^{-19}$ J