IB DP PHYSICS · THEME E NUCLEAR AND QUANTUM PHYSICS · E.2 (HL ONLY) · ~6 MIN READ

E.2 Quantum physics

The photon model of light, the photoelectric effect and Einstein's equation, threshold frequency and work function, de Broglie wavelength and electron diffraction, photon momentum and Compton scattering.

Photons | Photoelectric effect | Work function | Stopping potential | de Broglie wavelength | Electron diffraction | Compton scattering

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **E.2 is HL only.** Light comes in **photons** of energy E = hf. In the **photoelectric effect** one photon frees one electron: $E_{k\,max} = hf - \Phi$.
- Below the **threshold frequency** $f_0 = \Phi/h$ no electrons are emitted, however bright the light: brightness changes the number of photons, not their energy.
- Matter behaves like a wave too: $\lambda = h/p$ (de Broglie). Electron diffraction proves it.
- Photons carry momentum $p = h/\lambda$. **Compton scattering** of X-rays by electrons ($\lambda' - \lambda = h(1 - \cos\theta)/m_e c$) is the clearest evidence.

BY THE END YOU CAN

- Explain the photoelectric effect and why the wave model fails to explain it. HL
- Use $E_{k\,max} = hf - \Phi$, threshold frequency and stopping potential. HL
- Interpret the graph of $E_{k\,max}$ against frequency. HL
- Calculate de Broglie wavelengths and describe electron diffraction as evidence for matter waves. HL
- Use photon momentum and the Compton scattering equation. HL

1 The photoelectric effect HL

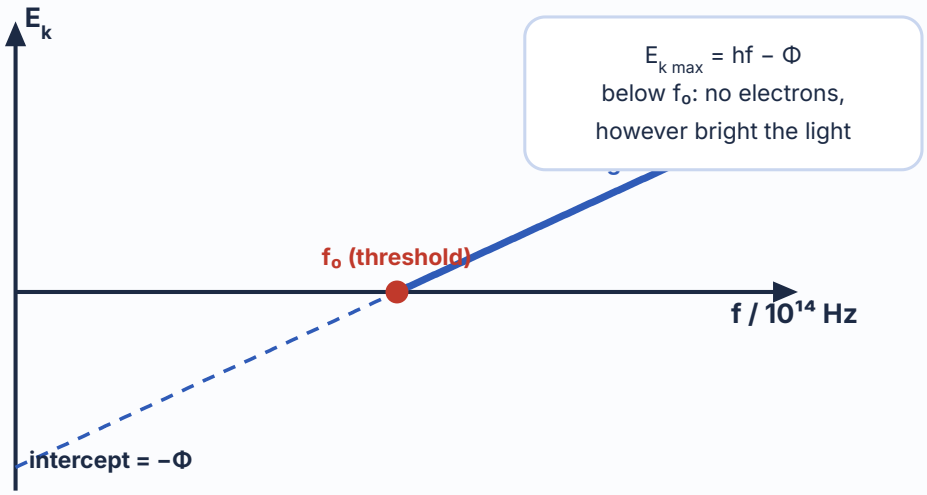
- **Observations:** (1) no electrons below a threshold frequency, whatever the intensity; (2) above it, electrons come off instantly, even in dim light; (3) the maximum kinetic energy depends on frequency, not intensity; (4) the number of electrons per second is proportional to the intensity.
- **Why waves fail:** a wave's energy depends on its amplitude, so bright enough light of any frequency should eventually free electrons, after a delay. Neither prediction is seen.

$$E = hf$$ DATA BOOKLET

energy of one photon

$$E_{k\,max} = hf - \Phi$$ DATA BOOKLET

Φ = work function, the minimum energy needed to free an electron from the surface



One graph, three facts: gradient h (the same for every metal), x-intercept f_0, y-intercept −Φ.

WORKED EXAMPLE

Light of 400 nm falls on sodium (Φ = 2.3 eV). Find the maximum kinetic energy of the electrons, the stopping potential and the threshold frequency.

1. photon energy = hc/λ = 4.97×10^{-19} J = 3.11 eV M1
2. $E_{k\,max}$ = 3.11 − 2.3 = **0.81 eV** A1
3. stopping potential $V_s = E_{k\,max}/e$ = **0.81 V** A1
4. **$f_0 = \Phi/h = 2.3 \times 1.6 \times 10^{-19}/6.63 \times 10^{-34} = 5.6 \times 10^{14}$ Hz** A1

Stopping potential V_s — the reverse potential difference that just stops the fastest photoelectrons: $eV_s = E_{k\,max}$.

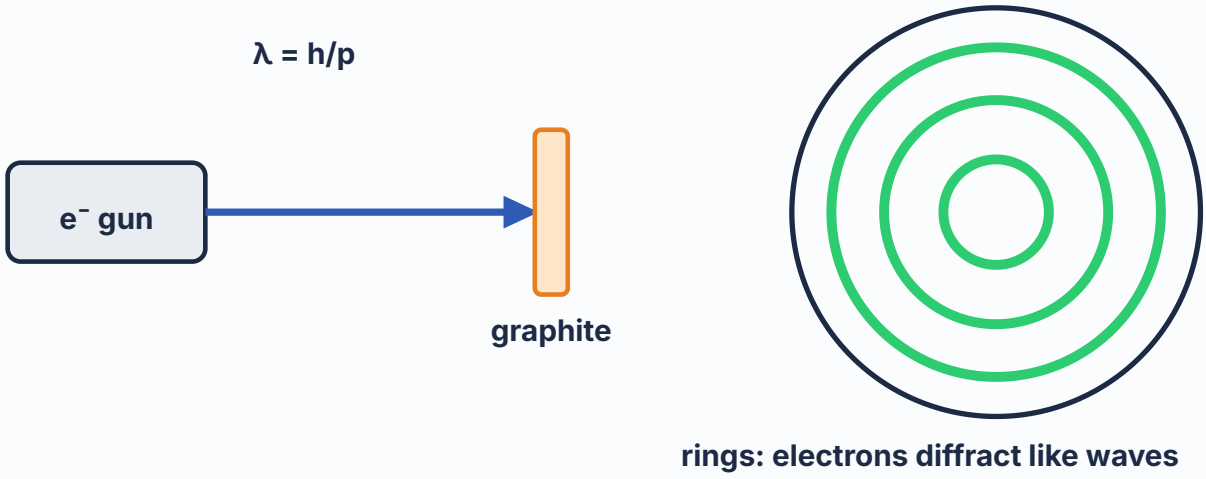
COMMON MISTAKE

Saying brighter light gives faster electrons. Brighter light means **more photons**, so more electrons, but each photon still has the same energy hf.

2 Matter waves HL

$$\lambda = \frac{h}{p}$$ DATA BOOKLET

de Broglie wavelength of any particle with momentum p



Electrons passing through a thin graphite film form rings, exactly like X-ray diffraction. Particles are behaving as waves.

WORKED EXAMPLE

Find the de Broglie wavelength of an electron accelerated from rest through 100 V.

1. E_k = 100 eV, $p = \sqrt{(2m_eE_k)} = \sqrt{(2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-17})} = 5.4 \times 10^{-24}$ kg m s^{-1} M1
2. **$\lambda = h/p = 1.2 \times 10^{-10}$ m, similar to atomic spacings, so it diffracts in crystals** A1

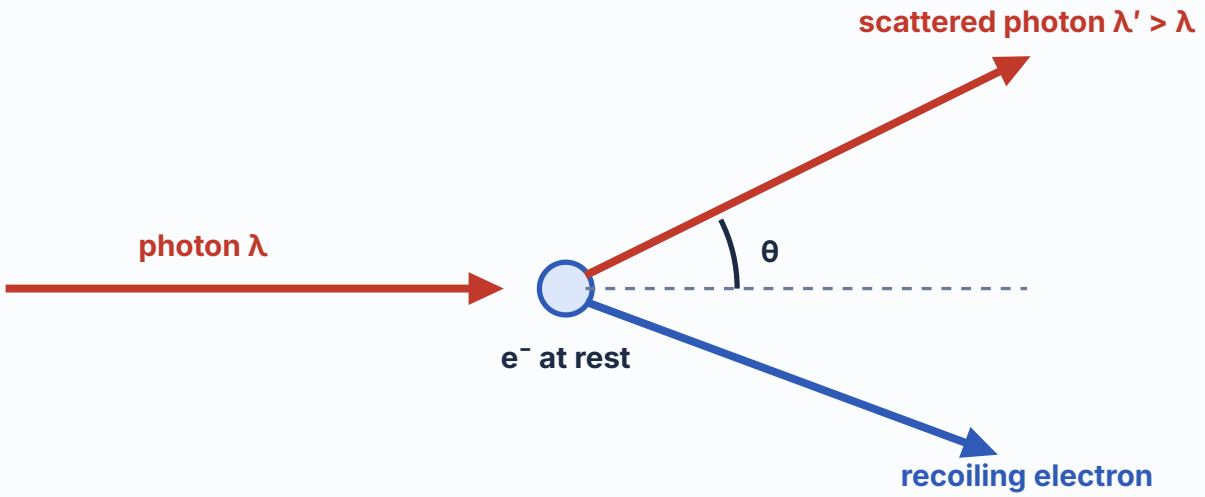
- **Faster electrons** (higher accelerating voltage) have a shorter wavelength, so their diffraction rings get **smaller**.
- **Wave–particle duality:** light shows wave behaviour (interference, C.3) and particle behaviour (photoelectric effect); electrons show both too. Which one you see depends on the experiment.

3 Photon momentum and Compton scattering HL

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

momentum of a photon (the same de Broglie equation)

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A photon collides with an electron like a billiard ball. It loses energy, so its wavelength increases.

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$ DATA BOOKLET

Compton shift; $h/m_e c = 2.43 \times 10^{-12}$ m

WORKED EXAMPLE

X-rays scatter from electrons at 90°. Find the change in wavelength.

1. $\Delta\lambda = (h/m_e c)(1 - \cos 90°) = 6.63 \times 10^{-34}/(9.11 \times 10^{-31} \times 3.00 \times 10^{8})$ M1
2. **$= 2.4 \times 10^{-12}$ m** A1

- **Why it proves photons:** treating light as particles with momentum and applying conservation of energy and momentum to each collision predicts Δλ exactly. A wave model gives no shift.

EXAM TIP

Use eV for energies until the last step. hf in eV: E (eV) = 1240/λ (nm) is a quick check (not in the booklet, so show the full calculation).

LINKING QUESTION

Quantised energy levels in atoms (E.1) and photon energies in greenhouse absorption (B.2) all rest on E = hf. Electron diffraction uses the grating equation from C.3.

IDEA FOR YOUR IA / EXPLORATION

Use LEDs of different colours to estimate Planck's constant: measure each LED's turn-on voltage V and use eV ≈ hc/λ, plotting V against 1/λ.

Test yourself — cover the answers first

QUICK CHECK

1. What does the work function represent?
2. Why are no electrons emitted below f_0?
3. What does the gradient of an $E_{k\,max}$–f graph equal?
4. What happens to the photocurrent if the intensity doubles (above f_0)?
5. What evidence shows electrons behave as waves?
6. Does a scattered Compton photon have a longer or shorter wavelength?

EXAM-STYLE

7. The stopping potential for a metal is 1.2 V with 300 nm light. Find the work function in eV.
8. Find the de Broglie wavelength of a 0.15 kg ball at 40 m s^{-1} and explain why it does not diffract.

Show answers

1. the minimum energy to free an electron from the metal surface
2. one photon has too little energy to free an electron, and electrons cannot add photon energies
3. Planck's constant h
4. it doubles
5. electron diffraction
6. longer
7. photon energy = $hc/\lambda = 6.63 \times 10^{-19}$ J = 4.14 eV
   $\Phi = 4.14 - 1.2$
   = **2.9 eV**
8. $\lambda = h/mv = 6.63 \times 10^{-34}/(0.15 \times 40)$
   = **1.1×10^{-34} m**
   far smaller than any gap or object, so diffraction is undetectable

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