A LEVEL PHYSICS 9702 · A LEVEL · TOPIC 22 · ~5 MIN READ

Quantum physics

Photons with E = hf and momentum p = E/c, the electronvolt, the photoelectric effect and Einstein's equation, wave–particle duality and the de Broglie wavelength, and energy levels with emission and absorption line spectra.

Photon energy E = hf | Photon momentum | Electronvolt | Photoelectric effect | Work function & threshold frequency | hf = Φ + ½mv²max | Electron diffraction | de Broglie λ = h/p

RS by Riyaz Sir
mentorriyaz.in

Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Light comes in photons:** E = hf = hc/λ, with momentum p = E/c. Energies are often given in electronvolts: 1 eV = 1.60 × 10^{-19} J.
- **Photoelectric effect:** one photon gives all its energy to one electron. hf = Φ + ½mv^2_{max}. Below the threshold frequency f_o = Φ/h, no electrons are emitted, however intense the light.
- **Particles have waves:** λ = h/p (de Broglie). Electron diffraction by graphite proves electrons behave as waves.
- **Energy levels:** an electron falling between levels emits one photon with hf = E_1 – E_2, giving a line spectrum.

BY THE END YOU CAN

- Understand photons, and use E = hf and p = E/c; use the electronvolt.
- Explain the photoelectric effect and why it supports a particle model of light; use hf = Φ + ½mv²max.
- Describe electron diffraction as evidence for wave behaviour, and use λ = h/p.
- Explain emission and absorption line spectra using discrete energy levels, and use hf = E_1 – E_2.

1 Photons

Energy and momentum

$$E = hf = hc/\lambda \; ; \; p = E/c \; ; \; 1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

$$h = 6.63 \times 10^{-34} \text{ J s}$$

Electronvolt — the energy gained by an electron moving through a potential difference of 1 V.

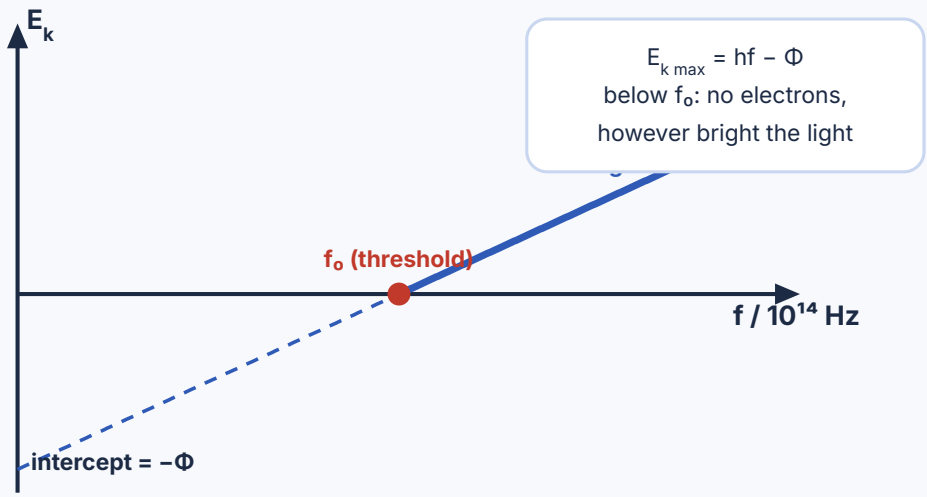
WORKED EXAMPLE

Find the energy of a 450 nm photon in joules and in eV.

1. E = hc/λ = 6.63 × 10^{-34} × 3.00 × 10^{8}/450 × 10^{-9} = **4.4 × 10^{-19} J** C1 A1
2. **÷ 1.60 × 10^{-19} = 2.8 eV** A1

2 The photoelectric effect

Evidence for photons



Maximum kinetic energy rises linearly with frequency: gradient h, intercept f_o.

Observation	Explanation with photons
No emission below f_o, however intense	one photon must have at least Φ; energy can't build up
Emission is instantaneous	a single photon–electron interaction
Max KE depends on frequency, not intensity	each photon has E = hf; intensity is just the number of photons
Photocurrent ∝ intensity (above f_o)	more photons per second release more electrons per second

Work function Φ — the minimum energy needed to remove an electron from the surface of a metal.

$$hf = \Phi + \tfrac{1}{2}mv^2_{max}$$

Einstein's photoelectric equation

WORKED EXAMPLE

Light of wavelength 400 nm falls on a metal of work function 2.3 eV. Find the maximum kinetic energy of the electrons and the threshold wavelength.

1. E = hc/λ = 3.11 eV C1
2. KE_{max} = 3.11 − 2.3 = **0.81 eV = 1.3 × 10^{-19} J** A1
3. **λ_o = hc/Φ = 6.63 × 10^{-34} × 3.0 × 10^8/(2.3 × 1.6 × 10^{-19}) = 540 nm** A1

COMMON MISTAKE

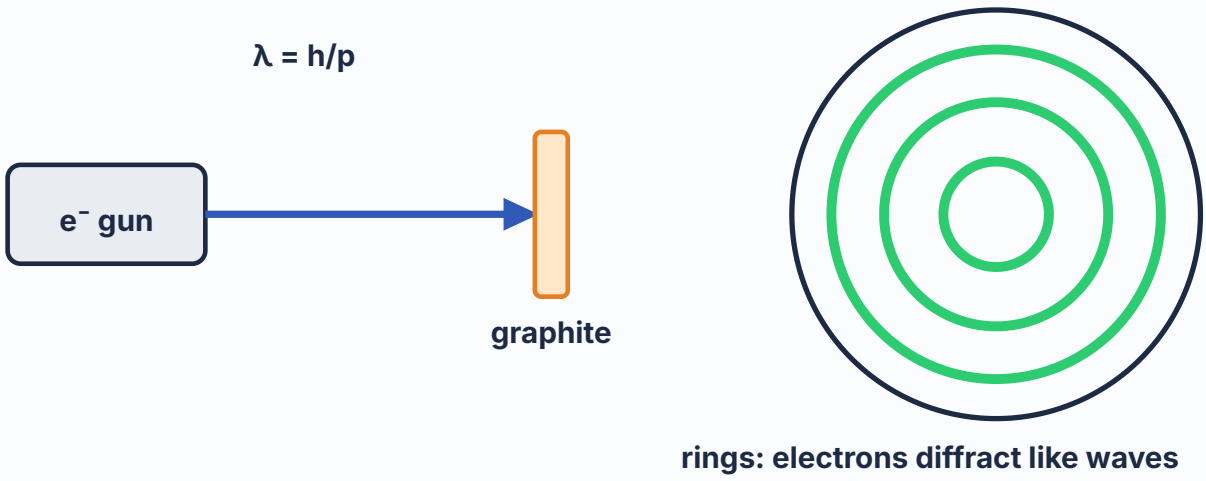
"More intense light gives faster electrons". Intensity changes the number of electrons per second, not their maximum energy. This is a perennial Paper 4 error.

3 Wave–particle duality

de Broglie

$$\lambda = h/p = h/(mv)$$

for an electron accelerated from rest through V: $p = \sqrt{(2meV)}$



Electrons through thin graphite form rings: a diffraction pattern, so they behave as waves.

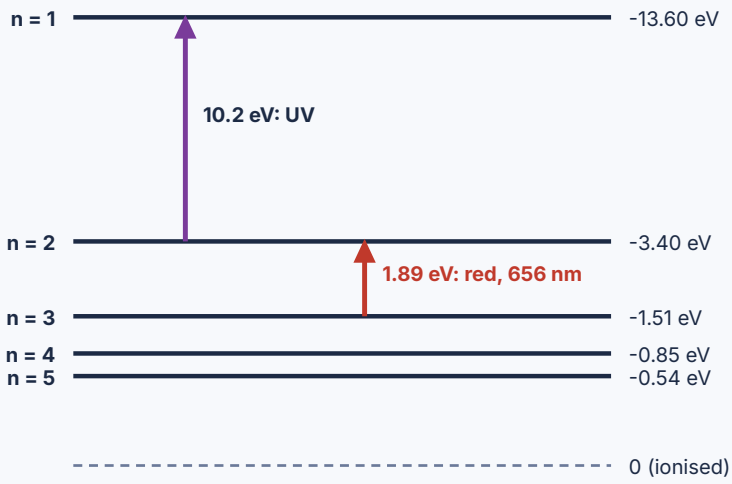
WORKED EXAMPLE

Find the de Broglie wavelength of an electron accelerated through 150 V.

1. $p = \sqrt{(2meV)} = \sqrt{(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 150)} = 6.6 \times 10^{-24}$ N s C1
2. **$\lambda = h/p = 1.0 \times 10^{-10}$ m A1 (similar to atomic spacing, so diffraction is visible)**

4 Energy levels

Line spectra

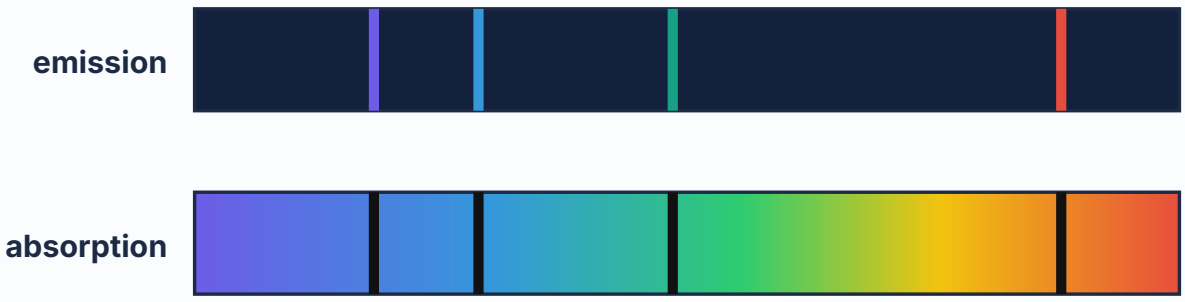


Emission: a falling electron emits one photon with E = hf = ΔE. (Not to scale.)

A falling electron emits one photon whose energy equals the gap between the levels.

$$hf = E_1 - E_2$$

emission when an electron falls; absorption when a photon of exactly that energy lifts it



Same element, same wavelengths: bright lines from a hot gas,
dark lines when white light passes through a cooler gas.

Emission spectrum: bright lines on dark. Absorption spectrum: dark lines at the same wavelengths.

WORKED EXAMPLE

An electron in hydrogen falls from −3.40 eV to −13.6 eV. Find the wavelength of the photon.

1. $\Delta E = 10.2\ \text{eV} = 1.63 \times 10^{-18}\ \text{J}$ C1
2. **$\lambda = hc/\Delta E = 1.22 \times 10^{-7}\ \text{m}$ (ultraviolet)** A1

- **Absorption lines:** white light through a cool gas loses exactly those photons whose energies match level gaps. The re-emitted photons go in all directions, so those wavelengths look dark.

LINKING QUESTION

Waves and diffraction are in Superposition; X-ray photons in Medical physics; and spectra of stars in Astronomy and cosmology.

Test yourself — cover the answers first

QUICK CHECK

1. Convert 5.0 eV to joules.
2. What does the gradient of a KE_max–f graph equal?
3. What evidence shows electrons behave as waves?
4. Does brighter light below the threshold frequency release electrons?
5. State the de Broglie equation.

EXAM-STYLE

6. Find the momentum of a photon of wavelength 600 nm.
7. The stopping potential for a metal under 250 nm light is 2.1 V. Find the work function in eV.
8. A proton and an electron have the same de Broglie wavelength. Compare their speeds.

Show answers

1. 8.0×10^{-19} J
2. the Planck constant h
3. electron diffraction
4. no
5. $\lambda = h/p$
6. $p = h/\lambda = 1.1 \times 10^{-27}$ N s
7. $E = 4.97$ eV; $\Phi = 4.97 - 2.1 = 2.9$ eV
8. same momentum, so $v \propto 1/m$: the electron is about 1840 times faster

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