Exercise walk-through

21.2
Quantum physics (full E.2, HL)

International Baccalaureate · IB Diploma · Physics · HL

Quantum · 2.1

Reasoning

A photon has energy proportional to frequency. The work function is the minimum energy needed to release an electron from a surface. Above threshold, excess photon energy can become electron kinetic energy. photon: A quantum of electromagnetic radiation. work function: Minimum surface energy needed to release an electron.

Exercises 2.1·2.3

2.1 State the photoelectric equation, defining each symbol. [2]

2.2 Give two observations of the photoelectric effect that the classical wave theory of light cannot explain. [2]

2.3 State the de Broglie hypothesis. [1]

Exercises 2.1·2.3

2.1 State the photoelectric equation, defining each symbol. [2]

2.1 $E_{max} = hf - \Phi$: maximum photoelectron kinetic energy equals photon energy minus the metal's work function – the minimum energy to release an electron.

2.2 Give two observations of the photoelectric effect that the classical wave theory of light cannot explain. [2]

2.2 Any two of: emission is instantaneous even in dim light; no emission below a threshold frequency regardless of intensity; maximum electron energy depends on frequency, not intensity.

2.3 State the de Broglie hypothesis. [1]

2.3 A particle of momentum p has a wavelength $\lambda = h/p$ – matter behaves as a wave.

Exercises 2.4·3.2

2.4 In Compton scattering, state what happens to the wavelength of a photon scattered off an electron at 180°. [1]

3.1 Light of frequency 6.0×10^{14} Hz strikes a metal of work function 1.9 eV. Calculate the photon energy in eV and the maximum kinetic energy of the photoelectrons. [4]

3.2 An electron beam accelerated through 54 V shows a diffraction maximum from a nickel crystal. Calculate the electron speed from $\tfrac{1}{2}mv^2 = eV$ and its de Broglie wavelength, and compare with an atomic spacing of about 0.2 nm. [5]

Exercises 2.4·3.2

2.4 In Compton scattering, state what happens to the wavelength of a photon scattered off an electron at 180°. [1]

2.4 The wavelength increases by the maximum shift $2h/m_e c \approx 4.9 \times 10^{-12}$ m.

3.1 Light of frequency 6.0×10^{14} Hz strikes a metal of work function 1.9 eV. Calculate the photon energy in eV and the maximum kinetic energy of the photoelectrons. [4]

3.1 $E = hf = (6.6 \times 10^{-34} \times 6.0 \times 10^{14}) = 4.0 \times 10^{-19}$ J $= 2.5$ eV; $E_{max} = 2.5 - 1.9 = 0.6$ eV.

3.2 An electron beam accelerated through 54 V shows a diffraction maximum from a nickel crystal. Calculate the electron speed from $\tfrac{1}{2}mv^2 = eV$ and its de Broglie wavelength, and compare with an atomic spacing of about 0.2 nm. [5]

3.2 $\tfrac{1}{2}mv^2 = eV$: $v = \sqrt{2eV/m} = \sqrt{(2 \times 1.6 \times 10^{-19} \times 54)/(9.1 \times 10^{-31})} = \sqrt{1.9 \times 10^{13}} = 4.4 \times 10^{6}$ m/s; $\lambda = h/mv = (6.6 \times 10^{-34})/(9.1 \times 10^{-31} \times 4.4 \times 10^{6}) = 1.7 \times 10^{-10}$ m $= 0.17$ nm; comparable with the 0.2 nm atomic spacing, so diffraction is strong – the pattern appears where the spacing and wavelength match.

Exercises 3.3·3.4

3.3 Explain why Compton scattering is described as evidence for the particle nature of light, and why the shift depends on the scattering angle. [3]

3.4 A metal has work function 2.5 eV. Calculate its threshold frequency, and state what is observed when light of twice that frequency illuminates it. [3]

Exercises 3.3·3.4

3.3 Explain why Compton scattering is described as evidence for the particle nature of light, and why the shift depends on the scattering angle. [3]

3.3 The wavelength shift means each photon lost energy in a collision with a single electron – a particle–particle interaction transferring energy and momentum; a wave would spread its energy continuously, giving no discrete shift; at larger scattering angles the photon transfers more momentum to the electron, losing more energy – hence a larger $\Delta\lambda = (h/m_e c)(1 - \cos\theta)$.

3.4 A metal has work function 2.5 eV. Calculate its threshold frequency, and state what is observed when light of twice that frequency illuminates it. [3]

3.4 $f_0 = \Phi/h = (2.5 \times 1.6 \times 10^{-19})/(6.6 \times 10^{-34}) = 6.1 \times 10^{14}$ Hz; at $2f_0$ photons carry $2\Phi = 5.0$ eV, so photoelectrons are emitted instantly with maximum kinetic energy $5.0 - 2.5 = 2.5$ eV.