21.2 Quantum physics (full E.2, HL)

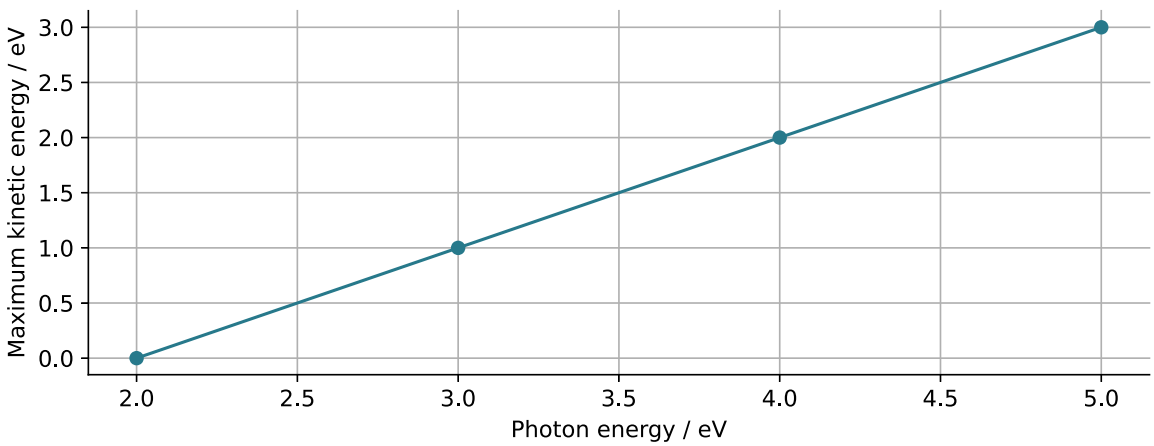
Name: _____ Class: _____ Date: _____ **Total: 21 marks**

KEY WORDS photoelectric effect • work function • threshold frequency • de Broglie wavelength • Compton scattering

Objective

Practise the full guide E.2 toolkit (HL only): the photoelectric effect as evidence for the particle nature of light, threshold frequency, Einstein's relation $E_{max} = hf - \Phi$, the failures of classical wave theory, particle diffraction and the de Broglie wavelength $\lambda = h/p$, and Compton scattering with the wavelength shift $\Delta\lambda = (h/m_e c)(1 - \cos\theta)$. Original practice; not an official IB paper.

1 Key knowledge and worked examples



■ **The E.2 equation set (HL)**

$$E = hf \qquad E_{max} = hf - \Phi \qquad f_0 = \frac{\Phi}{h} \qquad \lambda = \frac{h}{p} \qquad \Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

Wave theory fails on three counts: emission is instantaneous, there is a threshold frequency below which nothing is emitted however bright the light, and maximum electron energy follows frequency, not intensity.

■ **Worked example: one metal, two frequencies**

A metal with $\Phi = 2.3$ eV: threshold $f_0 = \Phi/h = (3.7 \times 10^{-19})/(6.6 \times 10^{-34}) = 5.6 \times 10^{14}$ Hz. At 7.0×10^{14} Hz each photon carries 2.9 eV, so $E_{max} = 2.9 - 2.3 = 0.6$ eV. Two habits: convert the work function to joules before dividing by h; and check any proposed observation against the three wave-theory failures.

2 Practice

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]

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

3 Exam-style questions

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 $\frac{1}{2}mv^2 = eV$ and its de Broglie wavelength, and compare with an atomic spacing of about 0.2 nm. [5]

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]

Solutions

Original-task marking: M1 method, A1 accuracy, B1 reasoning.

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

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

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 $\frac{1}{2}mv^2 = eV$: $v = \sqrt{2eV/m} = \sqrt{(2 \times 1.6 \times 10^{-19} \times 54)/(9.1 \times 10^{-31})} = \sqrt{1.9 \times 10^{13}} = 4.4 \times 10^6$ 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.

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 $f_0 = \Phi/h = (2.5 \times 1.6 \times 10^{-19})/(6.6 \times 10^{-34}) = 6.1 \times 10^{14}$ 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.