2.5 Photons and the photoelectric effect

Name: _____ Class: _____ Date: _____ **Total: 23 marks**

KEY WORDS Photons • photoelectric effect • work function • threshold frequency • electronvolt • discrete energy levels

Objective

Build the methods for WPH12 statements 57–63: photons and the photoelectric effect. These are original teaching questions, not copied past-paper items.

1 Key knowledge and worked examples

Wave ideas explain interference, diffraction and polarisation. They did not explain all observations of energy transfer. **Photons** describe discrete packets of electromagnetic energy:

$$E = hf = \frac{hc}{\lambda}$$

Historically, interference and diffraction supported wave models of light. Quantum ideas developed to explain observations including the photoelectric effect and atomic spectra. Modern physics uses both wave and photon descriptions according to the measurement. A successful new model must explain evidence that the older model explains too.

■ One photon and one electron

In the **photoelectric effect**, a surface electron absorbs a photon and may escape. The **work function** ϕ is the minimum energy needed to remove an electron from the surface. The **threshold frequency** is $f_0 = \phi/h$.

$$hf = \phi + E_{k,\max} = \phi + \frac{1}{2}mv_{\max}^2$$

- Below threshold, increasing intensity does not cause emission in the usual single-photon model.
- Above threshold, higher frequency raises maximum kinetic energy. A graph of $E_{k,\max}$ against f has gradient h, frequency intercept f_0 and extrapolated energy intercept $-\phi$.

- At fixed frequency above threshold, higher intensity supplies more photons per second. More electrons can be emitted per second, so the saturation photocurrent rises. Their maximum kinetic energy does not rise.
- Emission starts without the energy-building delay predicted by a simple continuous-wave energy model, even at low intensity above threshold.
- Electrons escape with a range of kinetic energies. Some lose more energy within the material. The equation describes the largest energy, not every electron's energy.

The **electronvolt** is an energy unit: 1 eV = 1.60×10^{-19} J. It is not a unit of potential difference. A stopping potential V_s just prevents even the fastest photoelectrons reaching the collector, so $eV_s = E_{k,\max}$.

Worked example. Light of frequency 8.0×10^{14} Hz reaches a surface with work function 2.0 eV.

- Known: photon frequency and work function. Convert the work function into joules before subtracting.

$$\phi = 2.0 \times 1.60 \times 10^{-19}\ \text{J} = 3.20 \times 10^{-19}\ \text{J}$$

$$E_{k,\max} = hf - \phi = 6.63 \times 10^{-34}\ \text{J s} \times 8.0 \times 10^{14}\ \text{Hz} - 3.20 \times 10^{-19}\ \text{J} = 2.10 \times 10^{-19}\ \text{J}$$

$$V_s = \frac{E_{k,\max}}{e} = \frac{2.10 \times 10^{-19}\ \text{J}}{1.60 \times 10^{-19}\ \text{C}} = 1.3\ \text{V}$$

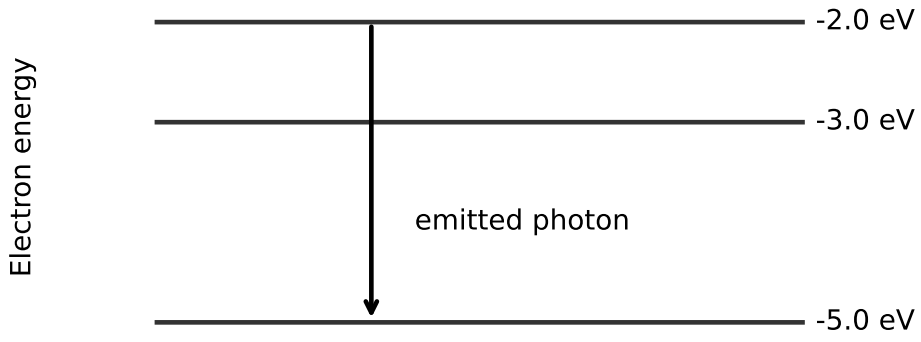
- The positive kinetic energy confirms that this frequency is above threshold. A negative subtraction would mean no emission, not negative kinetic energy.

Atomic line spectra

Atoms have **discrete energy levels** . An electron moving down between two allowed levels emits a photon. Moving up requires absorption of the matching energy:

$$|\Delta E| = hf = \frac{hc}{\lambda}$$

A line spectrum has particular frequencies because only certain level differences are allowed. The largest downward energy difference gives the highest frequency and shortest wavelength. Count possible transitions by checking level pairs and which upper levels are populated; do not automatically count the number of levels as the number of lines.



The photon energy equals the difference between the two levels.

Worked example. An electron drops from -2.0 eV to -5.0 eV.

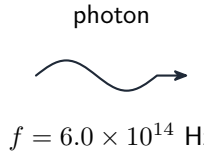
$$E_\gamma = E_{\text{upper}} - E_{\text{lower}} = [-2.0 - (-5.0)] \text{ eV} = 3.0 \text{ eV}$$

$$f = \frac{E_\gamma}{h} = \frac{3.0 \times 1.60 \times 10^{-19} \text{ J}}{6.63 \times 10^{-34} \text{ J s}} = 7.2 \times 10^{14} \text{ Hz}$$

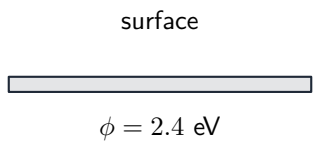
Photon absorption in a material does not always eject an electron from its surface. Excitation followed by emission, for example in a light-activated material, is not automatically the photoelectric effect.

2 Practice

2.1 A photon has frequency 6.0×10^{14} Hz. Calculate energy in joules and electronvolts. Use $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C. [3]



2.2 A surface has work function 2.4 eV. Calculate threshold frequency. Explain why increasing intensity below threshold does not cause ordinary single-photon emission. [3]

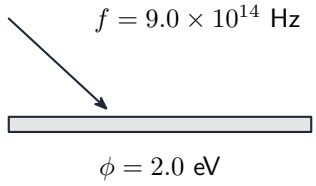
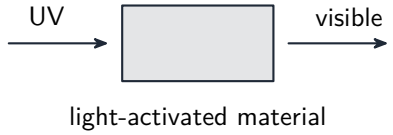


2.3 An atom has allowed levels −6.0, −3.0 and −1.0 eV. Electrons can start in the upper level and cascade. State the three possible emitted photon energies and identify the shortest-wavelength transition. [3]

3 Exam-style questions

3.1 For one surface above threshold, explain the effects of (a) doubling intensity at constant frequency; (b) increasing frequency at constant intensity. Discuss maximum kinetic energy and photon arrival rate. [4]

3.2 Light of frequency 9.0×10^{14} Hz reaches a surface of work function 2.0 eV. Calculate maximum kinetic energy and stopping potential. Explain how a kinetic-energy–frequency graph gives Planck's constant and threshold frequency, and why the wave model was revised. [6]



3.3 A light-activated material absorbs ultraviolet photons and then emits visible light. Explain why this alone does not prove photoelectric emission. Name two observations that support a photon explanation of photoelectric emission, and one observation that supports the wave description of light. [4]