# AQA AS Photoelectric Effect, Energy Levels and Wave–Particle Duality solutions

*Matching solutions and teaching prompts for the class review*

## Specification points covered

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| • 3.2.2.1(a) Threshold frequency and the photon model.<br>• 3.2.2.1(b) Work function and stopping potential.<br>• 3.2.2.1(c) Use $hf = \varphi + E_k(max)$.<br>• 3.2.2.1(d) Meaning of maximum photoelectron kinetic energy.<br>• 3.2.2.1(e) Stopping-potential method is not required.<br>• 3.2.2.2(a) Excitation and ionisation by electron collision.<br>• 3.2.2.2(b) Fluorescent tubes.<br>• 3.2.2.2(c) Electronvolt–joule conversion. | • 3.2.2.3(a) Line spectra and discrete energy levels.<br>• 3.2.2.3(b) Use $hf = E_1 - E_2$.<br>• 3.2.2.3(c) Energy levels in joules or electronvolts.<br>• 3.2.2.4(a) Electron diffraction as wave evidence.<br>• 3.2.2.4(b) Photoelectric effect as particle evidence.<br>• 3.2.2.4(c) Use de Broglie $\lambda = h/(mv)$.<br>• 3.2.2.4(d) Diffraction and particle momentum.<br>• 3.2.2.4(e) Evidence, peer review and changing scientific understanding. |

**Teaching focus**

Insist on precise particle, wave and energy language as well as correct calculations.
Use each common-error prompt to correct the pupil's model or reasoning, not only the final answer.

## 1. Photoelectric sensor

**1. The laboratory illuminates a contamination sensor with ultraviolet light of wavelength 310 nm. Calculate the energy of one photon in joules and electronvolts. [2 marks]**

**Answer / mark points:** $E = hc/\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^{8})/(310 \times 10^{-9}) = 6.42 \times 10^{-19}$ J. $E = 6.42 \times 10^{-19}/(1.60 \times 10^{-19}) = 4.01$ eV.

**Teacher prompt / common error:** Convert nanometres before using $hc/\lambda$ and divide joules by e to obtain electronvolts.

**2. The candidate sensor surfaces have work functions: caesium 2.14 eV, magnesium 3.66 eV and zinc 4.31 eV. State which surfaces emit photoelectrons under the 310 nm light and justify each decision. [3 marks]**

**Answer / mark points:** Caesium and magnesium emit because 4.01 eV is greater than their work functions. Zinc does not emit because 4.01 eV is below 4.31 eV.

**Teacher prompt / common error:** Emission depends on photon energy, not total beam energy.

## 2. Testing the photon model

**3. For the magnesium surface, calculate the maximum kinetic energy of an emitted electron in joules and the stopping potential. [3 marks]**

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| **Answer / mark points:** $E_k(max) = hf - \varphi = 4.01 - 3.66 = 0.35$ eV $= 5.6 \times 10^{-20}$ J. Since $eV_s = E_k(max)$, the stopping potential is 0.35 V. |
| **Teacher prompt / common error:** Stopping potential in volts has the same numerical value as maximum kinetic energy in electronvolts for an electron. |

**4. The intensity of the 310 nm light is increased without changing its wavelength. Explain the effect on (a) the photoelectric current and (b) the maximum kinetic energy of the electrons. [3 marks]**

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| **Answer / mark points:** Higher intensity means more photons arrive each second, so more electrons are emitted each second and the current increases. The energy of each photon is unchanged, so $E_k(max)$ is unchanged. Credit the threshold condition explicitly or implicitly. |
| **Teacher prompt / common error:** Intensity changes photon arrival rate; frequency changes photon energy. |

**5. Calculate the threshold frequency for magnesium. Use its work function from Question 2. [2 marks]**

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| **Answer / mark points:** $f_0 = \varphi/h = (3.66 \times 1.60 \times 10^{-19})/(6.63 \times 10^{-34}) = 8.83 \times 10^{14}$ Hz. |
| **Teacher prompt / common error:** At threshold, maximum kinetic energy is zero, so $hf_0 = \varphi$. |

**6. Electrons in a fluorescent calibration tube collide with gas atoms. Distinguish excitation from ionisation and state what determines whether either process occurs. [3 marks]**

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| **Answer / mark points:** Excitation raises an atomic electron to a higher bound energy level. Ionisation removes an electron from the atom. A collision can cause a change only if the incident electron transfers at least the required discrete excitation energy or ionisation energy. |
| **Teacher prompt / common error:** Excitation leaves the electron bound; ionisation removes it. |

## 3. Fluorescent calibration

**7. The gas has energy levels 0, 2.10, 3.40 and 5.10 eV above its ground state. An electron with kinetic energy 4.00 eV excites an atom through the largest possible energy change. State the excited level and calculate the electron's remaining kinetic energy. [2 marks]**

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| **Answer / mark points:** The largest accessible excitation is 3.40 eV; 5.10 eV is not accessible. Remaining kinetic energy = 4.00 - 3.40 = 0.60 eV. |
| **Teacher prompt / common error:** Atomic energy changes are discrete. An atom cannot take an arbitrary 4.00 eV excitation. |

**8. An atom falls from the 5.10 eV level to the 2.10 eV level. Calculate the wavelength of the emitted photon and identify the region of the electromagnetic spectrum. [3 marks]**

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| **Answer / mark points:** $\Delta E = 5.10 - 2.10 = 3.00$ eV $= 4.80 \times 10^{-19}$ J. $\lambda = hc/\Delta E = 4.14 \times 10^{-7}$ m = 414 nm, in the visible violet region. |
| **Teacher prompt / common error:** Use the difference between levels, not the energy of the upper level alone. |

**9. A coating absorbs 4.00 eV ultraviolet photons and emits 2.35 eV visible photons. Calculate the wavelength of the visible light and explain why the emitted photon has less energy. [3 marks]**

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| **Answer / mark points:** $\lambda = hc/E = (6.63 \times 10^{-34} \times 3.00 \times 10^{8})/(2.35 \times 1.60 \times 10^{-19}) = 5.29 \times 10^{-7}$ m, about 529 nm. Some absorbed energy is transferred in non-radiative transitions or to the lattice before the visible transition, so the emitted photon has lower energy. |
| **Teacher prompt / common error:** Do not say energy is lost. Account for the difference as other energy transfers or intermediate transitions. |

## 4. Electron diffraction

**10. A beam of electrons produces rings after passing through a thin graphite sample. Explain why this is evidence for wave behaviour and why the photoelectric effect is evidence for particle behaviour of electromagnetic radiation. [3 marks]**

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| **Answer / mark points:** Diffraction is a wave property, so the electron rings show electrons have a wavelength. In the photoelectric effect energy is delivered in individual photons of energy hf, with one photon transferring energy to one electron; the threshold frequency is explained by this particle model. | |
| **Teacher prompt / common error:** Name the observed wave property and the quantised photon interaction. | |

**11. Electrons of kinetic energy 1.20 keV enter the graphite. Calculate their de Broglie wavelength. Treat the electrons as non-relativistic. [4 marks]**

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| **Answer / mark points:** $E_k = 1.20 \times 10^{3} \times 1.60 \times 10^{-19} = 1.92 \times 10^{-16}$ J. $p = \sqrt{(2mE_k)} = \sqrt{(2 \times 9.11 \times 10^{-31} \times 1.92 \times 10^{-16})} = 1.87 \times 10^{-23}$ kg m s$^{-1}$. $\lambda = h/p = 3.54 \times 10^{-11}$ m. | |
| **Teacher prompt / common error:** Convert keV to joules, then calculate momentum before applying $\lambda = h/p$. | |

**12. The accelerating potential is increased from 1.20 kV to 4.80 kV. Determine the factor change in electron momentum and de Broglie wavelength, and predict what happens to the diffraction-ring diameters. [3 marks]**

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| **Answer / mark points:** For electrons accelerated through V, momentum is proportional to $\sqrt{V}$. Increasing V by 4 increases p by 2. Since $\lambda = h/p$, $\lambda$ halves. Less diffraction occurs, so the ring diameters decrease. | |
| **Teacher prompt / common error:** Momentum varies with the square root of accelerating potential, not directly with it. | |

## 5. Evaluating the evidence

**13. Evaluate the laboratory claim: 'Electrons are particles, so the diffraction rings must be an equipment fault.' Use both experiments, the photon and de Broglie models, and the role of repeatable evidence and peer validation. [5 marks]**

**Answer / mark points:** A high-level response should reject the claim: electron impacts are localised, but the repeatable graphite pattern is diffraction and therefore wave evidence. The de Broglie relation predicts the wavelength and the observed smaller rings at higher momentum. The photoelectric threshold and $E_k(max) = hf - \varphi$ require photons, so electromagnetic radiation also has particle behaviour. Scientific models can include complementary behaviours; independent repetition, calibration, prediction and peer review distinguish a real effect from an equipment fault. Award any five linked points.

**Teacher prompt / common error:** Wave-particle duality is an evidence-based model, not a claim that an electron is a classical wave and classical particle at the same instant.

### Language and method check

Award independent, creditworthy physics steps; do not award extra marks for repeated statements.
Accept equivalent methods when the physical reasoning, units and final precision remain consistent.