

Photoelectric effect and stopping potential solutions

Matching worked solutions and teaching prompts | 37 marks

AQA AS Physics 7407 • First-year A Level 7408

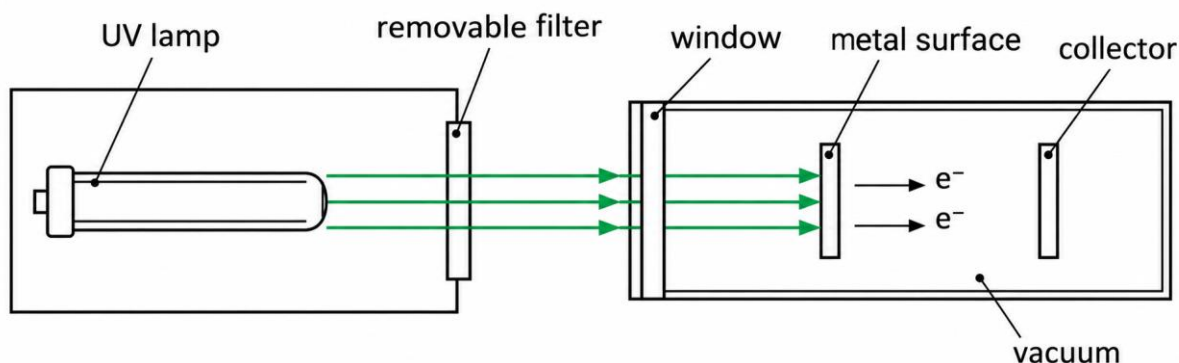
Specification points covered

AQA AS 7407 / first-year A Level 7408: 3.2.2.1 — threshold frequency, work function, stopping potential and the photoelectric equation; maximum photoelectron kinetic energy.

Supporting content: 3.2.1.3 — $E = hf = hc/\lambda$; 3.2.2.2 — electronvolt–joule conversion. No experimental determination of stopping potential is required.

UV-curing chamber monitor

A manufacturer uses a vacuum photocell to monitor ultraviolet radiation inside a UV-curing chamber. An interchangeable metal surface emits electrons when suitable radiation passes through the window. A collector receives the emitted electrons. The monitor must respond to the 254 nm UV lamp but not to stray 405 nm violet light.



Use $h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3.00 \times 10^8 \text{ m s}^{-1}$ and $e = 1.60 \times 10^{-19} \text{ C}$. $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. Except where a different model is stated, neglect losses at the window and collect every emitted electron. Show calculation working in blank spaces.

1. The UV monitor [3 marks]

(a) State what is meant by the work function of the metal surface. [1 mark]

The minimum energy needed to remove an electron from the metal surface. [1] Accept an equivalent definition; not the energy needed to excite an atom.

(b) Calculate the energy of one 254 nm photon in joules and in electronvolts. [2 marks]

$E = hc/\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^8)/(254 \times 10^{-9}) = 7.83 \times 10^{-19} \text{ J}$. [1] $E = (7.8307 \times 10^{-19})/(1.60 \times 10^{-19}) = 4.89 \text{ eV}$. [1]

Teaching prompt: Work function is a minimum removal energy. Photon energy and electron kinetic energy are different quantities.

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2. Choose a photoemissive surface [10 marks]

The candidate surfaces have work functions P: 2.30 eV, Q: 4.50 eV and R: 5.20 eV. Use the photon energy from Question 1(b) when needed.

(a) Calculate the energy of one 405 nm photon in electronvolts. [2 marks]

$$E = hc/\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^8)/(405 \times 10^{-9}) = 4.91 \times 10^{-19} \text{ J. [1]} \quad E = 3.07 \text{ eV. [1]}$$

(b) Choose the surface that responds to the 254 nm lamp but not to the 405 nm light. Justify your choice and explain why each other surface is unsuitable. [3 marks]

Q is suitable: $4.89 \text{ eV} > 4.50 \text{ eV}$ but $3.07 \text{ eV} < 4.50 \text{ eV}$. [1] P is unsuitable because both photon energies exceed 2.30 eV, so the violet light also produces emission. [1] R is unsuitable because even a 254 nm photon has less energy than its 5.20 eV work function. [1]

(c) For surface Q illuminated by 254 nm radiation, calculate the maximum kinetic energy of an emitted electron in joules. [2 marks]

$$E_k(\text{max}) = hc/\lambda - \phi, \text{ with } \phi = 4.50 \times 1.60 \times 10^{-19} = 7.20 \times 10^{-19} \text{ J. [1]} \quad E_k(\text{max}) = 7.8307 \times 10^{-19} - 7.20 \times 10^{-19} = 6.31 \times 10^{-20} \text{ J. [1]} \quad \text{Also accept } 0.394 \text{ eV converted consistently.}$$

(d) Calculate the magnitude of the stopping potential for these photoelectrons. Use $E_k(\text{max}) = eV_s$. [1 mark]

$$V_s = E_k(\text{max})/e = (6.3071 \times 10^{-20})/(1.60 \times 10^{-19}) = 0.394 \text{ V. [1]} \quad \text{Accept a consistent rounded answer from (c).}$$

(e) Calculate the threshold frequency and the longest wavelength that can produce emission from surface Q. [2 marks]

$$f_0 = \phi/h = (7.20 \times 10^{-19})/(6.63 \times 10^{-34}) = 1.09 \times 10^{15} \text{ Hz. [1]} \quad \text{Longest wavelength} = c/f_0 = 2.76 \times 10^{-7} \text{ m} = 276 \text{ nm. [1]} \quad \text{This is the threshold limit; photons with longer wavelength cannot eject electrons.}$$

Teaching prompt: Compare energies in the same unit. Stopping potential is a voltage, not a kinetic energy. Preserve guard digits when subtracting similar energies.



3. Frequency is not intensity [9 marks]

The chosen surface Q is now monitored under the 254 nm lamp. The metal remains unchanged. Unless stated otherwise, all emitted electrons reach the collector.

(a) The intensity at the surface is doubled while the wavelength stays at 254 nm. State and explain the effects on the collected current, maximum electron kinetic energy and stopping-potential magnitude. [3 marks]

The current doubles because twice as many photons arrive each second and twice as many electrons are emitted and collected each second. [1] $E_k(\text{max})$ is unchanged because photon energy hf and the work function are unchanged. [1] V_s is unchanged because $E_k(\text{max}) = eV_s$. [1]

(b) The lamp is switched off. Only 405 nm light reaches Q. A technician makes this light 100 times as intense and waits. Explain why this does not make Q emit photoelectrons in the single-photon model. [2 marks]

Each photon still supplies only 3.07 eV, less than Q's 4.50 eV work function. [1] An electron receives energy from one photon in one interaction; increasing photon arrival rate or waiting does not let it accumulate the required energy from these photons. [1]

(c) In a separate test, frequency is increased above threshold while the photon arrival rate is kept constant. Assume the same fraction of photons ejects electrons and every emitted electron is collected. State and explain the changes in current and stopping-potential magnitude. [2 marks]

The current is unchanged: the number of emitted and collected electrons each second is unchanged. [1] V_s increases because each photon has more energy and $E_k(\text{max}) = hf - \phi$ increases. [1] Do not assume constant intensity when constant photon arrival rate is specified.

(d) A learner says, "Every emitted electron leaves with the energy of the incoming photon." Explain two reasons why this statement is incorrect. [2 marks]

Some photon energy is needed to overcome the work function, so even the maximum kinetic energy is less than hf . [1] Electrons can lose additional energy before escaping, so emitted electrons have a range of kinetic energies up to $E_k(\text{max})$, not all the same kinetic energy. [1]

Teaching prompt: Model the chain explicitly: intensity at fixed frequency $\rightarrow$ photons per second $\rightarrow$ electrons per second $\rightarrow$ current. Frequency controls energy per photon, not photon number by itself.



4. Interpret calibration data [6 marks]

A different test surface is used to check the model. The table gives idealised rounded calibration data. V_s is the magnitude of the stopping potential. Treat the relationship over this range as linear. Use this table, not the schematic graph on the next page, for numerical work.

$f / 10^{14} \text{ Hz}$	6.0	8.0	10.0	12.0
V_s / V	0.40	1.20	2.00	2.80

(a) Use $hf = \phi + E_k(\text{max})$ and $E_k(\text{max}) = eV_s$ to write V_s as a linear function of f . [1 mark]

$V_s = (h/e)f - \phi/e$. [1] Hence the gradient of V_s against f is h/e , not h .

(b) Use the two most widely separated values in the table to calculate the gradient $\Delta V_s / \Delta f$, including its unit. [2 marks]

$\Delta V_s = 2.80 - 0.40 = 2.40 \text{ V}$ and $\Delta f = (12.0 - 6.0) \times 10^{14} = 6.0 \times 10^{14} \text{ Hz}$. [1] Gradient = $2.40 / (6.0 \times 10^{14}) = 4.0 \times 10^{-15} \text{ V Hz}^{-1}$ (equivalently V s). [1]

(c) Use this gradient to obtain an experimental estimate of the Planck constant. [1 mark]

$h = e \times \text{gradient} = 1.60 \times 10^{-19} \times 4.0 \times 10^{-15} = 6.4 \times 10^{-34} \text{ J s}$. [1] The idealised rounded table gives an estimate, not the supplied accepted value $6.63 \times 10^{-34} \text{ J s}$.

(d) Extrapolate the linear relationship algebraically to determine the threshold frequency of this test surface. [1 mark]

At $V_s = 0$, $f_0 = 6.0 \times 10^{14} - 0.40 / (4.0 \times 10^{-15}) = 5.0 \times 10^{14} \text{ Hz}$. [1] Equivalently find the f -axis intercept of the linear relationship.

(e) Using your experimental h from (c), calculate the work function of this test surface in joules. [1 mark]

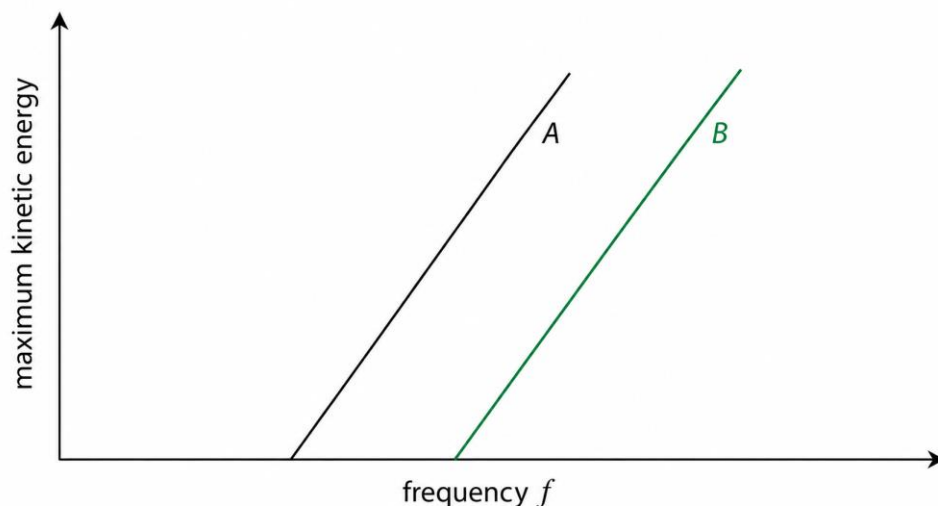
$\phi = hf_0 = 6.4 \times 10^{-34} \times 5.0 \times 10^{14} = 3.2 \times 10^{-19} \text{ J}$. [1] Accept a consistent result using the candidate's estimate from (c).

Teaching prompt: The horizontal heading carries a factor 10^{14} . A stopping-potential gradient gives h/e ; a maximum-kinetic-energy-in-joules gradient gives h .



5. Compare metal surfaces [5 marks]

The schematic graph shows line A for one metal. A second metal has a greater work function. Both follow the same single-photon model. This sketch is not to scale.



(a) Draw and label line B on the graph for the second metal. [2 marks]

B is a straight line parallel to A. [1] Its positive frequency-axis intercept is farther to the right, and it lies below A at a frequency above both thresholds. [1] Draw no negative-kinetic-energy branch.

(b) Explain the gradient and threshold-frequency features of your line B. [2 marks]

The gradient is h for both metals, so the lines have the same gradient. [1] $f_0 = \phi/h$, so the greater work function gives a greater threshold frequency. [1]

(c) For the metal represented by A, the light intensity is increased at unchanged frequency. State what happens to line A. [1 mark]

The line is unchanged. [1] $E_k(\text{max})$ at each frequency is independent of intensity in this model.

Teaching prompt: A line shifted down at a given frequency must also meet the frequency axis farther right. Never show negative kinetic energy as an emitted-electron result.



6. Diagnose a detector fault [4 marks]

A fresh detector gives $V_s = 0.46 \text{ V}$ at $f = 1.20 \times 10^{15} \text{ Hz}$. After surface contamination, it gives $V_s = 0.26 \text{ V}$ at the same frequency. Assume the only change is in work function. Use the supplied accepted value of h for this question.

(a) Determine the increase in work function in electronvolts. [1 mark]

At the same frequency, the maximum kinetic energy has fallen by 0.20 eV , so the work function has increased by 0.20 eV . [1] In joules this is $3.20 \times 10^{-20} \text{ J}$.

(b) Can increasing the intensity restore the original stopping-potential magnitude? Explain your answer. [1 mark]

No. Intensity changes photon arrival rate, not energy per photon; at the same frequency $E_k(\text{max})$ and V_s are unchanged. [1] A larger current is not restoration of the original stopping potential.

(c) Calculate the increase in lamp frequency needed to restore $V_s = 0.46 \text{ V}$ without removing the contamination. [2 marks]

The additional photon energy must equal the increase in work function: $h\Delta f = 0.20 \times 1.60 \times 10^{-19} \text{ J}$.
[1] $\Delta f = (3.20 \times 10^{-20}) / (6.63 \times 10^{-34}) = 4.83 \times 10^{13} \text{ Hz}$. [1] The new frequency would be $1.25 \times 10^{15} \text{ Hz}$ to 3 significant figures.

Teaching prompt: The question asks for the increase in frequency, not the new total frequency. The model isolates a work-function change; do not infer real detector behaviour beyond this stated model.

Review: distinguish photon energy, maximum electron kinetic energy and photon arrival rate. Correct any comparison made using unlike units.

