

Excitation ionisation and line spectra solutions

Matching worked solutions and teaching prompts | 39 marks

AQA AS Physics 7407 • First-year A Level 7408

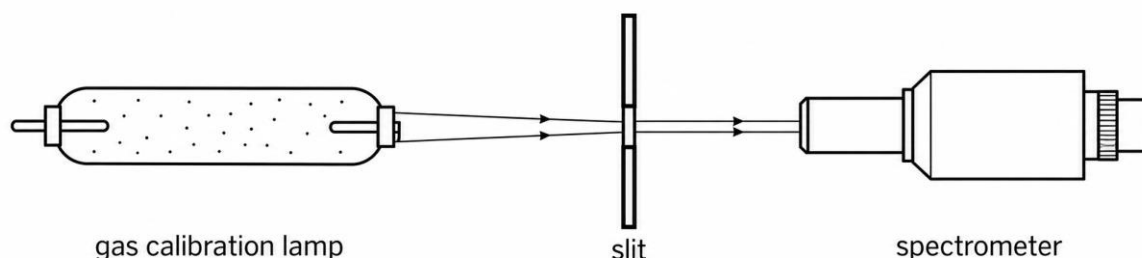
Specification points covered

AQA AS 7407 / first-year A Level 7408: 3.2.2.2 — excitation, ionisation, electron collisions, fluorescent tubes and electronvolt–joule conversion.

3.2.2.3 — line spectra as evidence for discrete energy levels; $hf = E_{\text{upper}} - E_{\text{lower}}$. Supporting 3.2.1.3 — photon energy $E = hf = hc/\lambda$.

A reference lamp for a sorting system

An engineering team uses a gas calibration lamp to check the spectrometer on an automated recycling line. A lamp cartridge must emit the correct spectral fingerprint before the sorting system is used. The team tests a model gas X, then applies the same physics to fluorescent inspection lighting at the site.



Use $h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3.00 \times 10^8 \text{ m s}^{-1}$ and $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. For this worksheet, take the visible range as 400–700 nm. Show numerical working in blank spaces; write explanations on the ruled lines.

1. Energy transferred by electrons [2 marks]

(a) Define the electronvolt. [1 mark]

The energy gained by an electron when it moves through a potential difference of 1 V. [1] Accept the corresponding energy transferred when a charge of magnitude e moves through 1 V.

(b) An electron entering the calibration lamp has kinetic energy 3.20 eV. Express this energy in joules. [1 mark]

$$E = 3.20 \times 1.60 \times 10^{-19} = 5.12 \times 10^{-19} \text{ J. [1]}$$

Teaching prompt: An electronvolt is a unit of energy, not potential difference or charge. eV and J cannot be subtracted without conversion.

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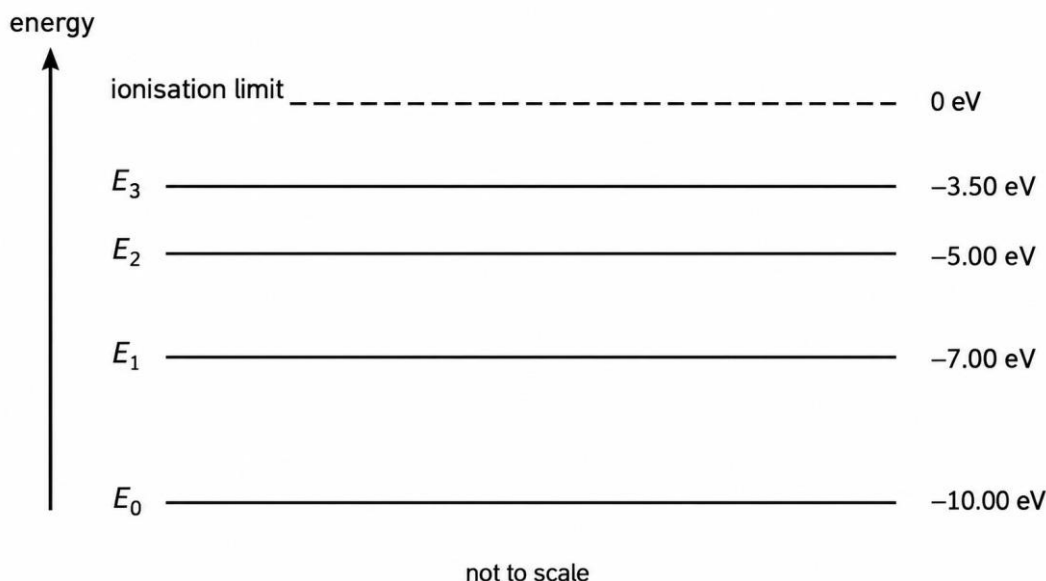
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2. Excitation or ionisation [7 marks]

For Questions 2–5, model gas X using only the four bound levels shown. The 0 eV limit represents an electron just freed from the atom. All downward transitions between the bound levels are allowed. Neglect atomic recoil energy. Unless a part says otherwise, an atom starts in its ground state E_0 .



(a) A free electron with kinetic energy 6.00 eV collides with an X atom. Identify the highest energy level it can excite and calculate its remaining kinetic energy if this excitation occurs. [2 marks]

The energy needed to reach E_2 is $(-5.00) - (-10.00) = 5.00$ eV; E_3 needs 6.50 eV and is inaccessible. The highest accessible state is E_2 . [1] Remaining electron kinetic energy = $6.00 - 5.00 = 1.00$ eV. [1]

(b) Can an electron with kinetic energy 2.80 eV cause electronic excitation of a ground-state X atom? Explain your answer. [1 mark]

No. The smallest excitation energy is $E_1 - E_0 = 3.00$ eV, greater than 2.80 eV. [1] This does not mean that no collision can occur; electronic excitation is the process ruled out.

(c) An incident electron has kinetic energy 12.50 eV and ionises a ground-state X atom. Determine the minimum energy needed for ionisation and the total kinetic energy of the two outgoing electrons. [2 marks]

The ionisation energy is $0 - (-10.00) = 10.00$ eV. [1] With negligible recoil, the total outgoing electron kinetic energy is $12.50 - 10.00 = 2.50$ eV. [1] The data do not determine how the two electrons share this energy.

(d) A 4.00 eV electron strikes an X atom already in E_3 . Determine whether it can ionise this atom and explain why the answer differs from that for a ground-state atom. [2 marks]

From E_3 , ionisation requires $0 - (-3.50) = 3.50$ eV, so the 4.00 eV electron can ionise the excited atom. [1] A ground-state atom requires 10.00 eV, which exceeds 4.00 eV; the excited electron is less tightly bound. [1]

Teaching prompt: Identify the starting state before finding an energy gap. In (c), 2.50 eV is shared by two outgoing electrons; it is not a uniquely determined energy of either one.

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3. Bound states and photon absorption [6 marks]

Use the same complete four-bound-level model of gas X from Question 2. Consider one photon–atom or electron–atom interaction at a time.

(a) Explain why the bound energy levels in this diagram have negative values. [1 mark]

Zero is assigned to a just-free electron, and energy must be supplied to remove a bound electron from the atom. Its energy is therefore below this zero reference. [1]

(b) Ground-state X atoms are exposed separately to 6.00 eV photons and to 6.00 eV free electrons. Explain why the electrons can excite the atoms but the photons cannot cause a bound-state excitation in this model. [3 marks]

The allowed ground-state excitation energies are 3.00, 5.00 and 6.50 eV. [1] A bound-state absorption takes the whole photon energy, and 6.00 eV matches none of these gaps. [1] A colliding electron can transfer only part of its energy, for example 3.00 or 5.00 eV, and retain the rest as kinetic energy. [1] Also, a 6.00 eV photon is below the 10.00 eV ground-state ionisation threshold.

(c) An X atom already in E_3 absorbs a 4.00 eV photon. Determine whether an electron can be emitted and calculate its kinetic energy. Neglect recoil. [2 marks]

Ionisation from E_3 requires 3.50 eV, so the photon can free the electron. [1] The ejected electron has kinetic energy $4.00 - 3.50 = 0.50$ eV. [1] Above the ionisation threshold, excess photon energy can become kinetic energy; it need not equal a discrete bound–bound gap.

Teaching prompt: Exact photon-energy matching applies to a particular bound–bound transition. It does not prohibit ionisation by a photon with energy above the binding energy.

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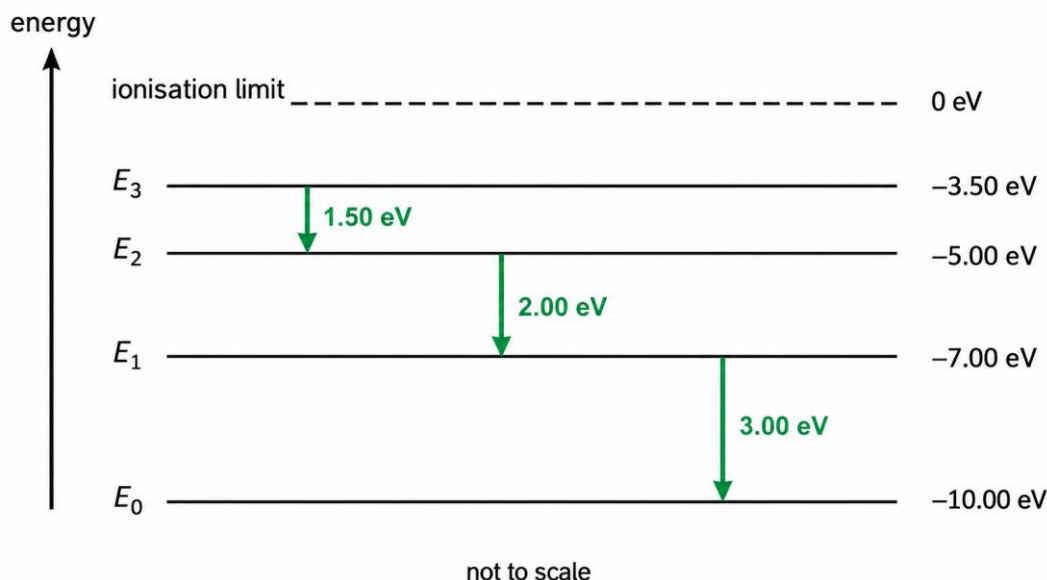


4. Photons from a cascade [8 marks]

The beam energy is raised to 8.00 eV, so collisions can populate E_3 . Use the same X energy levels. Add your transition arrows for part (b) to the diagram in Question 2.

(a) For a direct transition from E_3 to E_1 , calculate the photon energy in eV and its wavelength in nm. Identify the region of the electromagnetic spectrum. [3 marks]

Photon energy = $(-3.50) - (-7.00) = 3.50$ eV. [1] $E = 3.50 \times 1.60 \times 10^{-19} = 5.60 \times 10^{-19}$ J and $\lambda = hc/E = 3.55 \times 10^{-7}$ m = 355 nm. [1] This is ultraviolet. [1]



(b) On the diagram in Question 2, draw the cascade $E_3 \rightarrow E_2 \rightarrow E_1 \rightarrow E_0$. Label each downward arrow with the energy of its emitted photon in eV. [3 marks]

Draw all three arrows downward between the specified adjacent levels. [1] Photon energies are $E_3 \rightarrow E_2$: 1.50 eV; $E_2 \rightarrow E_1$: 2.00 eV; $E_1 \rightarrow E_0$: 3.00 eV. Award [1] for any two correct energy labels and [1] for all three. The total emitted energy is 6.50 eV, the difference $E_3 - E_0$; this check earns no additional mark.

(c) Among all allowed transitions between these four bound states, identify the one producing the longest wavelength. Calculate this wavelength in nm. [2 marks]

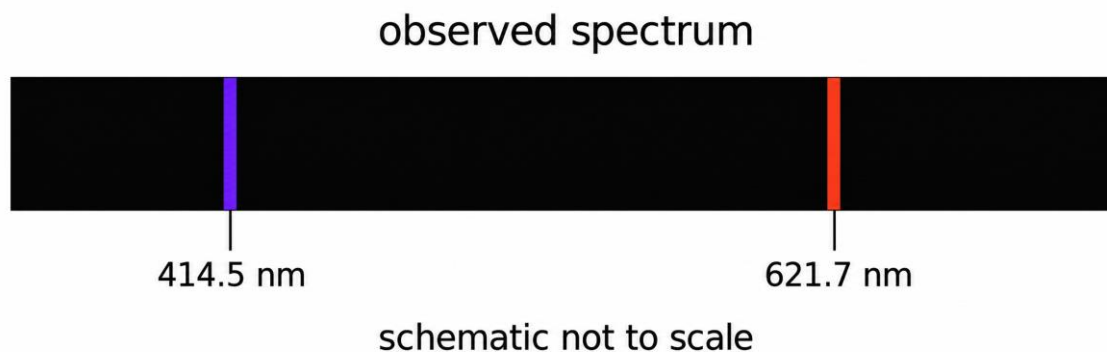
The smallest gap is 1.50 eV for $E_3 \rightarrow E_2$, so it gives the longest wavelength. [1] $\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^8) / (1.50 \times 1.60 \times 10^{-19}) = 8.29 \times 10^{-7}$ m = 829 nm. [1] This is infrared, outside the stated visible range.

Teaching prompt: The emitted photon energy is a positive difference between levels. A cascade produces several photons; their energies add to the total drop, but their wavelengths do not add.



5. Accept or reject the lamp cartridge [7 marks]

The spectrometer records the two visible lines shown. Only candidates X and Y are being considered. Candidate Y would have visible lines at 430.0 nm and 590.0 nm. Treat a measured line as a match if its wavelength is within 1.0 nm of the prediction. The observed line positions are schematic: use their numerical labels.



(a) Only two transitions in model X produce light in the stated 400–700 nm visible range. Identify these two transitions and calculate their wavelengths. [3 marks]

The visible transitions are $E_1 \rightarrow E_0$ (3.00 eV) and $E_2 \rightarrow E_1$ (2.00 eV). [1] For 3.00 eV, $\lambda = hc/(3.00 \times 1.60 \times 10^{-19}) = 414.375$ nm, approximately 414 nm. [1] For 2.00 eV, $\lambda = 621.5625$ nm, approximately 622 nm. [1] Other gaps give ultraviolet or infrared photons.

(b) Which candidate is consistent with the measured pair? Use numerical evidence for your choice and rule out the other candidate. [2 marks]

X is consistent: 414.5 nm and 621.7 nm differ from its unrounded predictions by about 0.13 nm and 0.14 nm, both within 1.0 nm. [1] Y is inconsistent: its predictions differ from the corresponding observations by 15.5 nm and 31.7 nm, outside the tolerance. [1] Accept a consistent comparison using suitably rounded calculated wavelengths.

(c) Explain why narrow emission lines, rather than a continuous spectrum, provide evidence for discrete atomic energy levels. [2 marks]

The lines show that emitted photons have particular frequencies and therefore particular energies $E = hf$. [1] These energies are the fixed differences between allowed atomic levels; a continuous range of energy differences is not observed. [1]

Teaching prompt: Match the entire supplied fingerprint, not one convenient line. The violet/red appearance is illustrative; identification uses wavelengths, not screen colour or drawn spacing.



6. From ultraviolet to inspection light [9 marks]

The same team tests a fluorescent inspection lamp. Electron collisions in its low-pressure gas produce 250 nm ultraviolet photons. An inner coating absorbs these photons and emits visible light. This is a separate model from gas X.

(a) Calculate the energy of one 250 nm ultraviolet photon in electronvolts. [2 marks]

$$E = hc/\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^8)/(250 \times 10^{-9}) = 7.956 \times 10^{-19} \text{ J. [1]} \quad E = 7.956 \times 10^{-19}/(1.60 \times 10^{-19}) = 4.97 \text{ eV. [1]}$$

(b) In one possible event in the coating, the energy of one absorbed ultraviolet photon produces two 550 nm photons. The remaining energy is transferred to thermal stores. Calculate this remaining energy per event in eV. [2 marks]

Each 550 nm photon has energy $hc/(550 \times 10^{-9}) = 3.616 \times 10^{-19} \text{ J} = 2.2602 \text{ eV. [1]}$ Remaining energy = $4.9725 - 2 \times 2.2602 = 0.452 \text{ eV. [1]}$ Keep unrounded energies until the subtraction. This is one modelled event, not a claim of a fixed photon yield for every real coating.

(c) Explain how electron collisions in the gas cause ultraviolet emission. [2 marks]

Accelerated free electrons transfer kinetic energy to the atoms in collisions, exciting bound atomic electrons to higher levels. [1] When those atomic electrons move to lower levels, photons are emitted with energies equal to the level differences; the stated transitions give ultraviolet photons. [1]

(d) Explain how the coating produces visible radiation, and why the overall light can appear white rather than having one colour. [3 marks]

Atoms or centres in the coating absorb ultraviolet photons and become excited. [1] Subsequent transitions with smaller energy gaps emit lower-energy, longer-wavelength visible photons. [1] Many different transitions or coating components produce a mixture of visible wavelengths that can appear white. [1] One photon is not itself white; the equal 550 nm pair in (b) describes only one possible event.

Teaching prompt: Distinguish free electrons colliding with gas atoms from bound electrons changing atomic levels. The coating absorbs and re-emits energy; ultraviolet light does not merely change colour continuously.

