Edexcel International A Level (IAL) Physics

Your notes

The Photoelectric Effect & Atomic Spectra

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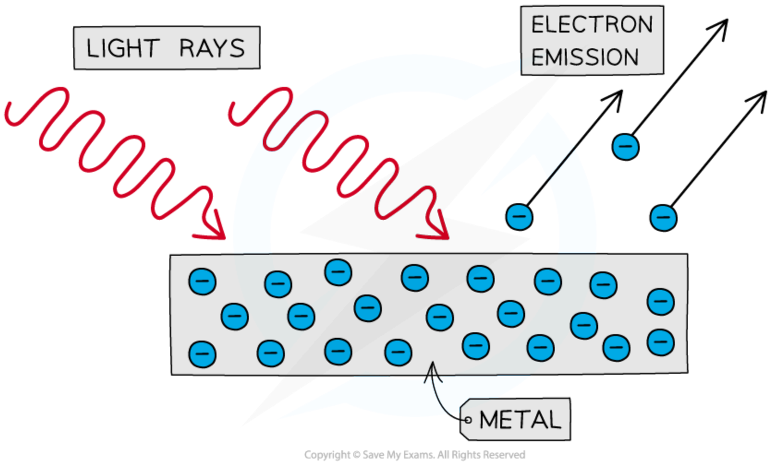
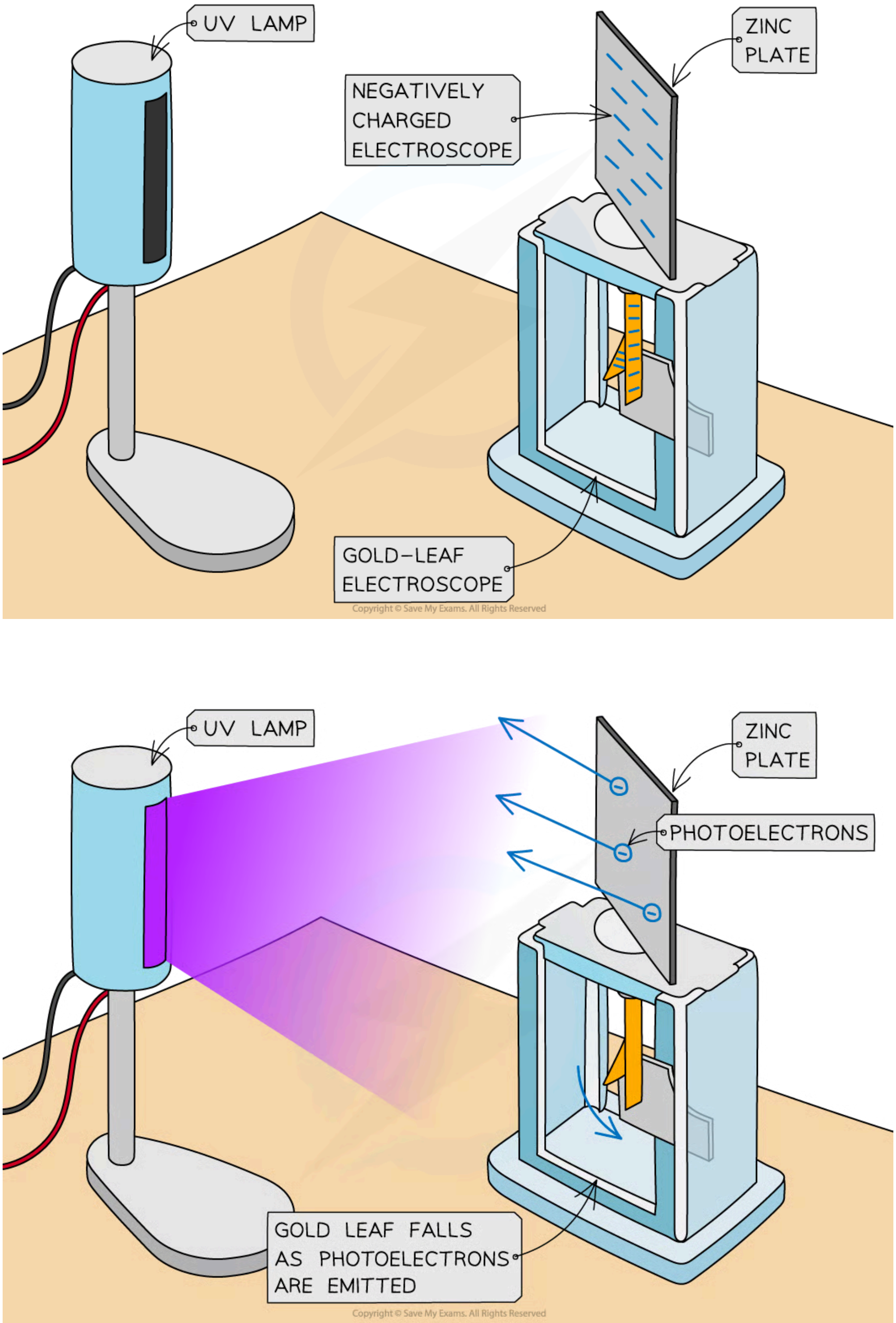
The Photoelectric Effect

- The **photoelectric effect** is the phenomena in which electrons are emitted from the surface of a metal **upon the absorption of electromagnetic radiation**
- Electrons removed from a metal in this manner are known as **photoelectrons**
- The photoelectric effect provides important evidence that light is **quantised**, or carried in discrete packets
  - This is shown by the fact each electron can absorb only a single photon
  - This means only the frequencies of light above a **threshold frequency** will emit a photoelectron



Photoelectrons are emitted from the surface of metal when light shines onto it

- The photoelectric effect can be observed on a **gold leaf electroscope**
- A plate of metal, usually **zinc**, is attached to a gold leaf, which initially has a negative charge, causing it to be repelled by a central negatively charged rod
  - This causes negative charge, or electrons, to build up on the zinc plate
- **UV light** is shone onto the metal plate, leading to the **emission** of **photoelectrons**
- This causes the extra electrons on the central rod and gold leaf to be removed, so, the gold leaf begins to fall back towards the central rod
  - This is because they become less negatively charged, and hence repel less



Typical set-up of the gold leaf electroscope experiment

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The Photoelectric Equation

- Since energy is always conserved, the energy of an incident photon is equal to:

  The work function + the maximum kinetic energy of the photoelectron

- The energy within a photon is equal to ***hf***
- This energy is transferred to the electron to release it from a material (the work function) and the remaining amount is given as kinetic energy to the emitted photoelectron
- This equation is known as the **photoelectric equation**:

$$E = hf = \Phi + \tfrac{1}{2}mv^2_{max}$$

- Where:
  - h = Planck's constant (J s)
  - f = the frequency of the incident radiation (Hz)
  - Φ = the work function of the material (J)
  - $\tfrac{1}{2}mv^2_{max} = KE_{max}$ = the maximum kinetic energy of the photoelectrons (J)
- This equation demonstrates:
  - If the incident photons do not have a high enough frequency and energy to overcome the work function (Φ), then no electrons will be emitted
  - $hf_0 = \Phi$, where f_0 = threshold frequency, photoelectric emission only just occurs
  - KE_{max} depends only on the frequency of the incident photon, and **not** the intensity of the radiation
  - The majority of photoelectrons will have kinetic energies **less than** KE_{max}

Work Function

- The work function Φ, or threshold energy, of a material, is defined as:

  The minimum energy required to release a photoelectron from the surface of a metal

- Consider the electrons in a metal as trapped inside an 'energy well' where the energy between the surface and the top of the well is equal to the work function Φ
- A single electron absorbs one photon
- Therefore, an electron can only escape from the surface of the metal if it absorbs a photon which has an energy equal to Φ or higher

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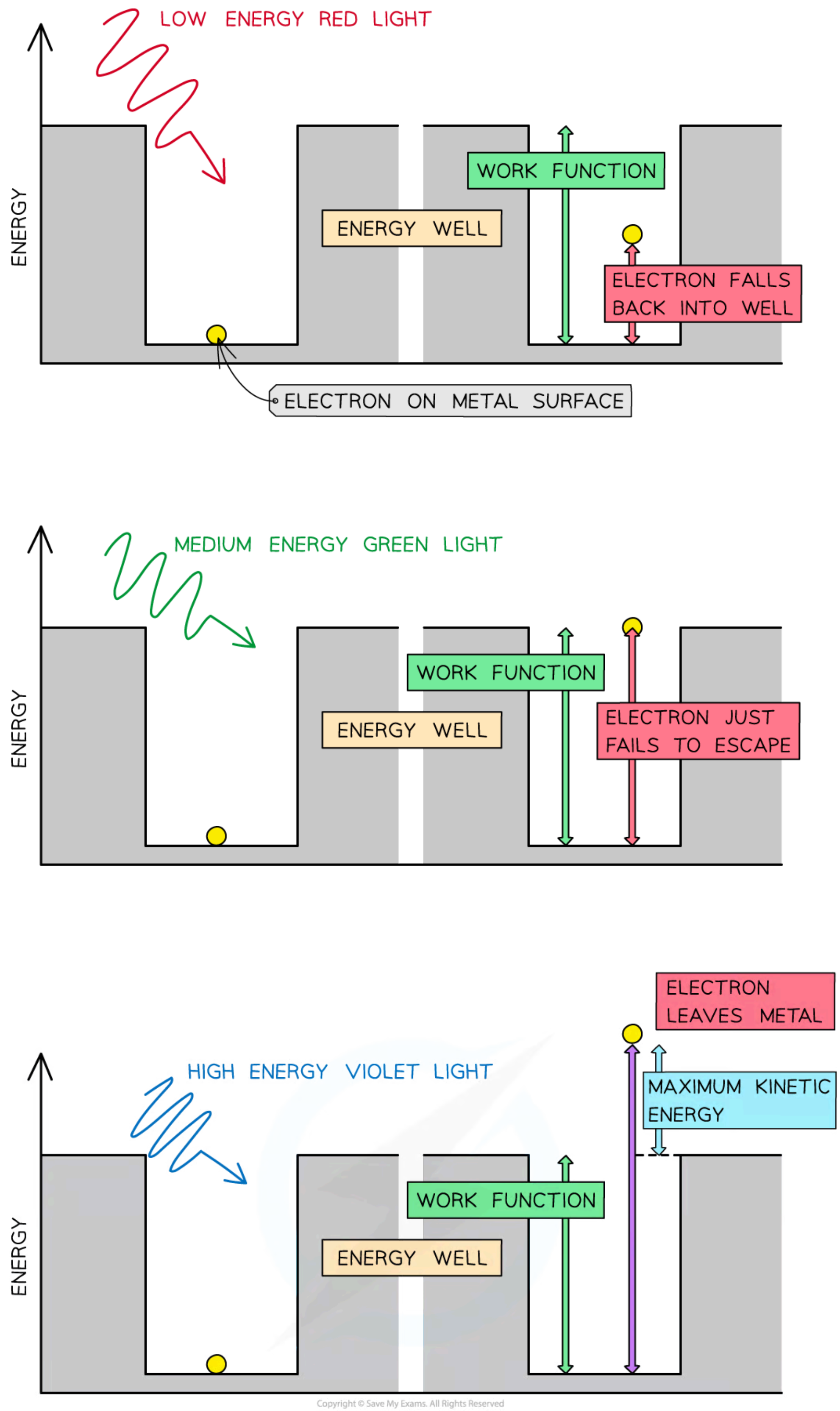


In the photoelectric effect, a single photon may cause a surface electron to be released if it has sufficient energy

Graphical Representation of Work Function

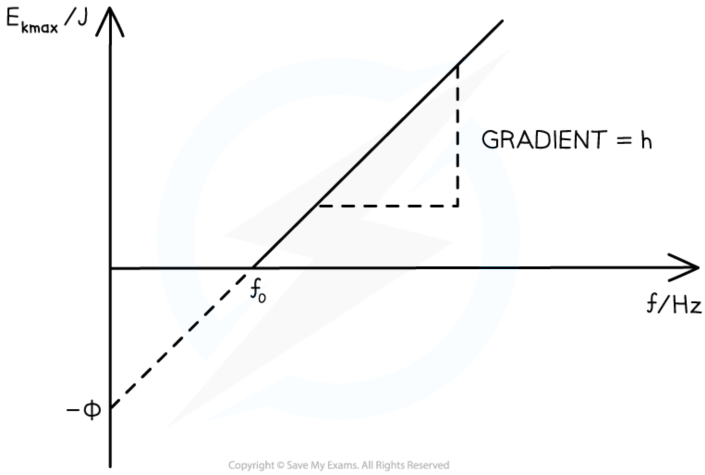
- The photoelectric equation can be rearranged into the straight line equation:

$$y = mx + c$$

- Comparing this to the photoelectric equation:

$$KE_{max} = hf - \Phi$$

- A graph of maximum kinetic energy KE_{max} against frequency f can be obtained



- The key elements of the graph:
  - The work function Φ is the **y-intercept**
  - The threshold frequency f_0 is the **x-intercept**
  - The **gradient** is equal to Planck's constant h
  - There are no electrons emitted below the threshold frequency f_0

Threshold Frequency

- The threshold frequency is defined as:

The minimum frequency of incident electromagnetic radiation required to remove a photoelectron from the surface of a metal

Worked Example

The graph below shows how the maximum kinetic energy E_k of electrons emitted from the surface of sodium metal varies with the frequency f of the incident radiation.

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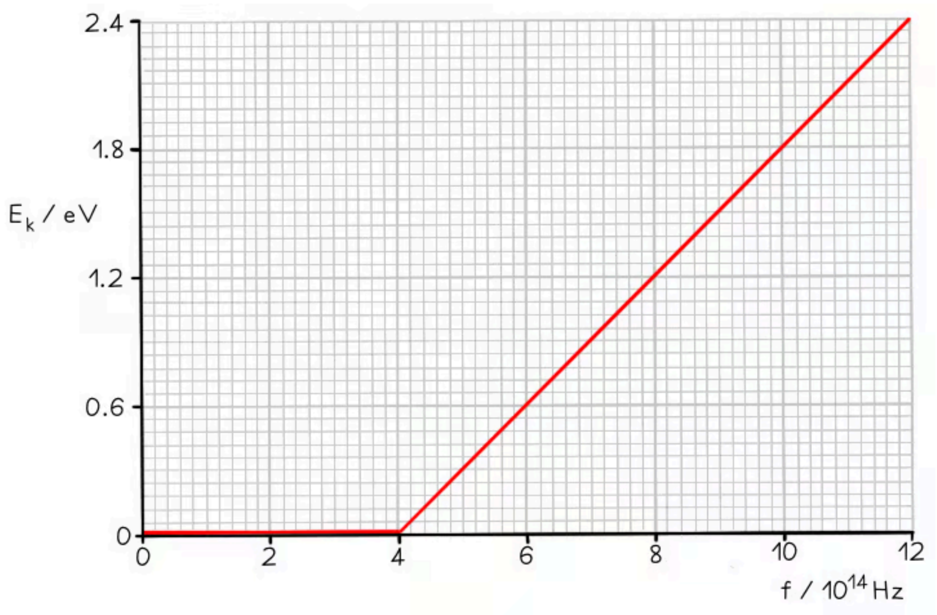

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Calculate the work function of sodium in eV.

Answer:

Step 1: Write out the photoelectric equation and rearrange to fit the equation of a straight line

$$E = hf = \Phi + \frac{1}{2} m v^2_{max} \quad \rightarrow \quad KE_{max} = hf - \Phi$$

$$y = mx + c$$

Step 2: Identify the threshold frequency from the x-axis of the graph

When $E_k = 0$, $f = f_0$

Therefore, the threshold frequency is $f_0 = 4 \times 10^{14}$ Hz

Step 3: Calculate the work function

From the graph at f_0, $\frac{1}{2} m v_{max}{}^2 = 0$

$$\Phi = hf_0 = (6.63 \times 10^{-34}) \times (4 \times 10^{14}) = 2.652 \times 10^{-19} \text{ J}$$

Step 4: Convert the work function into eV

1 eV = 1.6×10^{-19} J J → eV: divide by 1.6×10^{-19}

$$E = \frac{2.652 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.66 \ eV$$

Examiner Tips and Tricks

When using the photoelectric effect equation, hf, Φ and KE_{max} must all have the **same** units, and that the S.I. unit of energy is Joules.

But the energy involved in these interactions is tiny, which is why we use a different unit for it, the electron volt. Make sure to convert any values given in eV into Joules before starting to calculate.

Remember that the eV is much smaller than the Joule, so your value of eV will be high in comparison. This is why we often use MeV when describing these energies.

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The Electronvolt

- The electronvolt is a unit which is commonly used to express very small energies
- This is because quantum energies tend to be much smaller than 1 joule
- The electronvolt is derived from the definition of potential difference:

$$V = \frac{E}{Q}$$

- When an electron travels through a potential difference, energy is transferred between two points in a circuit, or electric field
- If an electron, with a charge of 1.6×10^{-19} C, travels through a potential difference of 1 V, the energy transferred is equal to:

$$E = QV = 1.6 \times 10^{-19}\ \text{C} \times 1\ \text{V} = 1.6 \times 10^{-19}\ \text{J}$$

- Therefore, an electronvolt is defined as:

The energy gained by an electron travelling, from rest, through a potential difference of one volt

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

Relation to kinetic energy

- When a charged particle is accelerated through a potential difference, it gains kinetic energy
- If an electron accelerates from rest, an **electronvolt** is equal to the kinetic energy gained:

$$eV = \tfrac{1}{2} mv^2$$

- Rearranging the equation gives the speed of the electron:

$$v = \sqrt{\frac{2eV}{m}}$$

Worked Example

Show that the photon energy of light with wavelength 700nm is about 1.8 eV.

Answer:

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Step 1: Write the equations for wave speed and photon energy

wave speed: $c = f\lambda \longrightarrow f = \frac{c}{\lambda}$

photon energy: $E = hf \longrightarrow E = \frac{hc}{\lambda}$

Step 2: Calculate the photon energy in Joules

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}) \times (3.0 \times 10^{8})}{700 \times 10^{-9}} = 2.84 \times 10^{-19} \text{ J}$$

Step 3: Convert the photon energy into electronvolts

$1 \text{ eV} = 1.6 \times 10^{-19}$ J J $\rightarrow$ eV: divide by 1.6×10^{-19}

$$E = \frac{2.84 \times 10^{-19}}{1.6 \times 10^{-19}} = \mathbf{1.78\ eV}$$

Examiner Tips and Tricks

- To convert between eV and J:
- eV $\rightarrow$ J: **multiply** by 1.6×10^{-19}
- J $\rightarrow$ eV: **divide** by 1.6×10^{-19}

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The Particle Nature of EM Radiation

The Particle Nature of Light

- In classical wave theory, electromagnetic (EM) radiation is assumed to behave as a wave
- This is demonstrated by the fact EM radiation exhibits phenomena such as **diffraction** and **interference**
- However, experiments from the last century, such as the **photoelectric effect** and **atomic line spectra**, can only be explained if EM radiation is assumed to behave as particles

Evidence for the Particle Nature of Light

- The best evidence for the particle nature of light comes from the photoelectric effect
- This is demonstrated using the Gold-leaf Electroscope

Observations of the Gold Leaf Experiment

- The explanation for these observations supports the theory of light as a particle, specifically a discrete packet (or photon) of energy
  - Placing the UV light source **closer** to the metal plate causes the gold leaf to **fall more quickly**
  - Using a higher frequency light source **does not change** how quickly the gold leaf falls
  - Using a filament light source causes **no change** in the gold leaf's position
  - Using a positively charged plate causes **no change** in the gold leaf's position
  - Emission of photoelectrons happens **as soon as the radiation is incident on the surface of the metal**
- Each of the observations is explained below

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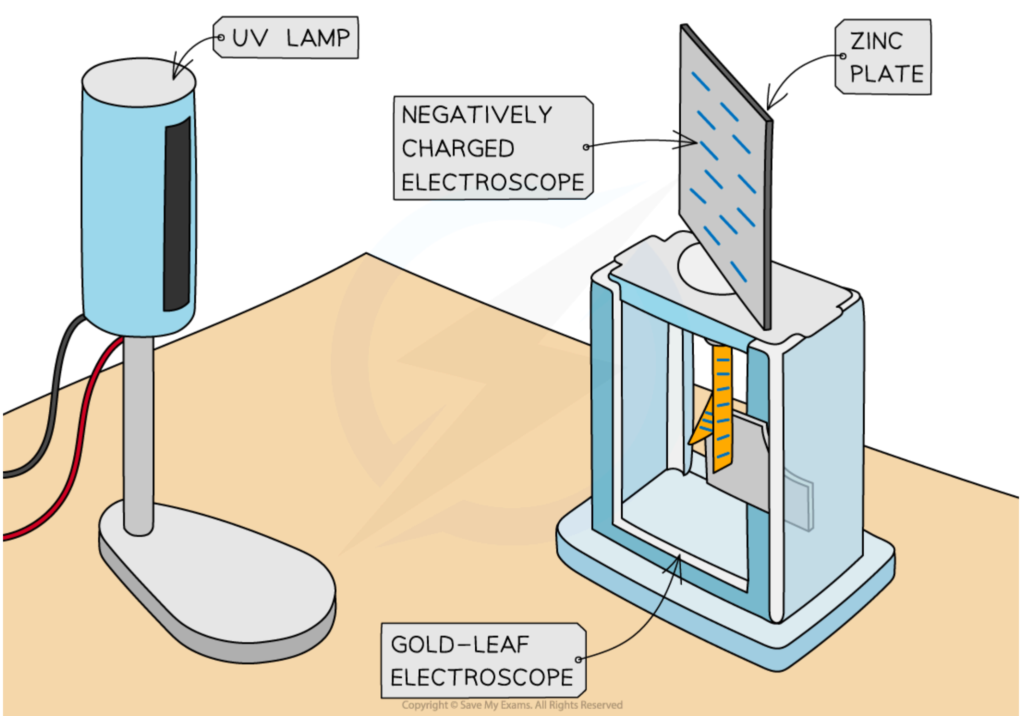

Typical set-up of the gold leaf electroscope experiment

Placing the UV light source closer to the metal plate causes the gold leaf to fall more quickly

- Placing the UV source closer to the plate increases the intensity incident on the surface of the metal
  - Increasing the intensity, or brightness, of the incident radiation increases the number of photoelectrons emitted per second
  - Therefore, the gold leaf loses negative charge more rapidly

Using a higher frequency light source does not change how quickly the gold leaf falls

- The maximum kinetic energy of the emitted electrons increases with the frequency of the incident radiation
  - In the case of the photoelectric effect, energy and frequency are **independent** of the intensity of the radiation
  - So, the intensity of the incident radiation affects how quickly the gold leaf falls, not the frequency

Using a filament light source causes no change in the gold leaf's position

- If the incident frequency is below a certain threshold frequency, no electrons are emitted, no matter the intensity of the radiation

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- A filament light source has a frequency below the threshold frequency of the metal, so, no photoelectrons are released

Using a positively charged plate causes no change in the gold leaf's position

- If the plate is positively charged, that means there is an excess of positive charge on the surface of the metal plate
  - Electrons are negatively charged, so they will not be emitted unless they are on the surface of the metal
  - Any electrons emitted will be attracted back by positive charges on the surface of the metal

Emission of photoelectrons happens as soon as the radiation is incident on the surface of the metal

- A single photon interacts with a single electron
  - If the energy of the photon is equal to the work function of the metal, photoelectrons will be released instantaneously

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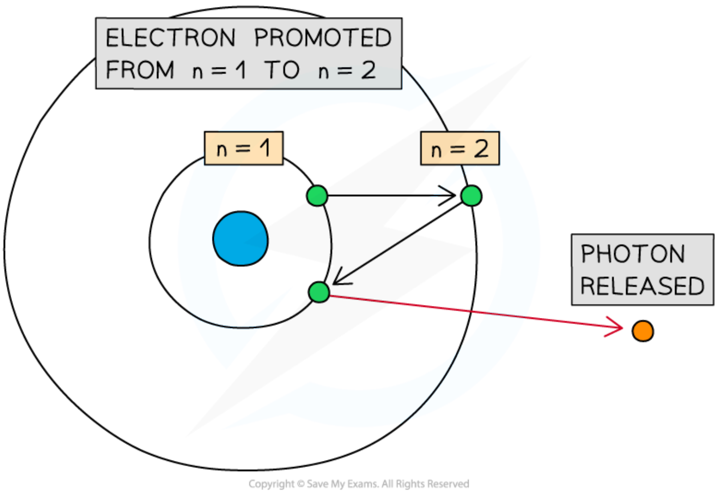
Atomic Line Spectra

- An emission line spectrum is produced when:

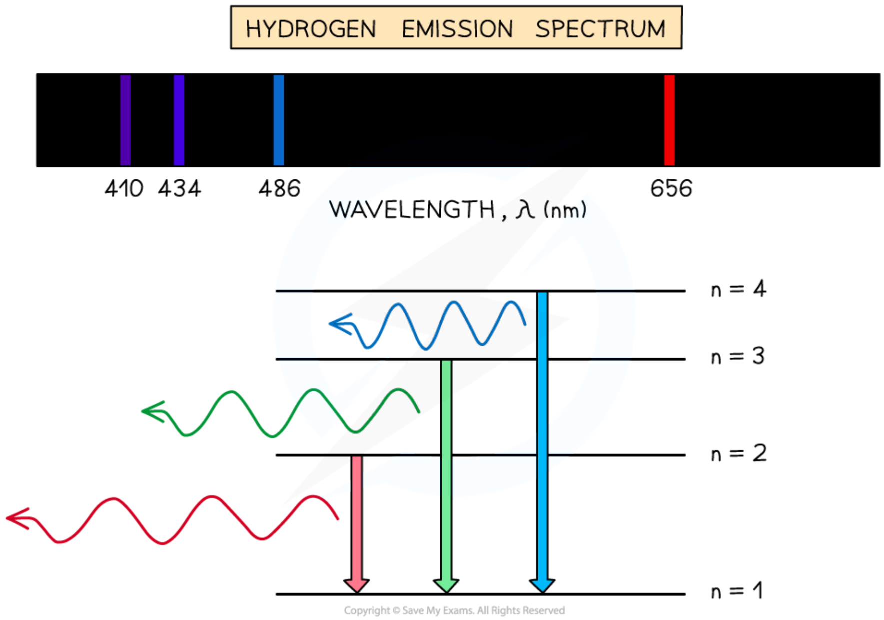
  An excited electron in an atom moves from a higher to a lower energy level and emits a photon with an energy corresponding to the difference between these energy levels

- Each element produces a unique **emission line spectrum** due to its unique set of energy levels
  - Hot gases produce emission line spectra, such as stars
- When the atoms of a gas are **excited**, electrons gain energy and move to higher energy levels



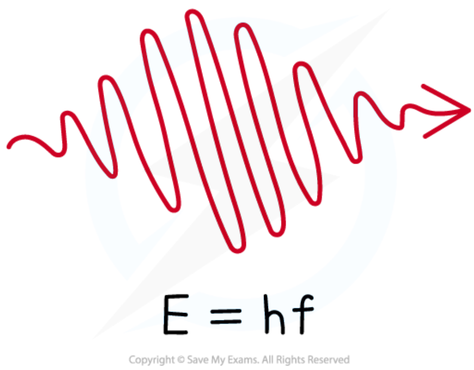
When an electron moves from a higher energy level to a lower energy level, a photon is released

- Electrons cannot stay in a continuous state of excitation, so they will move back to lower energy levels through **de-excitation**
  - During de-excitation, energy must be conserved, so transitions result in an **emission of photons** with discrete frequencies (or wavelengths) specific to that element
  - Since there are many possible electron transitions for each atom, there are many different radiated wavelengths
  - This creates a **line spectrum** consisting of a series of bright lines against a dark background
  - An emission line spectrum acts as a **fingerprint of the element**



An example of the emission line spectrum of hydrogen

- Each line of the emission spectrum corresponds to a different **energy level** transition within the atom
  - Electrons can transition between energy levels absorbing or emitting a **discrete amount of energy**
  - An excited electron can transition down to the next energy level or move to a further level closer to the ground state
- For example, if an atom has six energy levels:
  - At low temperatures, most electrons will occupy the ground state n = 1
  - At high temperatures, electrons may be excited to the most excited state n = 6



Energy and frequency of a photon are directly proportional

- The energy of a photon is given by the equation:

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$$E = hf$$

- Using energy can be written as:

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

- Where:
  - E = energy of the photon (J)
  - h = Planck's constant(J s)
  - c = speed of light (m s^{-1})
  - f = frequency (Hz)
  - λ = wavelength (m)
- The energy required to move from one energy level to another is given by the difference of energy between the two energy levels:

$$\Delta E = E_1 - E_2$$

- Where:
  - E_1 = energy associated with the level that the electron has left (eV)
  - E_2 = energy associated with the level that the electron moves to (eV)
- The difference of energy corresponds to the energy of the absorbed (or emitted) photon:

$$\Delta E = E_1 - E_2 = hf = \frac{hc}{\lambda}$$

- For each transition, a photon will be emitted with a specific wavelength
- In the case of hydrogen, all wavelengths are in the visible range:
  - From n = 6 to n = 2 - violet
  - From n = 5 to n = 2 - blue
  - From n = 4 to n = 2 - light blue
  - From n = 3 to n = 2 - red


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If the emitted photons are in the visible range, wavelengths can be represented as lines of the respective colour against a black background

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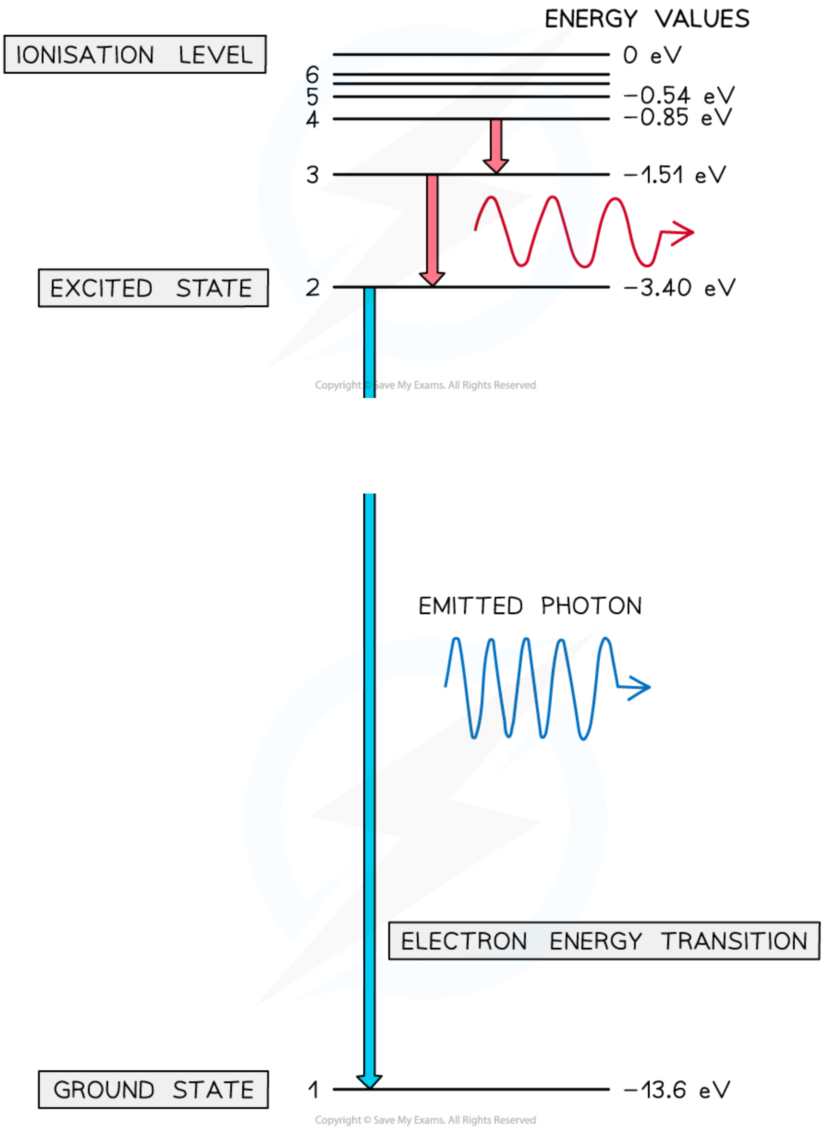
- Emitted photons can have a range of wavelengths spanning the whole electromagnetic spectrum
  - The wavelength is inversely proportional to the energy level transition associated with the emitted photon
- For example, the transitions for hydrogen will be as follows:
  - To n = 1 (ground level) – ultraviolet, highest energy, high frequency, short wavelength
  - To n = 2 – visible light, violet is the highest energy, red is the lowest energy
  - To n = 3 – infrared light, lowest energy, low frequency, longest wavelength



The larger the energy transition, the shorter the wavelength of the emitted photon

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Examiner Tips and Tricks

Although the difference in energy $\Delta E = E_1 - E_2$ can be expressed in eV, you need to convert this value in Joules when you are asked to calculate either the frequency or wavelength of the emitted photon.

You are expected to be able to calculate the frequency or the wavelength of a photon, given a specific transition on an energy levels diagram or to identify a specific transition on a given diagram when provided with the value of frequency or wavelength.

You are not expected to know the Bohr formula as given in the worked example - this is just an example of an unfamiliar context you could be given that you have to apply your knowledge to.

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