OCR A Level Physics

Your notes

The Photoelectric Effect

Contents

The Photoelectric Effect

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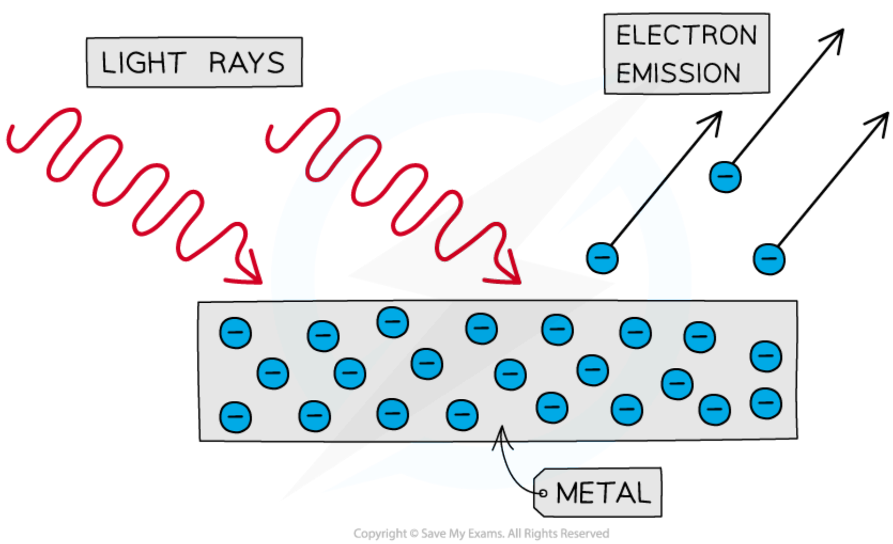
The Photoelectric Effect

- 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



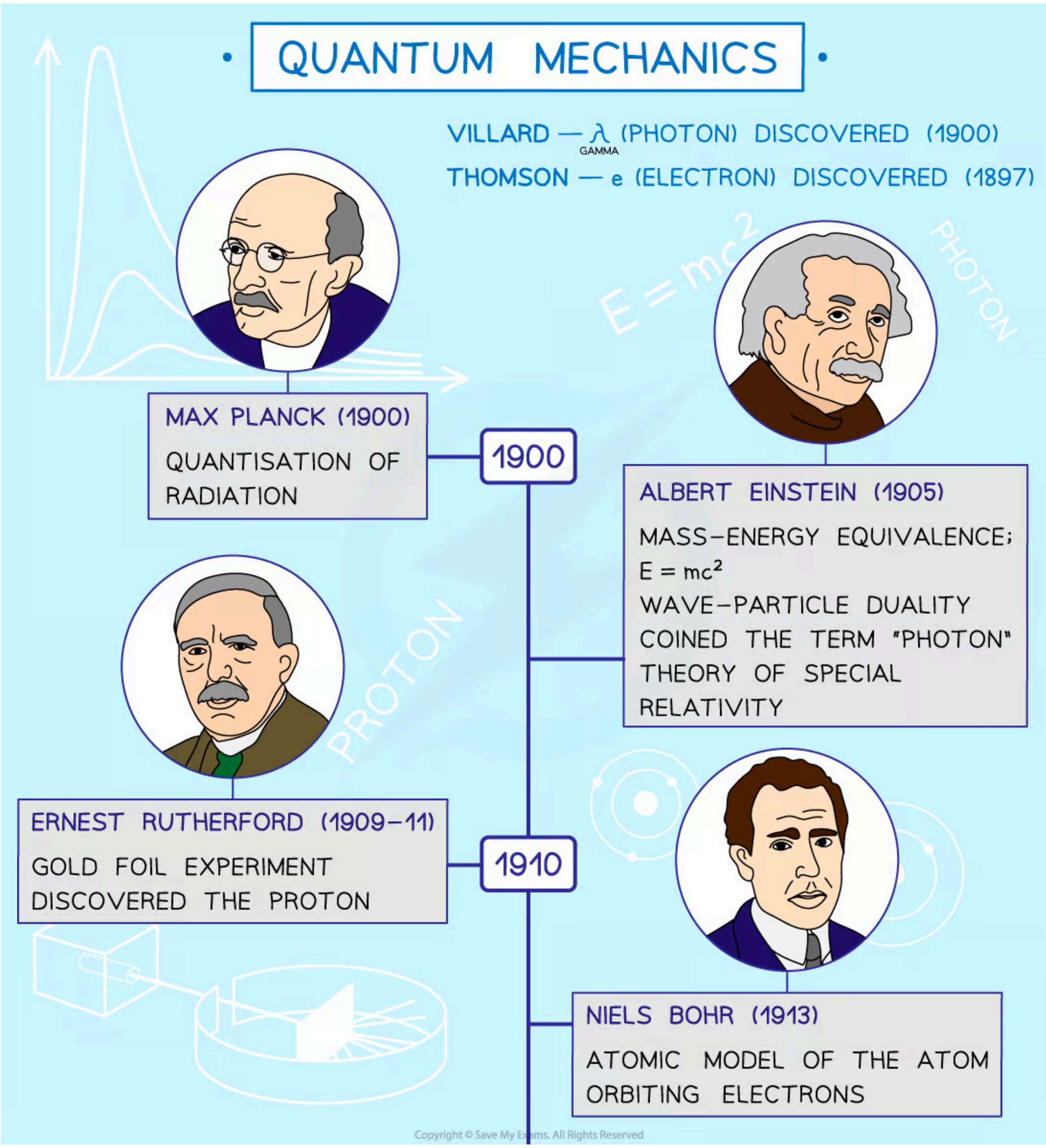
Photoelectrons are emitted from the surface of metal when light shines onto it

The 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

The Development of Quantum Physics

- The field of quantum mechanics is a relatively new field of research, compared to fields in classical mechanics (Newton's laws, wave theory etc)
- Around 1900, discoveries, such as the electron and the gamma photon, began to conflict with the existing models scientists held about the nature of matter
- Soon after, new theories about the nature of matter began to emerge from **Max Planck**, **Niels Bohr** and **Albert Einstein**, who are seen as the pioneers of **Quantum Theory**



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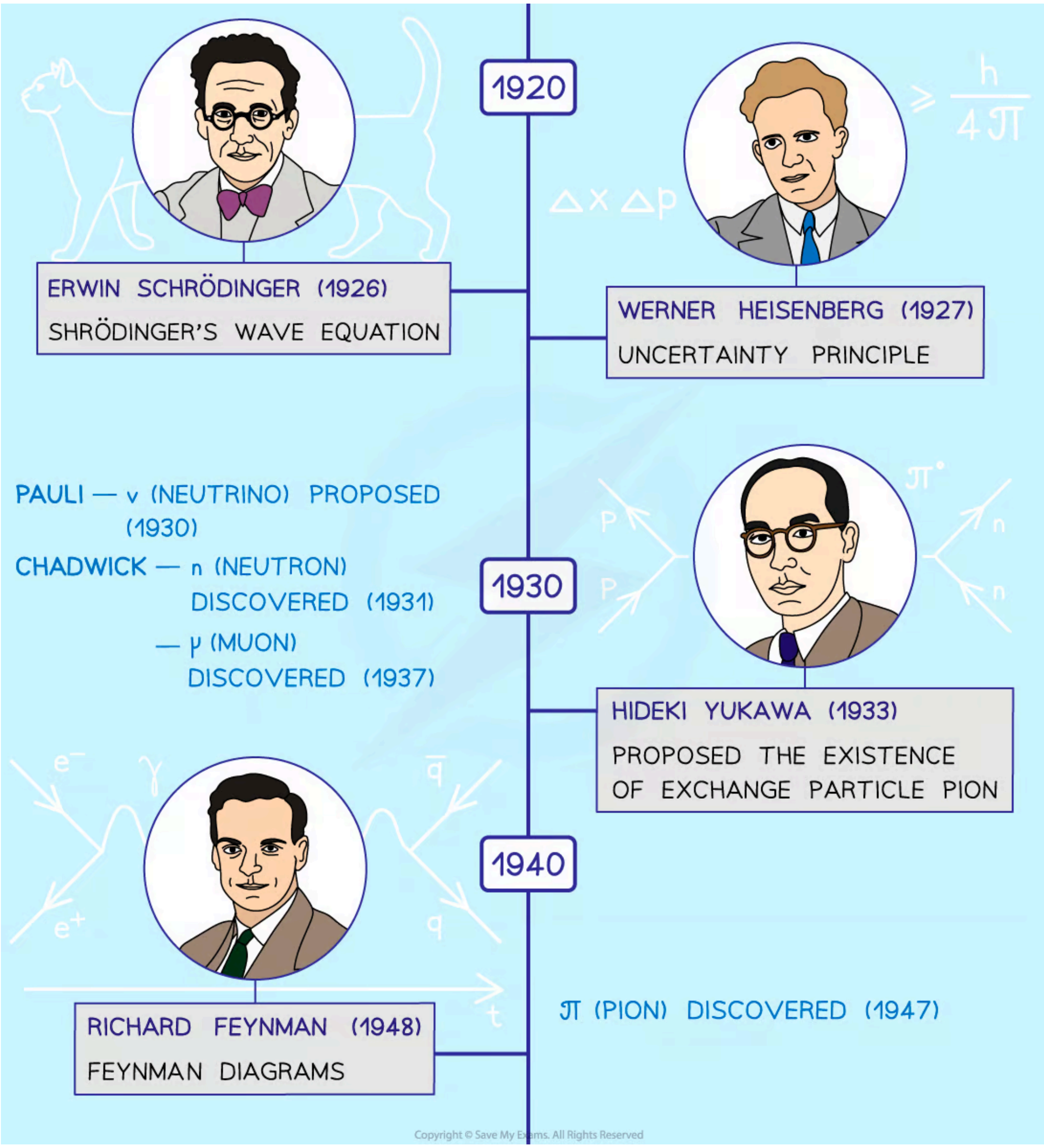
1920
ERWIN SCHRÖDINGER (1926)
SHRÖDINGER'S WAVE EQUATION
WERNER HEISENBERG (1927)
UNCERTAINTY PRINCIPLE
$\Delta x \Delta p \geq \frac{h}{4\pi}$
PAULI — ν (NEUTRINO) PROPOSED (1930)
CHADWICK — n (NEUTRON) DISCOVERED (1931)
— μ (MUON) DISCOVERED (1937)
1930
HIDEKI YUKAWA (1933)
PROPOSED THE EXISTENCE OF EXCHANGE PARTICLE PION
1940
RICHARD FEYNMAN (1948)
FEYNMAN DIAGRAMS
π (PION) DISCOVERED (1947)
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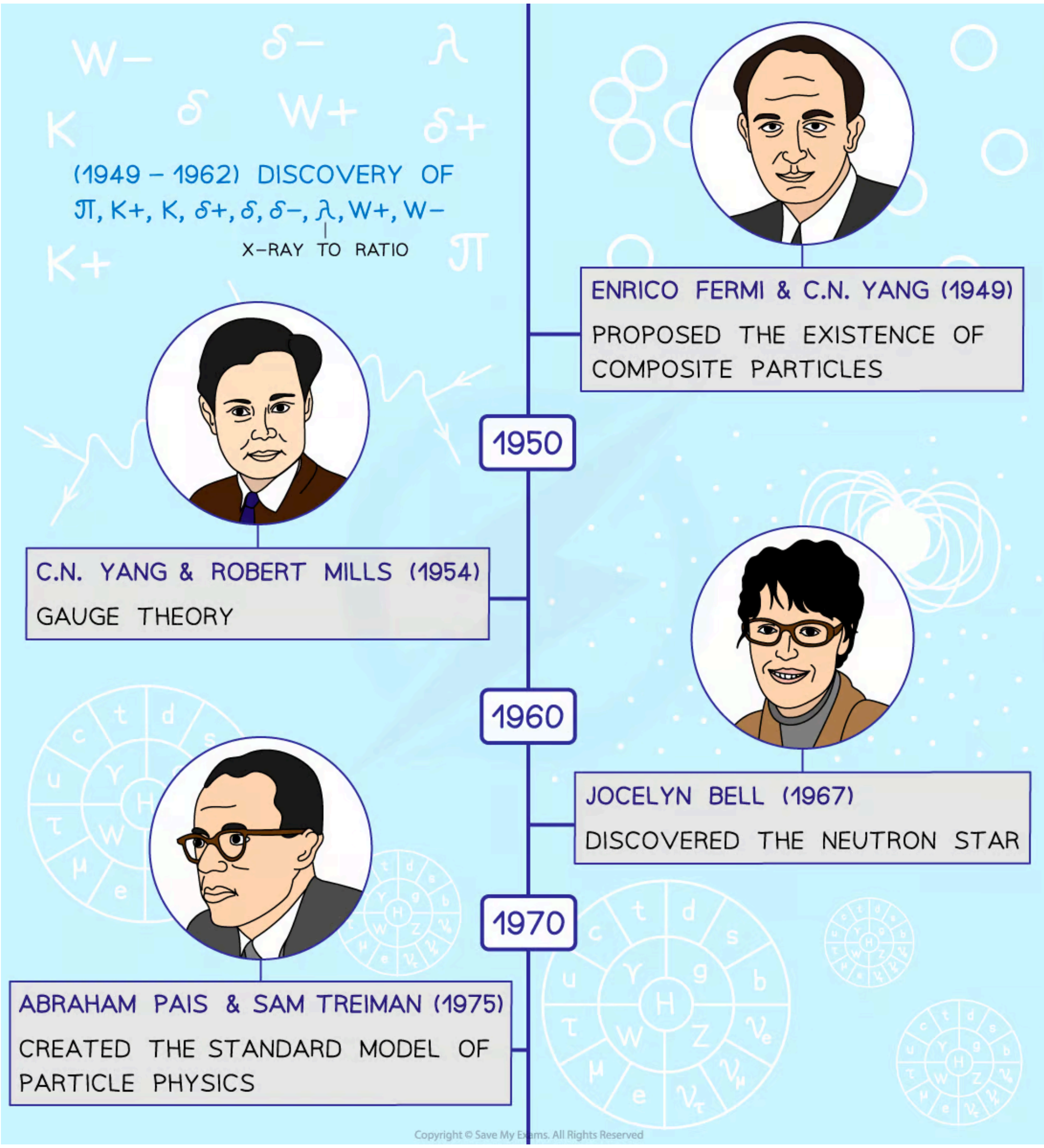
W−
δ−
λ
K
δ
W+
δ+
(1949 – 1962) DISCOVERY OF
π, K+, K, δ+, δ, δ−, λ, W+, W−
X−RAY TO RATIO
K+
π
ENRICO FERMI & C.N. YANG (1949)
PROPOSED THE EXISTENCE OF COMPOSITE PARTICLES
1950
C.N. YANG & ROBERT MILLS (1954)
GAUGE THEORY
1960
JOCELYN BELL (1967)
DISCOVERED THE NEUTRON STAR
1970
ABRAHAM PAIS & SAM TREIMAN (1975)
CREATED THE STANDARD MODEL OF PARTICLE PHYSICS
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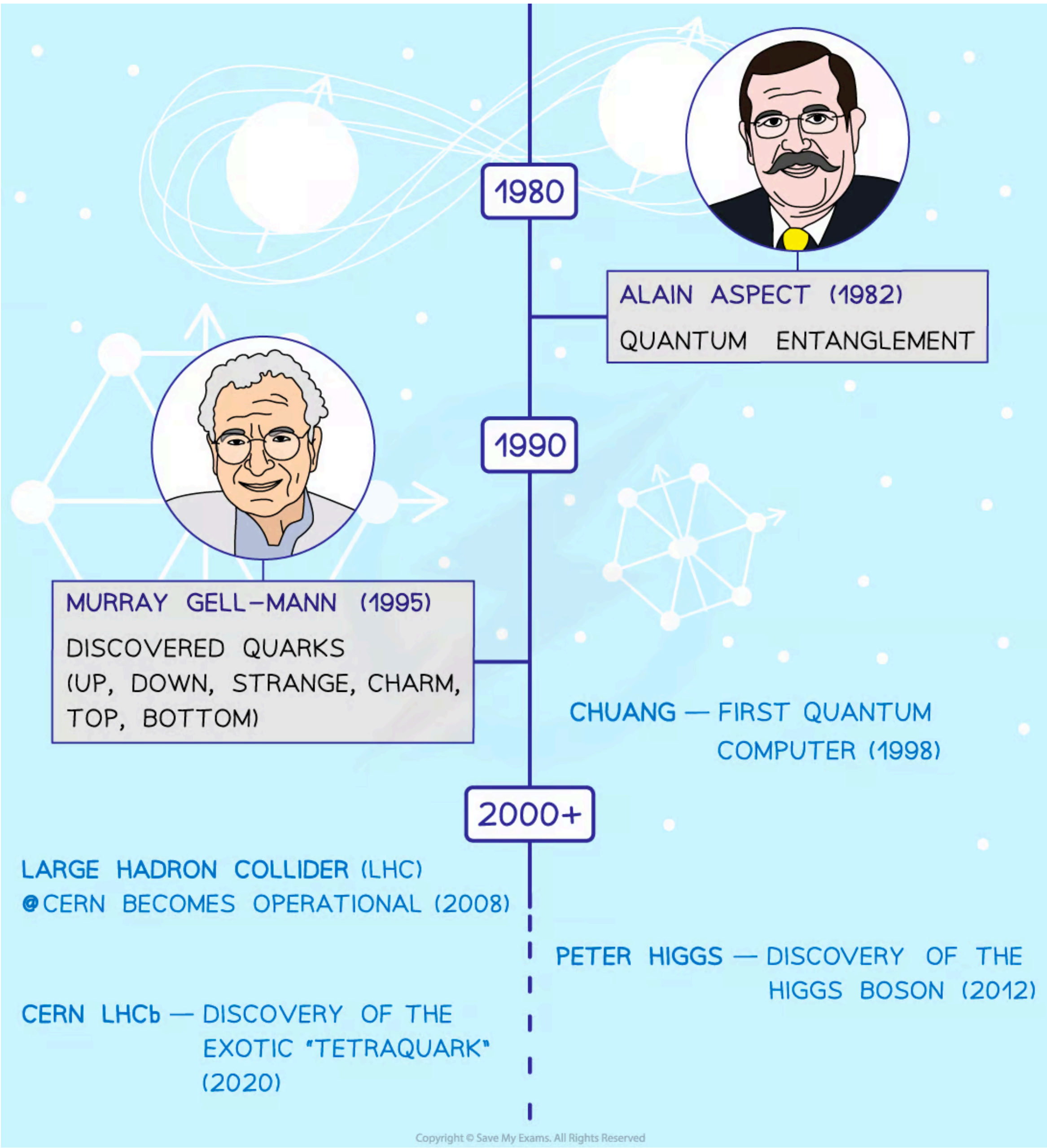

Timeline of the great advancements in quantum theory since 1900

Demonstrating the Photoelectric Effect

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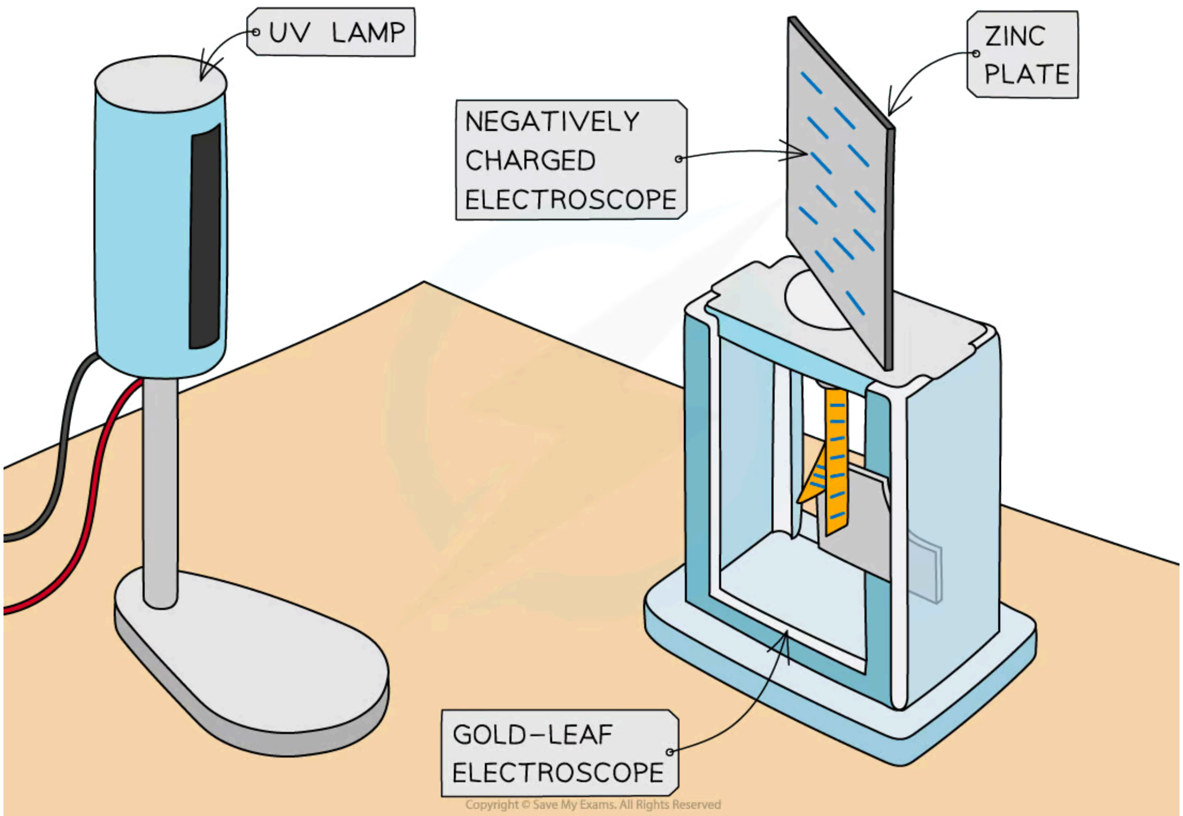
Demonstrating the Photoelectric Effect

- 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

Observations of the Gold Leaf Experiment

- 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**


UV LAMP
NEGATIVELY CHARGED ELECTROSCOPE
ZINC PLATE
GOLD-LEAF ELECTROSCOPE
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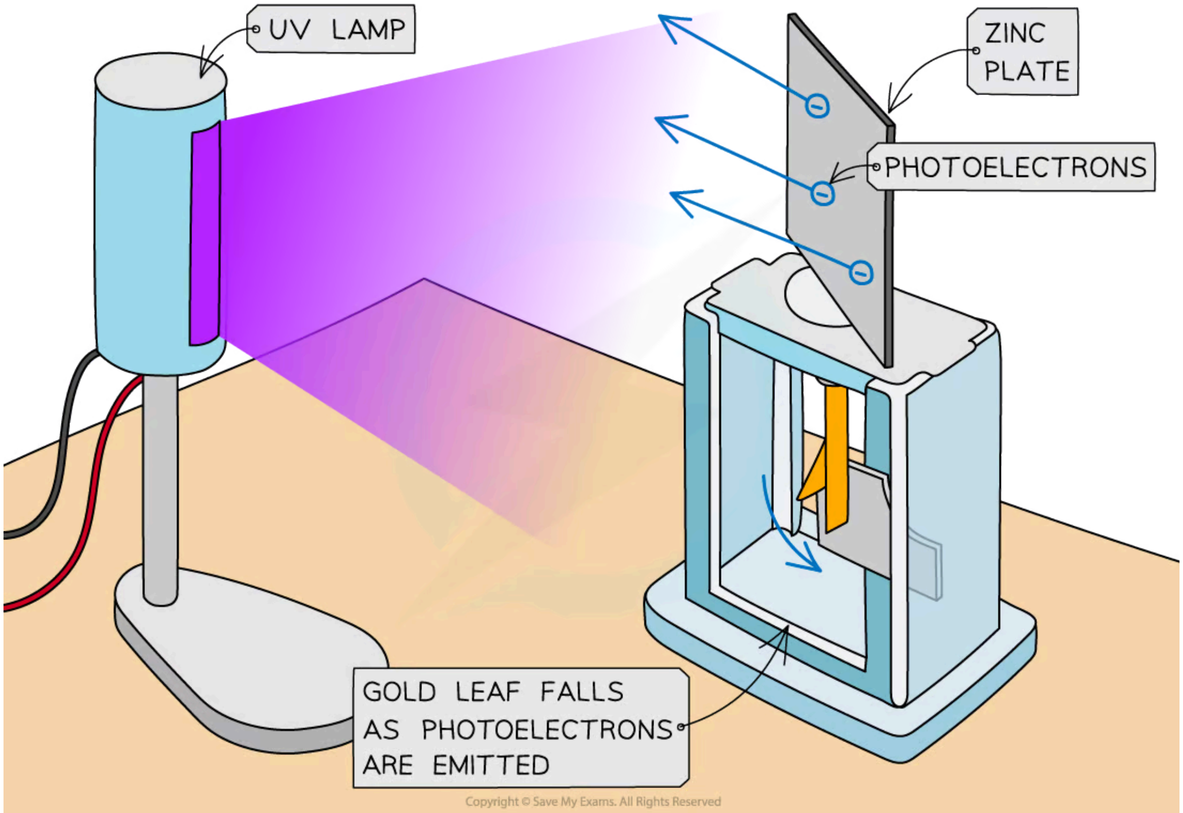

Typical set-up of the gold leaf electroscope experiment

Explaining the Observations

- Observation:

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

- Explanation:
  - 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

- Observation:

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

- Explanation:
  - 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
- Observation:

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

- Explanation:
  - If the incident frequency is below a certain threshold frequency, no electrons are emitted, no matter the intensity of the radiation
  - A filament light source has a frequency below the threshold frequency of the metal, so, no photoelectrons are released
- Observation:

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

- Explanation:
  - 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
- Observation:

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

- Explanation:
  - 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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The Photoelectric Equation

Interaction Between a Photon & Surface Electron

- In the photoelectric effect, it is very important to note:

  Each surface electron can only interact with a single photon

- This provides important evidence that light is **quantised** or carried in discrete packets
- This also means the number of photoelectrons emitted is exactly equal to the number of photons incident on the surface in which the photoelectric effect is taking place
- Increasing the **intensity** of the electromagnetic radiation increases the number of photons per area **incident** on the surface
  - From the one-to-one interaction, this also means this increases the number of photoelectrons emitted **from** the surface

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**:

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

- Where:
  - h = Planck's constant (J s)
  - f = the frequency of the incident radiation (Hz)
  - Φ = the work function of the material (J)
  - $\tfrac{1}{2} m v^2_{max} = KE_{max}$ = 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}

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Graphical Representation of Work Function

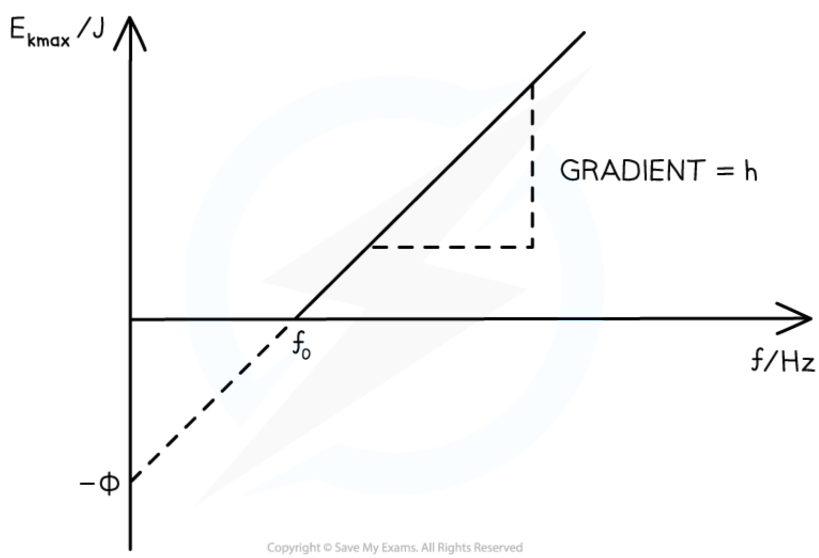
- The photoelectric equation can be rearranged into the straight line equation:

$$y = mx + c$$

- 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

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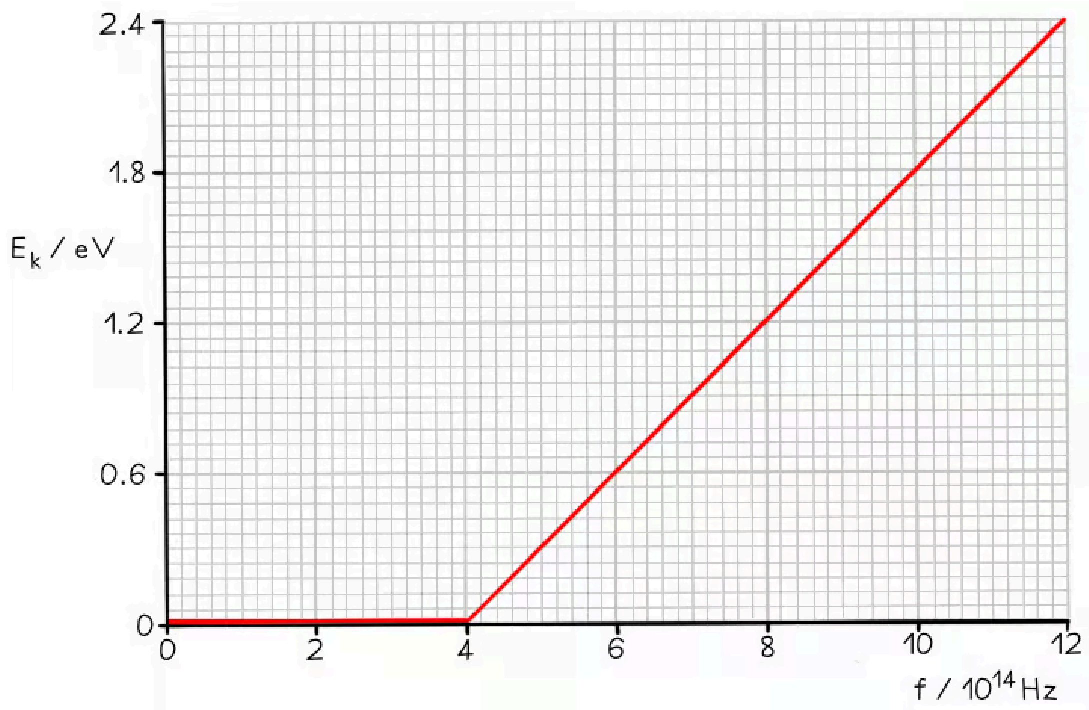
Worked Example

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.



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

$$E = hf = \Phi + ½\, mv^2_{max} \quad \rightarrow \quad KE_{max} = hf - \Phi$$

$$y = mx + c$$

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, $½\, mv_{max}^2 = 0$

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

Step 4: Convert the work function into eV

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

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

Examiner Tips and Tricks

When using the photoelectric effect equation, hf, Φ and KE_{max} must all have the **same** units (joules). Therefore make sure to convert any values given in eV into Joules (× (1.6×10^{-19}))

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Work Function & Threshold Frequency

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Work Function & Threshold Frequency

- 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

Threshold Frequency & Wavelength

- The threshold frequency is defined as:

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

- The threshold wavelength, related to threshold frequency by the wave equation, is defined as:

  The longest wavelength of incident electromagnetic radiation that would remove a photoelectron from the surface of a metal

- Threshold frequency and wavelength are properties of a material, and vary from metal to metal

Threshold frequencies and wavelengths for different metals

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Metal	Threshold Frequency (f_0) / Hz	Threshold Wavelength (λ_0) / nm
Sodium	4.40×10^{14}	682
Potassium	5.56×10^{14}	540
Zinc	1.02×10^{15}	294
Iron	1.04×10^{15}	289
Copper	1.13×10^{15}	266
Gold	1.23×10^{15}	244
Silver	9.71×10^{15}	30.9

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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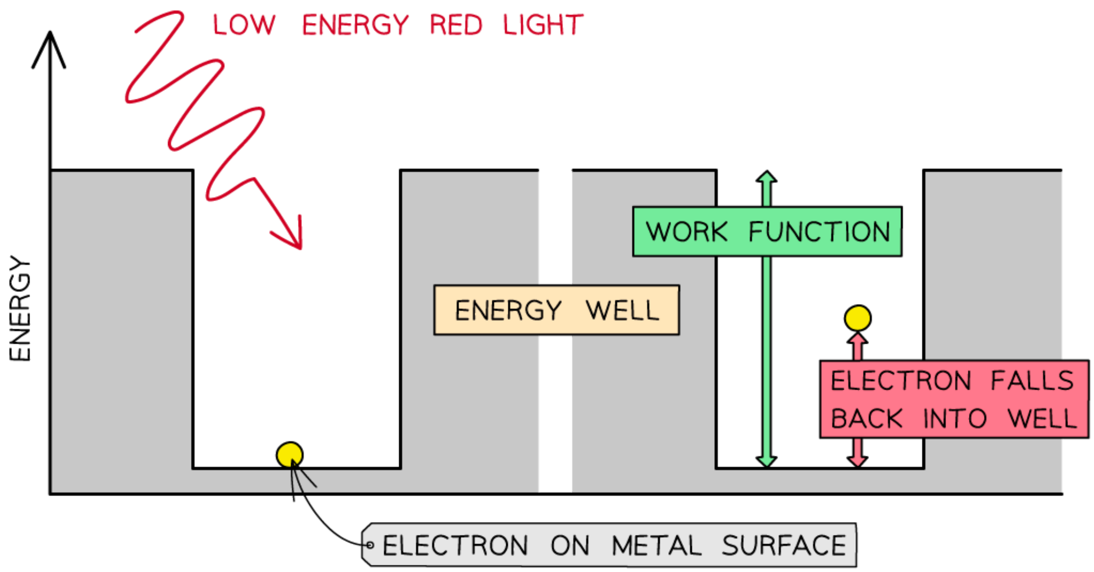
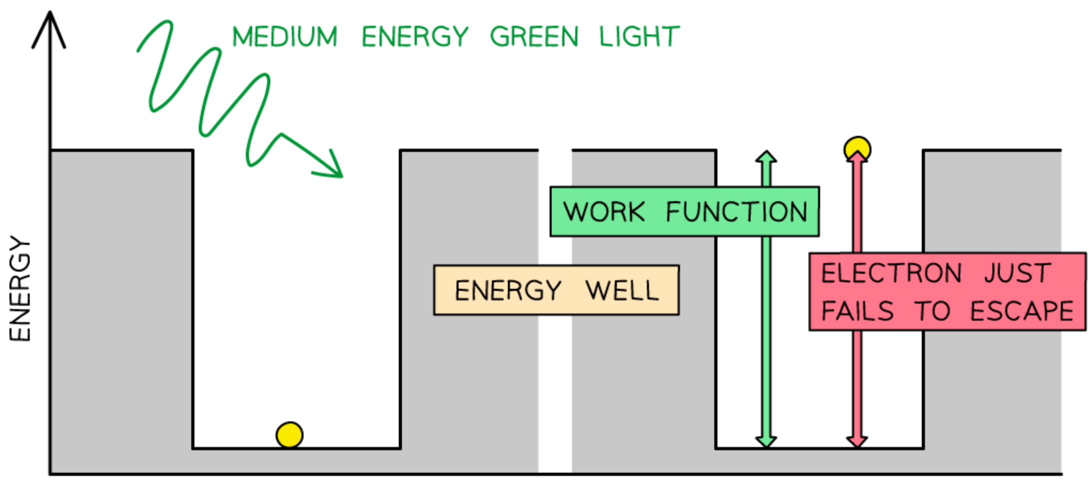

LOW ENERGY RED LIGHT
ENERGY
WORK FUNCTION
ENERGY WELL
ELECTRON FALLS BACK INTO WELL
ELECTRON ON METAL SURFACE


MEDIUM ENERGY GREEN LIGHT
ENERGY
WORK FUNCTION
ENERGY WELL
ELECTRON JUST FAILS TO ESCAPE

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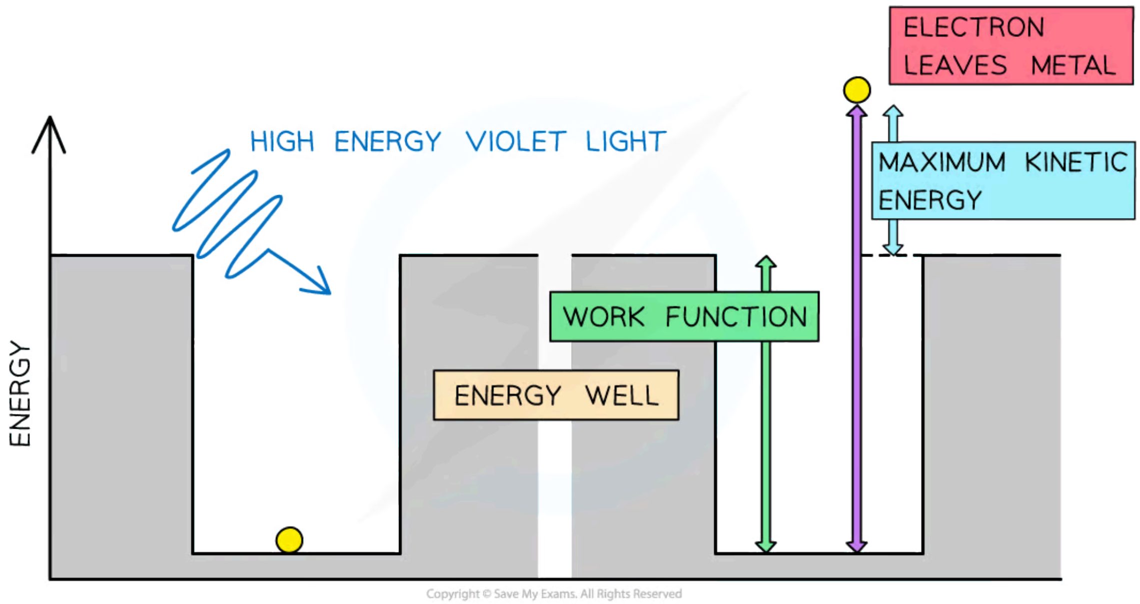

In the photoelectric effect, a single photon may cause a surface electron to be released if it has sufficient energy

- Different metals have different threshold frequencies and hence different work functions
- Using the well analogy:
  - A more tightly bound electron requires **more** energy to reach the top of the well
  - A less tightly bound electron requires **less** energy to reach the top of the well
- Alkali metals, such as sodium and potassium, have threshold frequencies in the **visible light region**
  - This is because the attractive forces between the surface electrons and positive metal ions are relatively weak
- Transition metals, such as zinc and iron, have threshold frequencies in the **ultraviolet region**
  - This is because the attractive forces between the surface electrons and positive metal ions are much stronger

Examiner Tips and Tricks

A useful analogy for threshold frequency is a fairground coconut shy:

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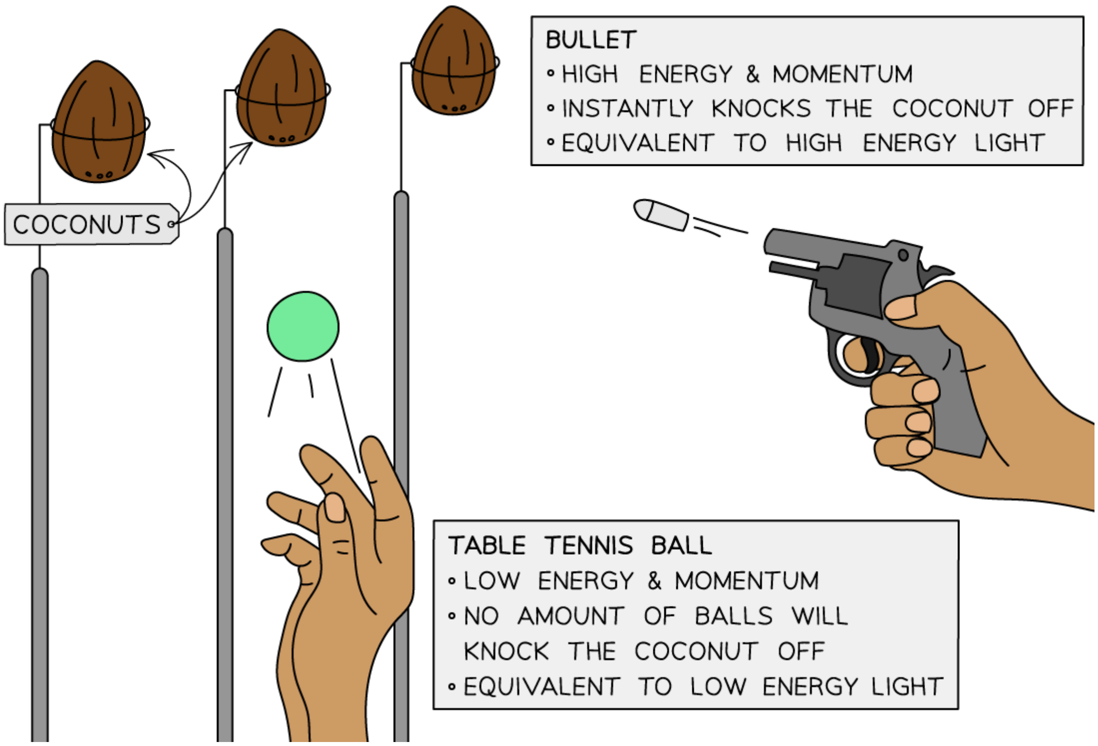
- One person is throwing table tennis balls at the coconuts, and another person has a pistol
- No matter how many of the table tennis balls are thrown at the coconut it will still stay firmly in place – this represents the **low frequency quanta**
- However, a single shot from the pistol will knock off the coconut immediately – this represents the **high frequency quanta**



Maximum Kinetic Energy & Intensity

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The Maximum Kinetic Energy of Photoelectrons & Intensity

- The **maximum kinetic energy** of the photoelectrons is **independent of the intensity** of the incident radiation
- This is because **each electron can only absorb one photon**
- Kinetic energy is only dependent on the **frequency** of the incident radiation
- Intensity is a measure of the number of photons incident on the surface of the metal
- So, increasing the number of photons striking the metal will not increase the kinetic energy of the electrons, it will increase the **number** of photoelectrons emitted

Rate of Emission of Photoelectrons

- The photoelectric current is the rate of emission of photoelectrons emitted per second
- **Photoelectric current** is proportional to the **intensity** of the radiation incident on the surface of the metal
- This is because intensity is proportional to the number of photons striking the metal per second
- Since each photoelectron absorbs a single photon, the photoelectric current must be proportional to the intensity of the incident radiation

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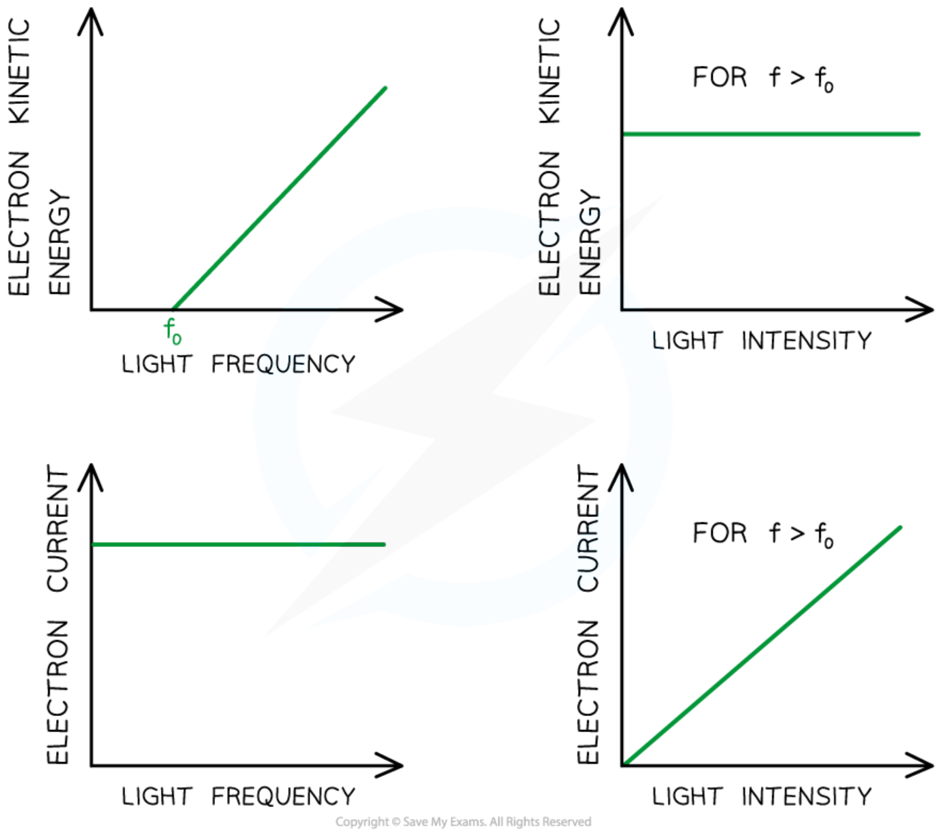

Kinetic energy of photoelectrons is independent of intensity, whereas the photoelectric current is proportional to intensity and independent of frequency