2.4 The Photoelectric Effect

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

2.4 The Photoelectric Effect

CONTENTS

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 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.

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

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

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

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

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

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

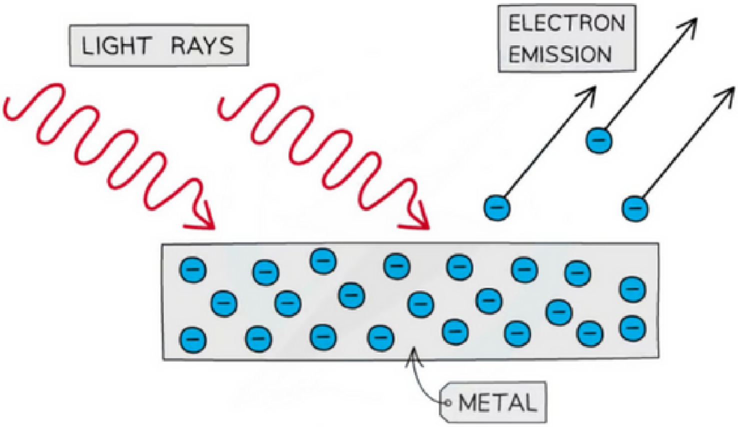
Exam Tip

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

2.4.2 Threshold Frequency & Work Function

Threshold Frequency

- 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



The photoelectric effect: photons of sufficient energy are able to liberate electrons from the surface of a metal

Threshold Frequency & Wavelength

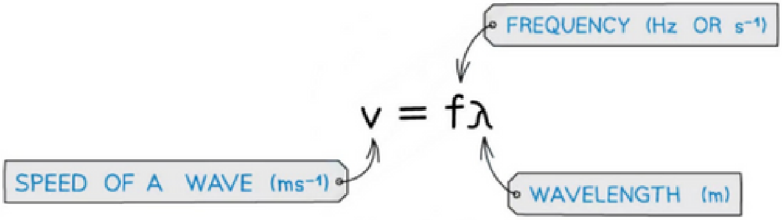
- The **threshold frequency** is defined as:

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

- The frequency and wavelength are related by the equation



- Since photons are particles of light, $v = c$ (speed of light)
- Threshold frequency and wavelength are properties of a material, and vary from metal to metal

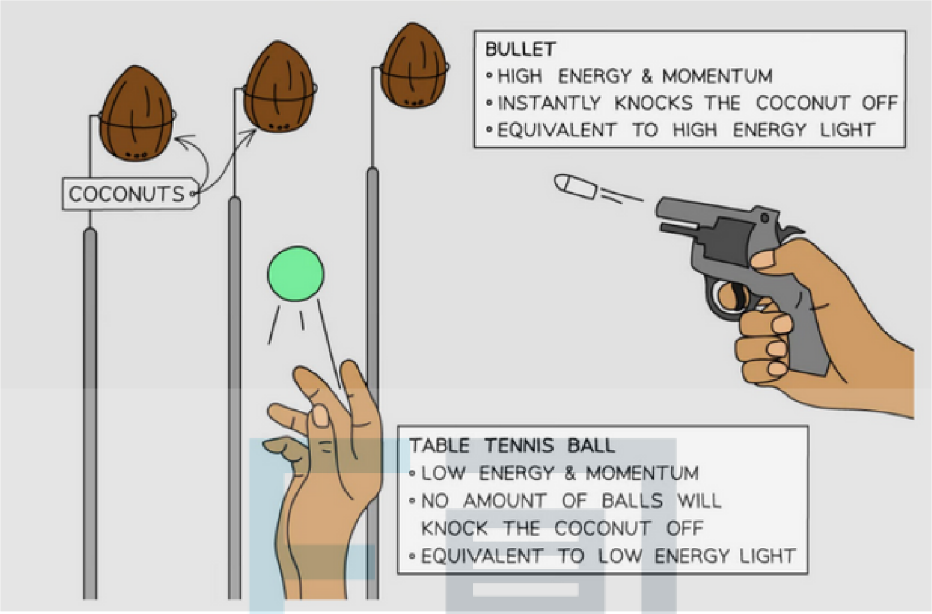
Threshold frequencies and wavelengths for different metals

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

Exam Tip

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

- 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**

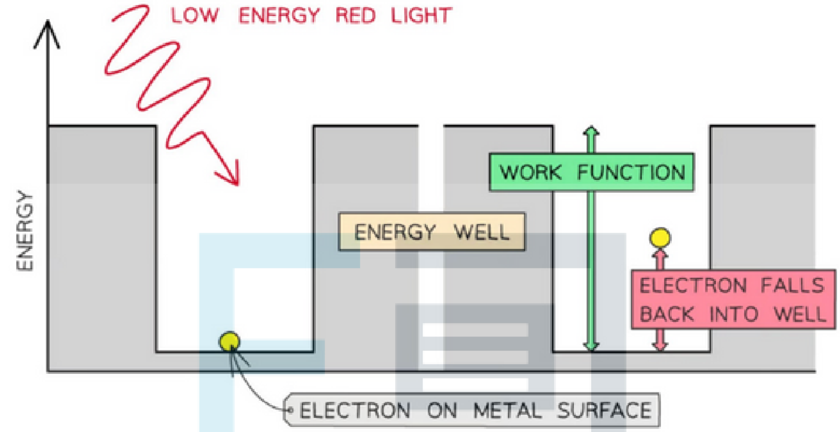


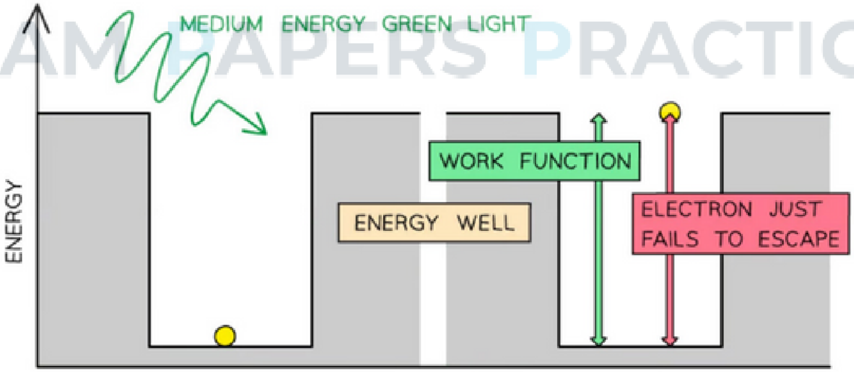
The Work Function

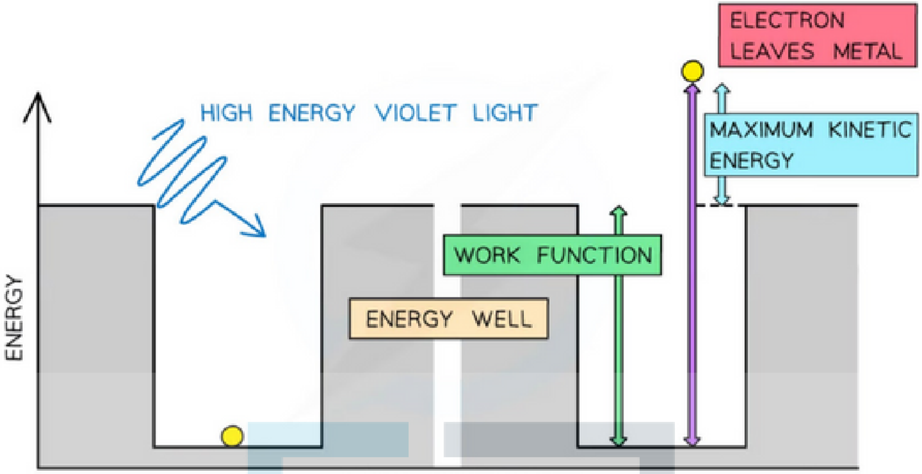
- The work function Φ, or threshold energy, of a material, is defined as:

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


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



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

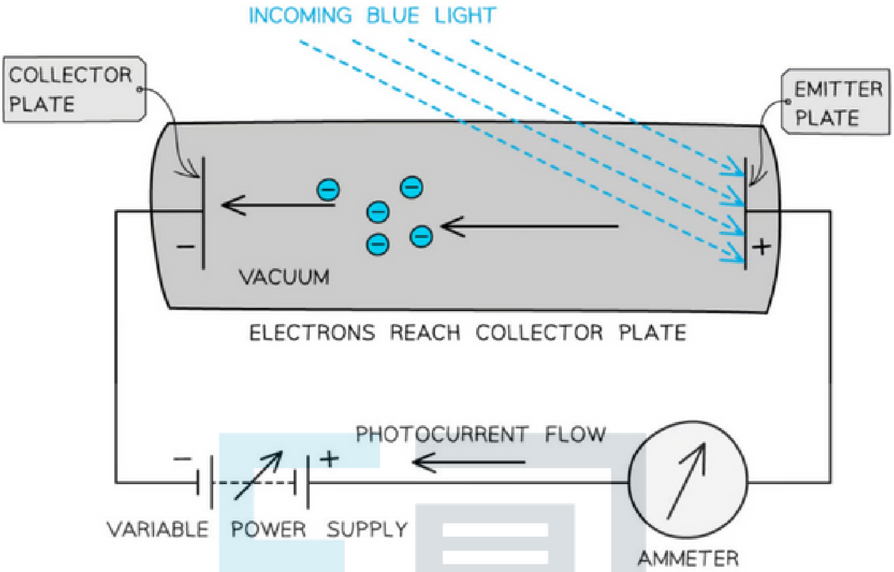
- Different metals have different threshold frequencies and hence different work functions
- Using the well analogy:
  - A more tightly bound electron requires **more** energy to reach the top of the well
  - A less tightly bound electron requires **less** energy to reach the top of the well
- Alkali 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

Stopping Potential

- Stopping potential, V_s, is defined as:

The potential difference required to stop photoelectron emission from occurring

- The photons arriving at the metal plate cause photoelectrons to be emitted
  - This is called the **emitter plate**
- The electrons that cross the gap are collected at the other metal plate
  - This is called the **collector plate**



This set up can be used to determine the maximum kinetic energy of the emitted

- The flow of electrons across the gap results in an e.m.f. between the plates that causes a current to flow around the rest of the circuit
    - Effectively, it becomes a photoelectric cell producing a **photoelectric current**

- If the e.m.f. of the variable power supply is initially zero, the circuit operates **only** on the photoelectric current
- As the supply is turned up, the emitter plate becomes more **positive** (because it is connected to the positive terminal of the supply)
- As a result, electrons leaving the emitter plate are attracted back towards it
    - This is because the p.d. across the tube **opposes** the motion of the electrons between the plates

- If any electrons escape with enough kinetic energy, they can overcome this attraction and cross to the collector plate
    - And if they don't have enough energy, they can't cross the gap

- By increasing the e.m.f. of the supply, eventually a p.d. will be reached at which no electrons are able to cross the gap – this is the stopping potential, V_s
- At this point, the energy needed to cross the gap is equal to the maximum kinetic energy KE_{max} of the electrons

$$KE_{max} = eV_S$$

Exam Tip

It is important to note that the stopping voltage actually holds a **negative value**, but since we use it to determine the maximum kinetic energy of the emitted electrons, its sign is not important in calculations, it's acceptable to just quote its magnitude.

2.4.3 The Photoelectric Equation

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)
    - $\tfrac{1}{2}mv^2_{max} = E_{k(max)}$ = 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
    - $E_{k(max)}$ 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** $E_{k(max)}$

Graphical Representation of Work Function

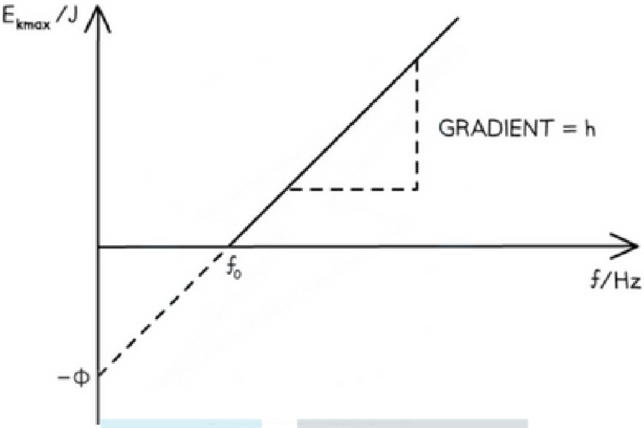
- The photoelectric equation can be rearranged into the straight line equation:

$$y = mx + c$$

- Comparing this to the photoelectric equation:

$$E_{k(max)} = hf - \Phi$$

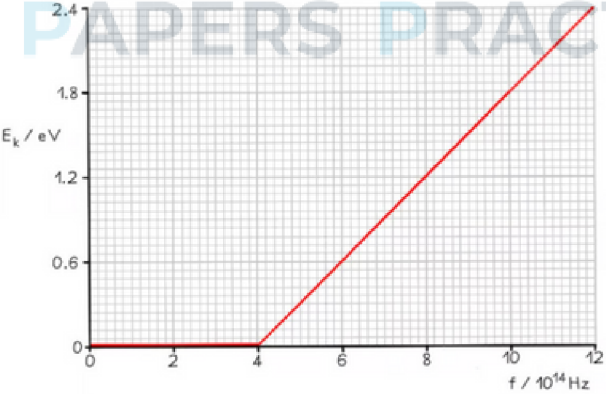
- A graph of maximum kinetic energy $E_{k(max)}$ against frequency f can be obtained



- 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

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.

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

$$E = hf = \Phi + ½mv^2_{max} \rightarrow E_{k(max)} = hf - \Phi$$

$$y = mx + c$$

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, $½mv_{max}^2 = 0$

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

Step 4: Convert the work function into eV

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

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

Exam Tip

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

Maximum Kinetic Energy

Kinetic Energy & Intensity

- The **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

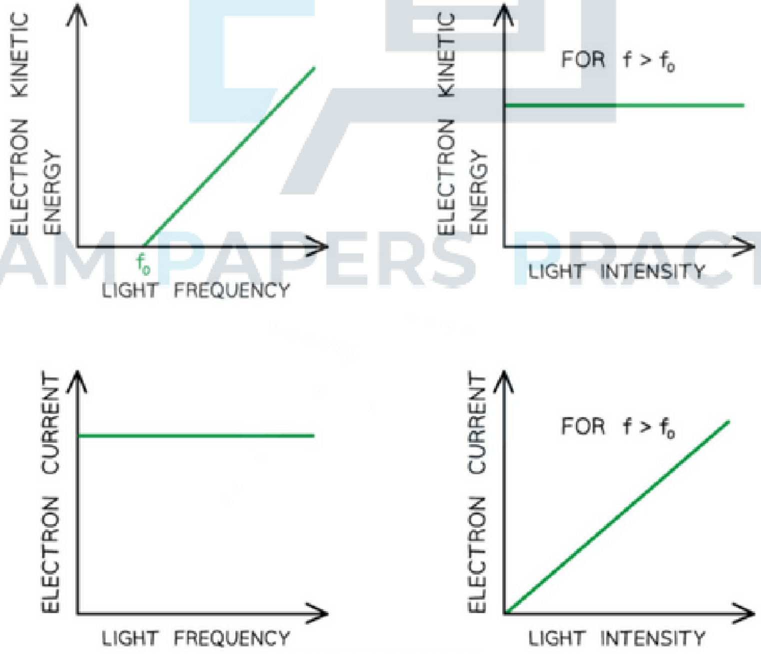
Why the Kinetic Energy is a Maximum

- Each electron in the metal acquires the same amount of energy from the photons in the incident radiation

- However, the energy required to remove an electron from the metal varies because some electrons are on the surface whilst others are deeper in the metal
    - The photoelectrons with the maximum kinetic energy will be those on the **surface** of the metal since they do not require much energy to leave the metal
    - The photoelectrons with lower kinetic energy are those deeper within the metal since some of the energy absorbed from the photon is used to approach the metal surface (and overcome the work function)
    - There is less kinetic energy available for these photoelectrons once they have left the metal

Photoelectric Current

- The photoelectric current is the number 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



Graphs showing the variation of electron KE and photocurrent with the frequency of the incident light