- Candidates should be able to :

  - **Describe** and **explain** the phenomenon of the **Photoelectric Effect.**

  - Explain that the photoelectric effect provides evidence for the **particulate nature** of electromagnetic radiation, while phenomena such as interference and diffraction provide evidence for a **wave nature.**

  - **Define** and **use** the terms **WORK FUNCTION** and **THRESHOLD FREQUENCY.**

  - State that **energy is conserved** when a photon interacts with an electron.

  - **Select, explain** and **use EINSTEIN'S PHOTOELECTRIC EQUATION :**

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

  - Explain why the **maximum kinetic energy** of the electrons is **independent** of **intensity** and why the **photoelectric current** in a photocell circuit is **proportional** to the **intensity** of the incident radiation.

- THE PHOTOELCTRIC EFFECT

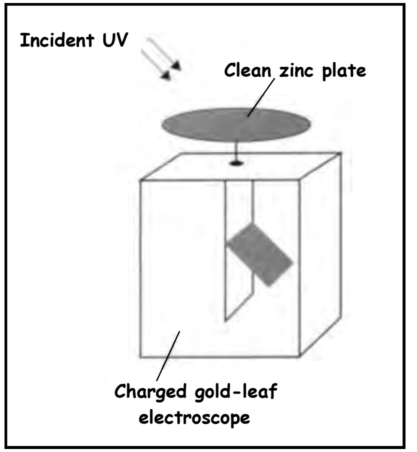
PHOTOELECTRIC EMISSION is the ejection of electrons from the surface of a metal when it is exposed to electromagnetic radiation of sufficiently high frequency (or short wavelength).

The table below gives some idea of the type of radiation which causes photoemission in zinc, sodium and caesium.

Electromagnetic radiation which causes photoemission	zinc	sodium	caesium
x-rays	*	*	*
ultra-violet	*	*	*
blue light		*	*
red light			*

SIMPLE DEMONSTRATION OF PHOTOELECTRIC EFFECT

When a gold-leaf electroscope is given a charge, the thin gold leaf acquires the same charge as the stem, is repelled and rises.

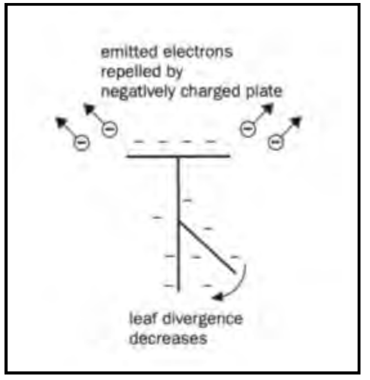


- A freshly cleaned zinc plate is placed on the electroscope cap. If the electroscope is then given a **negative** charge, the leaf rises and stays up. Ultra-violet radiation from a mercury vapour lamp is then directed at the zinc plate and the leaf is seen to fall slowly, showing that the electroscope is discharging.
  A glass sheet (which absorbs UV) placed between the lamp and the zinc halts the leaf's descent, showing that it is the UV which is causing the discharge.

EXPLANATION

The photoelectrons which are emitted from the zinc plate will be repelled by the negative charge on the electroscope (as shown in the diagram opposite).

The continuous loss of electrons, which is the result of photoemission from the zinc surface, is responsible for the discharge of the electroscope.



LAWS OF PHOTOELECTRIC EMISSION

Experimental observations of the photoelectric effect show that :

Increasing the **INTENSITY** (i.e. **BRIGHTNESS**) of the radiation incident on a metal surface **increases** the **NUMBER OF ELECTRONS EMITTED PER SECOND.**

If the incident radiation **FREQUENCY (f)** is < a certain **THRESHOLD FREQUENCY (f_0),** no electrons are emitted, no matter how intense the radiation is.

Similarly, for radiation of **WAVELENGTH (λ)** > a certain **THRESHOLD WAVELENGTH (λ_0),** no electrons are emitted.

Different metals have different **(f_0)** and **(λ_0)** values.

e.g. Even the light from the brightest industrial laser cannot cause photoelectric emission from zinc, whereas a weak UV light certainly will.

The photoelectrons are emitted from a given metal with a range of kinetic energies, from zero up to a maximum value.

The **MAXIMUM KINETIC ENERGY (KE_{max})** of the emitted electrons **INCREASES** with the **FREQUENCY** of the incident radiation and it is **INDEPENDENT** of the **INTENSITY** of the radiation.

e.g. Shining a brighter light of **f > f_0** causes **more electrons per second** to be emitted, but it does **NOT** affect their **kinetic energies**.

The **THRESHOLD FREQUENCY (f_0)** for a metal is the **MINIMUM FREQUENCY** of electromagnetic radiation which will cause photoelectric emission.

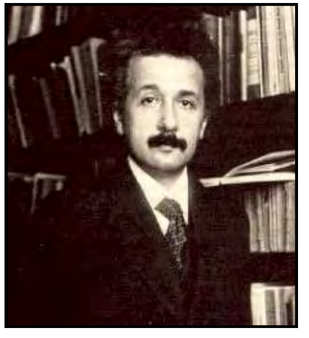
The **THRESHOLD WAVELENGTH (λ_0)** for a metal is the **MAXIMUM WAVELENGTH** of electromagnetic radiation which will cause photoelectric emission.

• *IMPLICATIONS OF THE PHOTOELECTRIC EFFECT*

- Although the **WAVE THEORY** provided good explanations for phenomena such as **interference** and **diffraction**, it failed to explain the **photoelectric effect.**

  According to **WAVE THEORY,** photoelectric emission should happen for **all frequencies** of incident radiation. Furthermore, the **kinetic energy** of the emitted electrons should **increase with radiation intensity**. The experimentally proven reality is that photoemission does **NOT OCCUR** with incident radiation **frequencies less than the threshold frequency** and the **kinetic energy** of the photoelectrons is **independent of radiation intensity**.

- In 1905, at the age of 26, **ALBERT EINSTEIN** published a scientific paper (For which he was awarded the Nobel Prize) in which he fully explained the **photoelectric effect** in terms of the **particulate nature** of electromagnetic radiation as outlined in **MAX PLANCK'S QUANTUM THEORY**.



  Thus was born the idea that electromagnetic radiation may be thought of as having a **dual nature**. Some of its properties (reflection, refraction, interference, diffraction and polarisation) are explicable in terms of its **wave-like** nature, but other phenomena, in particular the photoelectric effect, can only be explained in terms of the **particle-like** behaviour.

• *WORK FUNCTION (Φ)*

We have looked at the experimental observations of the photoelectric effect and and outlined the laws which these observations led to.

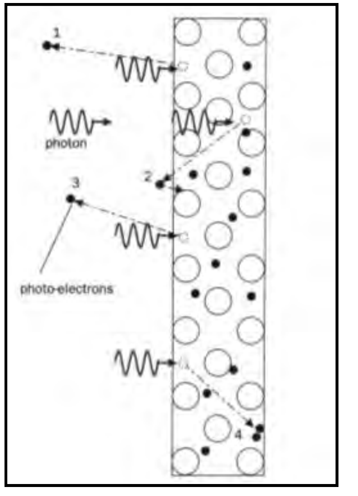
What follows is a very simplified explanation of what actually happens when photons of sufficiently high energy are directed at a metal surface.

Some photons are completely absorbed by electrons near the surface of the metal and since energy is conserved when a photon interacts with an electron :

Kinetic energy gained by the electron = energy of the incident photon

$$\frac{1}{2} mv^2 = hf$$

The diagram opposite shows some of the possible Results.

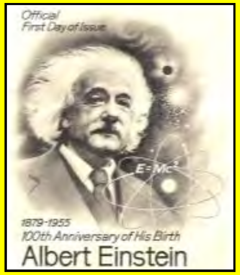


- <u>**Electron 1**</u> is at the surface and requires the least possible energy to liberate it, so it escapes with the maximum kinetic energy.
- <u>**Electron 2**</u> is deep within the metal and it has lost so much kinetic energy by the time it reaches the surface that it is attracted back.
- <u>**Electron 3**</u> is slightly deeper within the metal than electron 1 and so escapes with slightly less kinetic energy.
- <u>**Electron 4**</u> gains enough kinetic energy to escape, but it is moving in the wrong direction and is absorbed by the metal.

The **<u>WORK FUNCTION</u> (Φ)** is the minimum energy needed by an electron in order to escape from a metal surface.

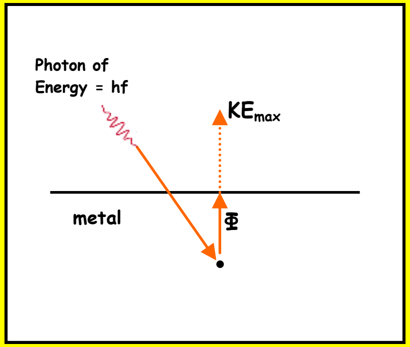
An electron at the surface of a metal which interacts with a **photon of energy** = **Φ**, would absorb the photon and gain enough energy to just escape from the metal with zero kinetic energy.

EINSTEIN'S PHOTOELECTRIC EQUATION



Einstein's explanation of the photoelectric effect can be summarised as follows :

When a photon of **energy (hf)** causes photoemission from a metal surface, some of the photon energy is used to overcome the **work function (Φ)**, while the remainder appears as **kinetic energy** of the emitted electron.



This is expressed mathematically in **EINSTEIN'S PHOTOELECTRIC EQUATION** :

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

- h (J s), f (Hz): Energy delivered by a photon of frequency (f)
- Φ (J): Minimum energy needed to free electrons from metal surface
- KE_{max} (J): Maximum kinetic energy of emitted electron

POINTS TO NOTE

- The photoelectric equation shows that KE_{max} of a photoelectron depends only on the **FREQUENCY (f)** of the incident photon.

  Increased intensity simply means that the incident radiation carries **more photons per second** and will therefore produce **more photoelectrons per second**, but it has **no effect** on the **maximum kinetic energy** (**KE_{max}**).

- The photoelectric equation can be expressed in terms of the **wavelength (λ)** of the incident photons :

$$\frac{hc}{\lambda} = \Phi + KE_{max}$$

h (J s), c ($m\ s^{-1}$), λ (m), Φ (J), KE_{max} (J)

- $KE_{max} = \frac{1}{2} mv_{max}^2$ (where v_{max} is the maximum velocity of the photoelectron)

  The majority of photoelectrons will have kinetic energies < KE_{max}

- Photoelectric emission just occurs when :

  incident photon energy, hf_0 = work function, Φ

  f_0: THRESHOLD FREQUENCY

So :

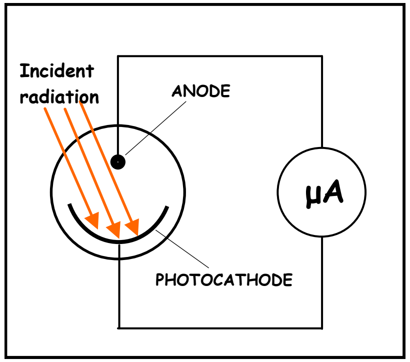
$$f_0 = \frac{\Phi}{h}$$

f_0 (Hz), Φ (J), h (J s)

- **THE VACUUM PHOTOCELL**

- Vacuum photocells consist of a metal electrode (called the **ANODE**) and a metal plate (called the **PHOTOCATHODE**) contained in an evacuated glass bulb.

- The diagram opposite shows a photocell connected in series with a microammeter (μA).



When radiation of **frequency (f) greater than the threshold frequency (f_0)** for the metal is incident on the photocathode, electrons emitted from it are transferred to the anode.

The **PHOTOELECTRIC CURRENT**, measured by the microammeter is proportional to the **number of electrons per second** which move from cathode to anode.

For a **photoelectric current (I)**, the **number of photoelectrons per second (N)** emitted by the cathode is given by :

$$N = I/e \quad \text{(where } e = \text{electronic charge)}$$

The **PHOTOELECTRIC CURRENT** is proportional to the **INTENSITY** of the radiation incident on the cathode.

EXPLANATION

This is because the **INTENSITY** is proportional to the **NUMBER OF PHOTONS PER SECOND** striking the cathode.

In order to be ejected, each photoelectron absorbs a photon, so the **NUMBER OF PHOTOELECTRONS EMITTED PER SECOND** (i.e. the **PHOTOELECTRIC CURRENT**) is proportional to the **INTENSITY** of the incident radiation.

The **MAXIMUM KINETIC ENERGY** of the photoelectrons is independent of the **INTENSITY** of the incident radiation.

EXPLANATION

The energy gained by each photoelectron is due to the absorption of a single photon, so the **MAXIMUM KINETIC ENERGY (KE_{max})** is given by :

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

So, for a given metal, it depends on the **incident photon energy (hf)**.

- **PRACTICE QUESTIONS** ($h = 6.63 \times 10^{-34}$ J s)

1 A metal surface having a work function of 3.0 eV is illuminated with Radiation of wavelength 350 nm. Calculate :

(a) The **THRESHOLD FREQUENCY (f_0)** and **WAVELENGTH (λ_0)**.

(b) The **MAXIMUM KINETIC ENERGY** of the emitted photoelectrons.

2 (a) Calculate the **work function (in eV)** for a magnesium surface if the minimum frequency of electromagnetic radiation which causes photoemission from the metal surface is **8.9×10^{14} Hz.**

(b) If the same surface were illuminated with radiation of wavelength **250 nm**, calculate :

(i) The **maximum kinetic energy,**

(ii) The **maximum velocity,** of the emitted photoelectrons.

(electron mass = **9.11×10^{-31} kg**)

3 When electromagnetic radiation of frequency **1.5×10^{14} Hz** is incident on a metal surface, the maximum kinetic energy of the emitted photoelectrons is found to be **3.8×10^{-20} J.**

Calculate the **work function** of the metal.

4 Photons of electromagnetic radiation having energies of **1.0 eV, 2.0 eV and 4.0 eV** are incident on a metal surface having a work function of **1.7 eV.**

(a) Which of these photons will cause photoemission from the metal surface ?

(b) Calculate the **maximum kinetic energies (in eV and J)** of the liberated electrons in each of those cases where photoemission occurs.

5 A vacuum photocell connected to a microammeter is illuminated with light of varying wavelength.

(a) **Explain** why :

(i) A photoelectric current is registered on the microammeter when light of a certain wavelength is incident on the photocell.

(ii) The current is found to increase when the light intensity is increased.

(b) When the incident light wavelength is increased, the photoelectric current falls to zero.

Explain why : (i) The current falls to zero.

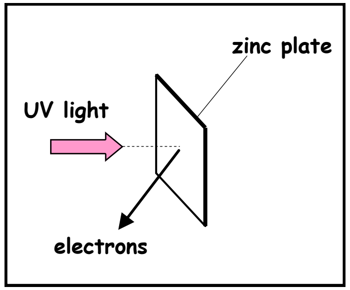
(ii) The current would still be zero if the light wavelength is kept the same and the intensity is increased.

UNIT G482	Module 5	2.5.2	The Photoelectric Effect

- **HOMEWORK QUESTIONS**

1 The diagram shows a zinc plate exposed to weak ultraviolet (UV) light.

The UV light causes electrons to be emitted from the surface of the plate.



(a) **Name** this phenomenon.

(b) Initially, the plate is **neutral** in charge. **State** and **explain** the effect on the charge of the plate as the zinc plate is exposed to the UV light.

(c) **State** and **explain** the effect on the **rate of emission of electrons** when the **intensity** of the UV light **is increased.**

(d) In a databook, the **work function energy** of zinc is quoted as 4.24 eV. **Explain** what is meant by work function energy (no calculations are necessary).

(OCR AS Physics - Module 2822)

2 (a) Einstein's photoelectric equation may be written as :

$$hf = \Phi + \tfrac{1}{2} mv_{max}^2$$

Identify the terms **hf**, Φ and $\frac{1}{2} mv_{max}^2$.

(b) The surface of sodium metal is exposed to electromagnetic radiation of wavelength **6.5 x10^{-7} m.** This wavelength is the **maximum for which photoelectrons are released.**

(i) Calculate the **threshold frequency.**

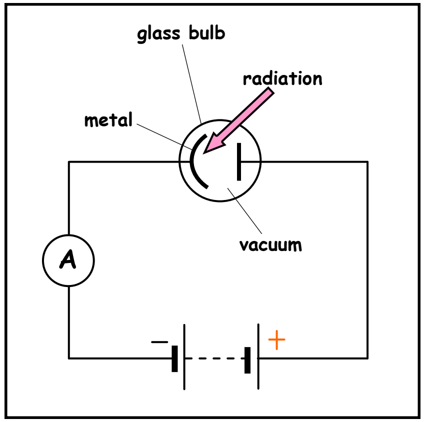
(ii) Show that the work function energy of the metal is **1.9 eV.**

(c) For a particular wavelength of incident light, sodium releases photoelectrons. **State** how the **rate of release of photoelectrons** changes when the **intensity of light is doubled.** **Explain** your answer.

(OCR AS Physics - Module 2822)

3 (a) The concept of the photon was important in the development of physics throughout the last century. **Explain** what is meant by a **photon.**

(b) The diagram shows a photocell. When the metal surface is exposed to electromagnetic radiation, photoelectrons are ejected.



The collector collects the photoelectrons and the sensitive ammeter indicates the presence of a tiny current.

(i) For a certain frequency and intensity of radiation, the ammeter shows a current of **1.2 x 10^{-7} A.** Calculate :

1. The **charge** reaching the collector in **5.0 s.**
2. The **number of photoelectrons** reaching the collector in **5.0 s.**

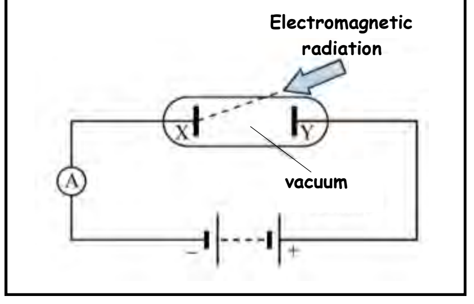
(ii) The work function energy of the metal is **3.5×10^{-19} J** and the incident radiation has a frequency of **7.0×10^{14} Hz.** Calculate the **maximum kinetic energy** of an ejected photoelectron.

(iii) The intensity of the incident radiation is **doubled,** but the wavelength is **kept constant. State** the effect this has on each of the following :

1. The **energy of each photon.**
2. The **maximum kinetic energy of each photoelectron.**
3. The **current in the photocell.**

(OCR AS Physics - Module 2822)

4 The diagram shows an electric circuit including a photocell. The photocell contains a metal plate **X** that is exposed to electromagnetic radiation. Photoelectrons emitted from the surface of the metal are accelerated towards the positive electrode **Y**. A sensitive ammeter measures the current in the circuit due to the photoelectrons emitted by the metal plate **X**.

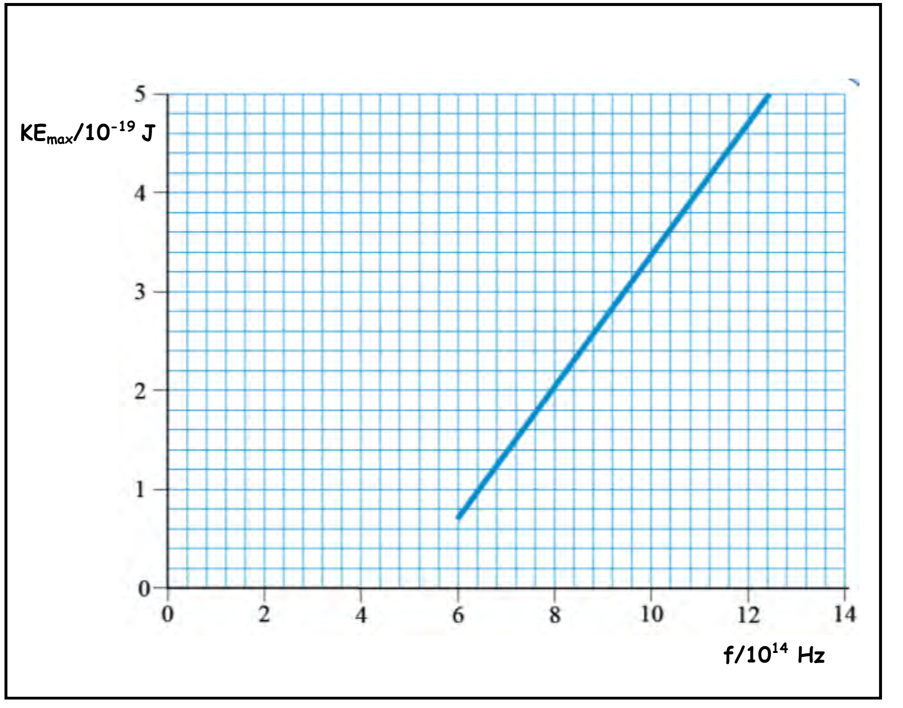


The metal plate X has a work function of **2.2 eV**. The maximum kinetic energy of an emitted photoelectron from this plate is **0.3 eV**.

(a) Calculate the **energy of a single photon** : (i) in **eV** (ii) in **joules**.
(b) Calculate the **frequency** of the incident electromagnetic radiation.
(c) Deduce the effect on the **current** if the radiation has the **same intensity,** but the **frequency is greater than in (b).**

(OCR AS Physics - Module 2822 - June 2004)

5 A negatively charged metal plate is exposed to electromagnetic radiation of frequency **(f).** The diagram below shows the variation with **(f)** of the maximum kinetic energy **KE_{max}** of the photoelectrons emitted from the surface of the metal. **8**



(a) Define the **THRESHOLD FREQUENCY** of a metal.

(b) (i) Explain how the graph shows that the threshold frequency Of this metal is **5.0×10^{14} Hz.**

(ii) Calculate the **work function** of this metal **in joules.**

(OCR AS Physics - Module 2822 - January 2006)