HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER
OPTO-ELECTRONICS
## 2) QUANTUM THEORY and THE PHOTOELECTRIC EFFECT

You must be able to:

- State that electromagnetic radiation can be regarded as a stream of tiny, individual "wave packets" called photons.

- State that each photon of electromagnetic radiation has an energy $E = hf$ where h is Planck's constant and f is the frequency of the radiation.

- Solve problems involving the above relationship.

- State that the irradiance (I) of electromagnetic radiation falling on a surface is given by the equation $I = Nhf$ where N is the number of photons per second falling on every square metre of the surface, h is Planck's constant and f is the frequency of the radiation.

- Solve problems involving the above relationship.

- Explain the photoelectric effect in terms of photons and emitted electrons.

- Describe an experiment to show that photoelectric emission occurs when the frequency of the incident electromagnetic radiation is sufficiently high and that increasing the irradiance of the incident electromagnetic radiation increases the photoelectric emission.

- Describe the energy conversion taking place in the photoelectric effect in terms of the equation $hf = hf_o + \frac{1}{2}mv^2$ where hf is the energy of the incident photon, hf_o is the work function of the metal and $\frac{1}{2}mv^2$ is the maximum kinetic energy of the emitted electron.

- Solve problems involving the above relationship.

1) CLASSICAL WAVE THEORY

We have seen that **electromagnetic energy** (such as **light**) behaves as a __continuous wave__ - It can be **reflected**, **refracted** and **diffracted**. More importantly, it can produce **interference** (which is the test for wave motion).

A **continuous electromagnetic wave** is shown:

λ

Amplitude - The greater the amplitude, the greater the wave energy.
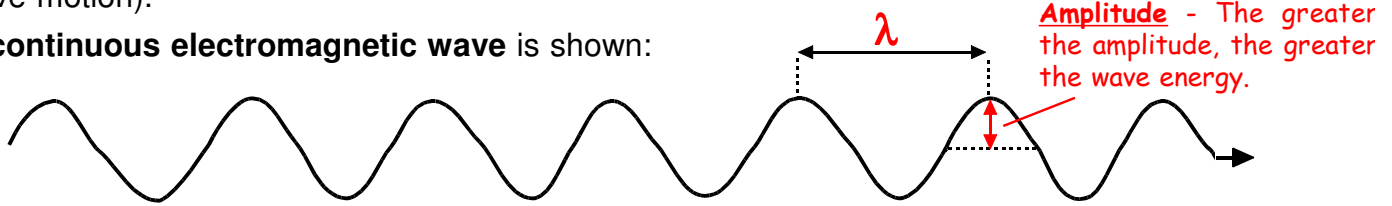
Such a **continuous electromagnetic wave** has a **velocity** (**v**) of 3 x 10^8 m s^{-1} in air, a **frequency** (**f**) measured in **hertz** and **wavelength** (λ) measured in **metres**.

The equation $v = f \lambda$ applies to the wave.

2) QUANTUM THEORY

In the early years of the 20 th century (about 100 years ago), scientists **Max Planck** and **Albert Einstein** proposed an alternative theory for **electromagnetic energy** - The __quantum theory__:

Max Planck
Clipart copyright S.S.E.R. Ltd

Albert Einstein
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Electromagnetic energy is a stream of tiny, individual "**wave packets**" called __quanta__ or __photons__:

λ
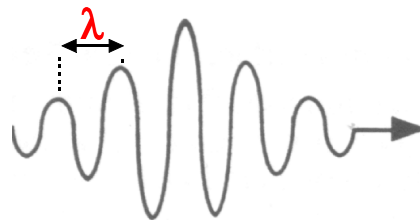
A photon of electromagnetic energy

As with **classical wave theory**, each **photon** has a **velocity** (**v**) of 3 x 10^8 m s^{-1} in air, a **frequency** (**f**) measured in **hertz** and **wavelength** (λ) measured in **metres**.

The equation $v = f \lambda$ applies to each **photon**.

However, the energy of a photon does not depend on amplitude.

The **energy** (**E**) of a **photon** is directly proportional to its **frequency** (**f**):

$$E \ \alpha \ f \qquad \text{or} \qquad E = constant \times f$$

The constant is named after Max Planck (**Planck's constant**) and is given the symbol **h**:

energy of photon $\leftarrow$ **E = h f** $\rightarrow$ frequency of photon
(unit: J)   (unit: Hz)

Planck's constant = 6.63 x 10^{-34} J s

Example

In air, a photon of **yellow** light has a wavelength of 589 nm (i.e., 589 x 10^{-9} m).

Calculate: (a) the **frequency** of the photon;   (b) the **energy** of the photon.

(a) $v = f\lambda$, so $f = \dfrac{v}{\lambda} = \dfrac{3 \times 10^8}{589 \times 10^{-9}}$ = **5.09 x 10^{14} Hz.**   (b) E = hf = $(6.63 \times 10^{-34}) \times (5.09 \times 10^{14})$

= **3.37 x 10^{-19} J.**

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1) In air, a photon of blue light has a wavelength of 480 nm (i.e., 480 x 10^{-9} m).
   Calculate:
   (a) the frequency of the photon;   **(b) the energy of the photon.**

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2) (a) Calculate the energy, in air, of a photon of:
   (i) red light;   **(ii) green light;**   **(iii) violet light.**
      (wavelength 700 nm)   **(wavelength 540 nm)**   **(wavelength 400 nm)**

   (b) In the visible spectrum, which colour of light has the highest energy?

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3) A photon of ultraviolet radiation has a frequency of 7.69 x 10^{14} Hz in air. Calculate the energy of this photon in air:

4) In air, a photon of infra-red radiation has an energy of 1.99 x 10^{-20} J. Calculate the frequency of this photon in air:

Irradiance of Electromagnetic Radiation

The **irradiance** (**I**) of electromagnetic radiation falling on any surface is given by the equation:

irradiance of radiation
(unit: W m^{-2})

$$I = N h f$$

frequency of radiation
(unit: Hz)

number of photons per second falling on every square metre of surface

Planck's constant = 6.63×10^{-34} J s

1) Every second, 2×10^{19} photons of light with a frequency of 7.5×10^{14} Hz fall on each square metre of a floor. Calculate the <u>irradiance</u> of the light on the floor.	2) How many photons per second fall on 1 m^2 of a table that is being illuminated by a lamp producing light of irradiance 8 W m^{-2} and frequency 4.5×10^{14} Hz?

3) THE PHOTOELECTRIC EFFECT

WORK FUNCTION

On the surface of metals, there are tiny particles called electrons.
The electrons are held on the metal surface by attractive forces.

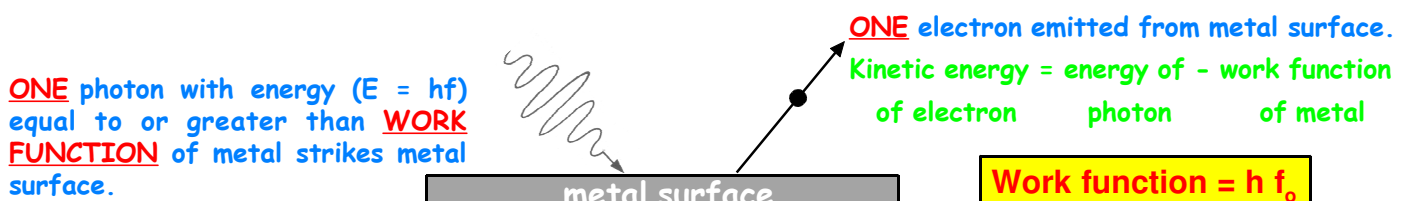If an electron is to escape from the metal surface, it must overcome these attractive forces.

The <u>work function</u> of a metal is the energy which must be supplied to enable an electron to escape from the metal surface.

PHOTOELECTRIC EFFECT / PHOTOELECTRIC EMISSION

If <u>one</u> photon of electromagnetic energy (**E = hf**) strikes a metal surface, it causes <u>one</u> electron to be emitted from the metal surface <u>if the photon's energy</u> (**hf**) <u>is equal to or greater than the</u> **work function** <u>of the metal</u>, part of the photon's energy being used to enable the electron to escape. The rest of the photon's energy is given to the emitted electron as **kinetic energy**. The photon then no longer exists - This is known as the **photoelectric effect** and the emission of the electron is known as **photoelectric emission** or **photoemission**.
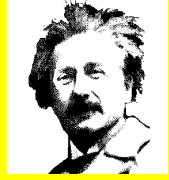
THRESHOLD FREQUENCY (f_o)

A photon must have a minimum energy equal to the **work function** of a metal <u>and hence a</u> **minimum frequency** (f_o) to emit an electron from the metal surface. This **minimum frequency** (f_o) is called the **threshold frequency** for the metal. Each metal has its own unique value of **threshold frequency** (f_o).
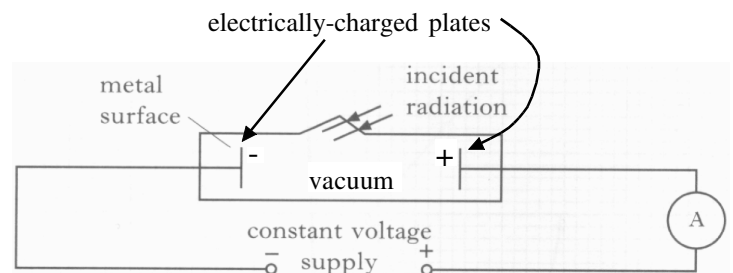
ONE photon with energy (E = hf) equal to or greater than <u>WORK FUNCTION</u> of metal strikes metal surface.

ONE electron emitted from metal surface.
Kinetic energy = energy of − work function
of electron   photon   of metal

metal surface

Work function = h f_o

Photoelectric emission is described by
EINSTEIN'S PHOTOELECTRIC EQUATION:

Energy of photon striking metal surface = **Energy needed to eject electron from metal surface (work function of metal)** + **Kinetic energy given to emitted electron**

$$h f = h f_o + \tfrac{1}{2} m v^2$$

Planck's constant = 6.63×10^{-34} J s

frequency of photon

Planck's constant = 6.63×10^{-34} J s

threshold frequency (minimum frequency photon must have to eject electron)

mass of electron = 9.11×10^{-31} kg

maximum velocity of electron

This apparatus is used to investigate the **photoelectric effect**:

When electromagnetic radiation of sufficient energy/frequency strikes the metal surface, electrons are emitted from the metal surface (1 electron per photon). The emitted electrons are attracted to the positively-charged plate through the vacuum (there are no air molecules to stop them) - An electric current (known as a **photoelectric current**) is thus created in the circuit, so the ammeter displays a current reading. [The constant voltage supply is used to give the plates inside the vacuum their - and + electric charge].

electrically-charged plates

metal surface

incident radiation

vacuum

constant voltage supply

A

Changing Frequency of Electromagnetic Radiation

Photoelectric current/ A

constant irradiance

sodium

calcium

0 f_o sodium f_o calcium   Frequency of radiation/ Hz
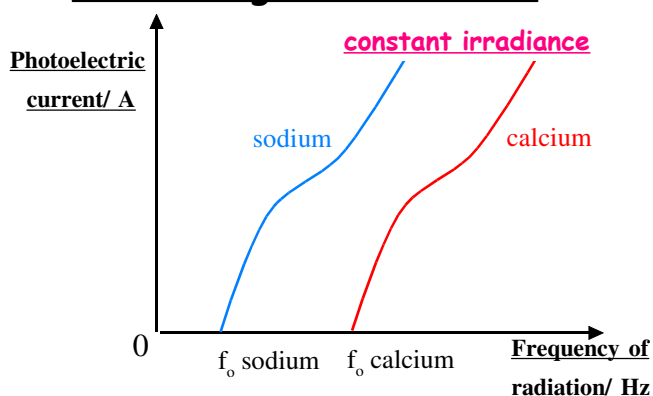
Below a certain frequency [the **threshold frequency (f_o)**], no electrons are emitted from the metal surface - There is no photoelectric current.

As the frequency (and hence energy) of the radiation is increased **above** the **threshold frequency** (f_o), more electrons are emitted - the photoelectric current increases.

Different metals produce different curves - Each metal has its own unique value of **threshold frequency** (f_o).

Changing Irradiance of Electromagnetic Radiation

Photoelectric current/ A

constant frequency above threshold frequency

0   Irradiance of radiation/ W m^{-2}
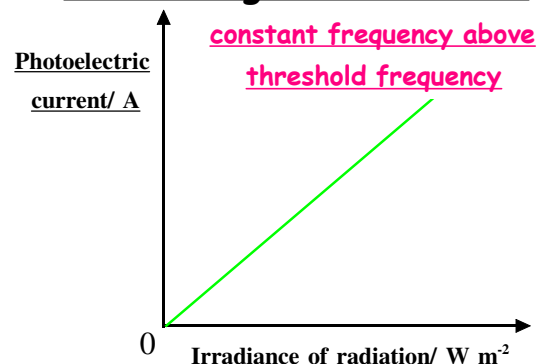
If the frequency of the radiation is high enough to cause emission of electrons from the metal surface, **more electrons are emitted as the irradiance of the radiation is increased** - **The photoelectric current is directly proportional to the irradiance of the radiation**.

Laboratory Demonstration of the Photoelectric Effect
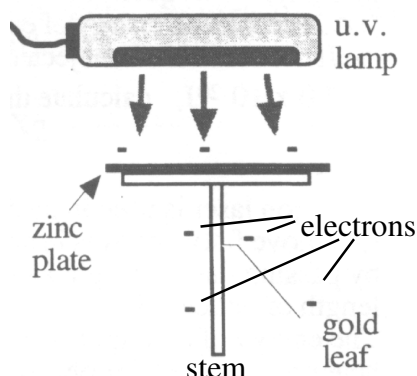
A gold leaf electroscope (with a zinc plate on top) is negatively-charged - The zinc plate, stem and gold leaf are all covered with negatively-charged electrons, so the gold leaf is repelled (pushed away) by the stem.

When photons of ultra-violet radiation are shone onto the zinc plate, the photons have sufficient energy to eject electrons from the surface of the zinc - The photons have energy higher than the work function of zinc.

The electrons on the zinc surface escape into the air and are replaced by the electrons from the stem and gold leaf - The gold leaf is no longer repelled by the stem, so it falls.

If the irradiance of the ultra-violet radiation is increased, the gold leaf falls faster because more ultra-violet photons strike the zinc plate, so electrons are emitted from the zinc faster.

If white light (which contains photons of all 7 colours of the visible spectrum - red, orange, yellow, green, blue, indigo and violet) is shone onto the zinc plate, the gold leaf does not fall. Photons of these colours of light do not have high enough energy to eject electrons from the zinc surface - The photons of these colours of light have energy lower than the work function of zinc.

If the zinc plate is replaced with a tin plate, and photons of ultra-violet or white radiation are shone onto the tin, the gold leaf does not fall - Photons of ultra-violet or white radiation have a lower energy than the work function of tin, so no electrons are emitted from the tin.

If the gold leaf electroscope is positively-charged, the gold leaf does not fall when the metal plate is illuminated by electromagnetic radiation of high enough energy/frequency because the stem and gold leaf lack electrons, so cannot replace the electrons emitted from the metal plate.
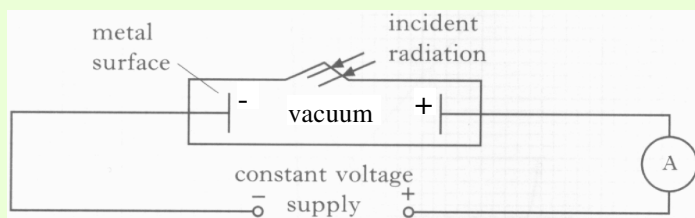
1) Explain the following terms:

(a) work function of a metal:

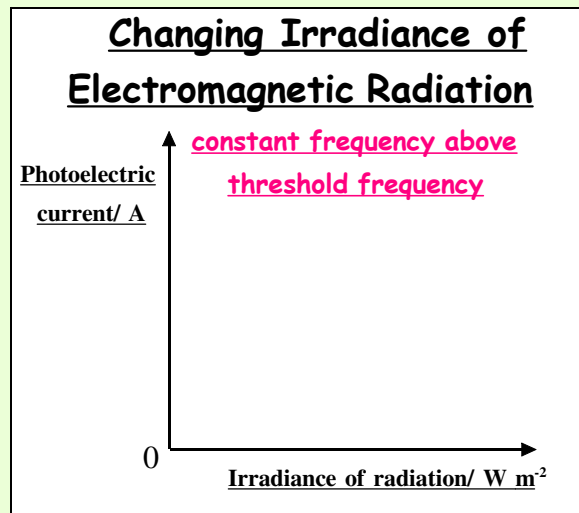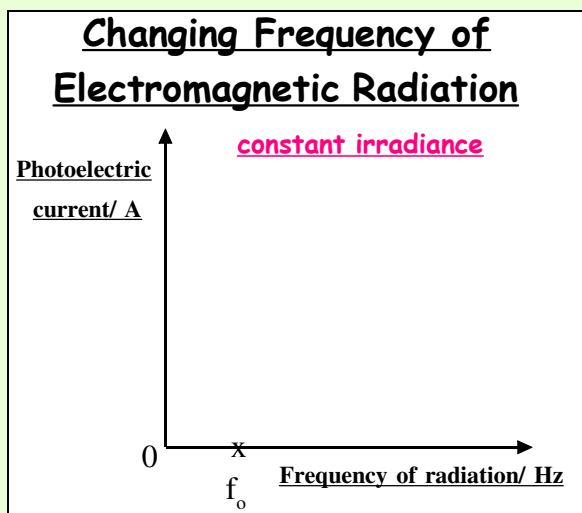### (b) photoelectric emission - INCLUDE A LABELLED DIAGRAM:

(c) threshold frequency:

2) **This apparatus is used to investigate the <u>photoelectric</u> effect.**

The metal used is caesium, which emits electrons when electromagnetic radiation of a frequency equal to or above 4.59 x 10¹⁴ Hz strikes it.

metal surface / incident radiation / vacuum / constant voltage supply / A

(a) Complete the following graphs:

<u>Changing Frequency of Electromagnetic Radiation</u>

constant irradiance

Photoelectric current/ A

0   x f_o Frequency of radiation/ Hz

<u>Changing Irradiance of Electromagnetic Radiation</u>

constant frequency above threshold frequency

Photoelectric current/ A

0   Irradiance of radiation/ W m⁻²

(b) Why are no electrons emitted from the caesium metal when photons of frequency <u>below</u> f_o strike its surface? _____

_____

_____

(c) Explain why increasing the irradiance of the electromagnetic radiation increases the number of electrons emitted from the caesium surface:

_____

_____

_____

(d) Calculate the <u>work function</u> of the caesium metal:

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3) **What frequency of photon is required to <u>just</u> <u>release</u> an electron from the surface of a metal that has a work function of 4.5 x 10⁻¹⁹J?**

4) **A metal has a work function of 2.16 x 10⁻¹⁹ J. Calculate the minimum frequency a photon must have in order to emit an electron from the metal surface.**

5) Write down EINSTEIN'S PHOTOELECTRIC EQUATION in words and symbols:

6) When a photon of electromagnetic radiation of frequency 7.5×10^{14} Hz strikes a metal surface, an electron is ejected from the metal surface with a maximum kinetic energy of 1.6×10^{-19} J.
Calculate the work function of this metal.

7) The work function of metal X is 1.5×10^{-20} J.

(a) A photon of frequency 3.0×10^{13} Hz strikes the surface of metal X, causing one electron to be emitted from the metal surface.
Determine the maximum kinetic energy of this emitted electron.

(b) Calculate the maximum velocity of the emitted electron.