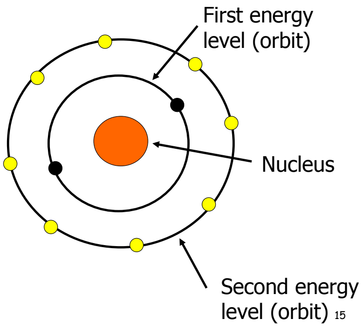
THE PHOTOELECTRIC EFFECT 18 AUGUST 2015

Section A: Summary Notes

The photoelectric effect is the process that occurs when electromagnetic radiation (light) shines on a metal surface and ejects electrons from the metal

In order to understand the photoelectric effect and spectra, we need to remind ourselves of Bohr's atomic model.



According to Bohr's model

- More than 1 electron could move in each orbit.
- Electrons release and absorb energy as they move between energy levels.
- Electrons move as waves within the orbitals.

Light has a **wave nature** which is shown by its ability to be reflected, refracted and diffracted.

Light also has a **particle nature**. The particles in light are called **photons**. The energy (**E**) of each photon is given by:

E = hf where **h** = Plank's constant = $6{,}63 \times 10^{-34}$ J.s ;

f = frequency of the light used

When a photon of high enough energy collides with an electron near the surface of a metal, it transfers all its energy to the electron. If there is enough energy for that particular metal, then the electron that the photon collided with, is knocked out of the metal.

If there is not quite enough energy to remove the electron from the metal, then the energy excites electrons into the next energy level, which then fall back emitting energy (the metal looks shiny).

Metal energy levels are close together and metal electrons are delocalised and can, therefore, be relatively easily removed from the lattice.

- Work is done in removing an electron from the surface of a metal. **The minimum amount of energy needed to remove an electron from the metal is called the Work function (W_o).** The corresponding frequency is called the cut-off or threshold frequency; and it is defined as the minimum frequency of radiation at which electrons will be ejected from the surface of a metal. This cut-off frequency depends on the type of metal used.

$W_o = hf_o$	W_o = work function of a metal (J) h = Plank's constant = $6{,}63 \times 10^{-34}$ J.s f_o = cut-off frequency of metal (Hz)
$c = f\lambda$	c = speed of light = 3×10^8 m.s^{-1} f = frequency of light (Hz) λ = wavelength (m)

The cut-off frequency is the minimum frequency of the light that can eject an electron from a certain metal.

The number of electrons ejected per second increases with the intensity of the incident radiation (light).

If the frequency of the incident radiation is below the cut-off frequency, then increasing the intensity of the radiation has no effect i.e. it does not cause electrons to be ejected.

If light with a frequency greater than the cut-off frequency is shone on the metal then the ejected electrons will have extra energy in the form of kinetic energy (E_k). These electrons will escape the surface of a metal with maximum kinetic energy (E_{kmax}).

Photon energy = Work function + maximum kinetic energy of electron

The photoelectric equation can be represented as follows:

$$E = W_o + E_{k\,max}$$

$$hf = hf_o + \frac{1}{2} mv_{max}^2$$

E = energy of the photon (J)

W_o = work function (J)

$E_{k\,max}$ = maximum kinetic energy of ejected electron (J)

h = Planck's constant = 6,63 x 10^{-34} J.s

f = frequency of light (Hz)

f_o = cut-off frequency of metal (Hz)

m = mass of electron = 9,11 x 10^{-31} kg

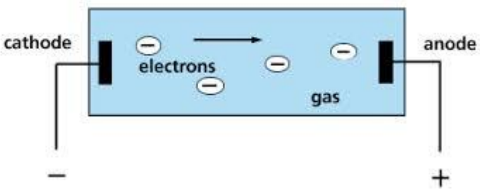
v_{max} = maximum speed of ejected electron ($m.s^{-1}$)

CONTINUOUS EMISSION SPECTRUM

The continuous emission spectrum is obtained when pure white light is passed through a triangular glass prism. The light is dispersed (split) into its component visible colours; often referred to as the rainbow.

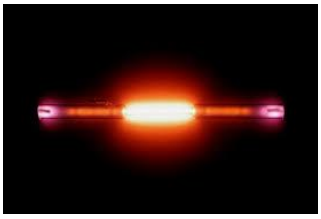
GAS DISCHARGE TUBE

A gas discharge tube is a transparent tube containing gas at low pressure. When a high voltage is applied across the electrodes, some electrons accelerate towards the anode and the atoms become positive ions. When the positive and negative charges recombine, photons of light are emitted.



A gas discharge tube

Each gas discharge tube contains atoms or molecules of a particular element. When a high voltage is applied across the electrodes, the light emitted by an element in a gas discharge tube can be seen.



A gas discharge tube emitting light

ATOMIC LINE EMISSION SPECTRUM

If the light emitted by a gas discharge tube containing a gas (e.g. hydrogen) is passed through a prism, the spectrum produced is no longer continuous but it is a line emission spectrum. It consists of a number of separate coloured lines.

The line spectrum of an element is characteristic of that element and can be used to identify that element. It is almost like a ‘fingerprint’ for the element. Only certain colours which correspond to specific frequencies of light are present in a line emission spectrum. Each colour in the line emission spectrum results from the emission of an electromagnetic wave of a particular frequency. In other words, every single element emits its own unique line emission spectrum.

So using E = hf we can deduce that each line represents photons of a different energy. The energy is released as electrons fall from a high energy level to a lower energy level.

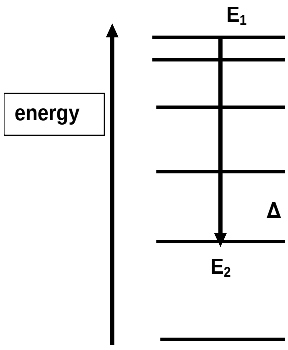


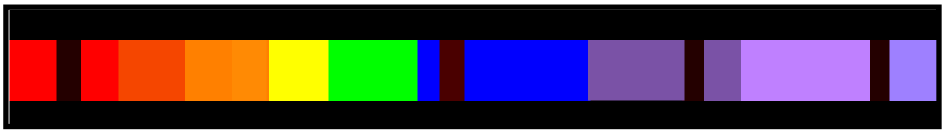
Diagram showing the energy levels in an atom

When the electron in a hydrogen atom is in the orbital closest to the nucleus, it possesses the least amount of energy. This is called the “ground state”.

An electron in an energy level further from the nucleus than it normally occupies, is said to be in the ‘excited state’.

Movement between orbitals causes energy to be released and absorbed. We see this as absorption and emission spectra

LINE ABSORPTION SPECTRA

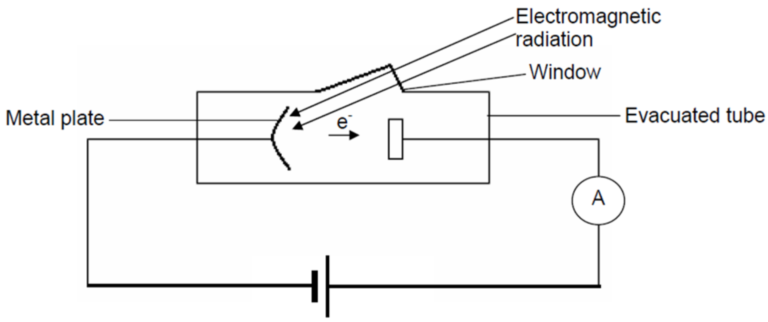


A line absorption spectrum is formed when white light is passed through a cold gas before being shone through a prism or a diffraction grating. The black lines represent wavelengths of light that have been absorbed by the gas. The frequency of the lines in the emission spectrum of an element is exactly the same as those of the missing lines in the absorption spectrum. Notice that the energy released and absorbed is at distinct positions.

Section B: Practice Questions

Question 1 *(Taken from November 2009(1))*

The diagram below shows a metal a plate that emits electrons when a certain frequency of electromagnetic radiation is incident on it. The plate is connected to a source of potential difference and an ammeter as shown in the circuit below.



1.1. Name the phenomenon described above. (1)

When radiation of wavelength 555 nm is incident on the metal plate, electrons are released with zero kinetic energy.

1.2. Define the term *work function* of a metal. (2)

1.3. Calculate the work function of this metal. (6)

1.4. How will the reading on the ammeter change if the intensity of the electromagnetic radiation is increased? Write down only INCREASES, DECREASES or REMAINS THE SAME.

Give a reason for your answer. (3)

1.5. Incident radiation with a longer wavelength is now used. How will the reading on the ammeter change? Write down only INCREASES, DECREASES or REMAINS THE SAME.

(1)

[13]

Question 2 *(Taken from Feb – March 2010)*

During an experiment to determine the work function of a certain light of different frequencies was shone on the metal surface and the corresponding kinetic energies of the photoelectrons were recorded as shown in the table below.

Frequency of incident light (x 10^{14} Hz)	Kinetic energy of photoelectrons (x 10^{-19} J)
6,6	0,7
8,2	1,6
9,2	2,2
10,6	3,0
12,0	3,8

2.1. Define the term work function. (2)

2.2. Use the date in the table above to draw a graph of kinetic energy versus frequency on the graph paper provided. (6)

2.3. Extrapolate your graph to cut the x-axis.

2.3.1. What is the frequency at the point of intercept? (2)

2.3.2. What term is used to describe this frequency? (1)

2.4. Use your graph to determine the work function of the metal. (3)

[14]

Question 3 *(Taken from DoE November 2010)*

A certain metal has a work function of 3,84 x 10^{-19} J. The surface of the metal is irradiated with ultraviolet light of wavelength 200 nm causing photoelectrons to be emitted.

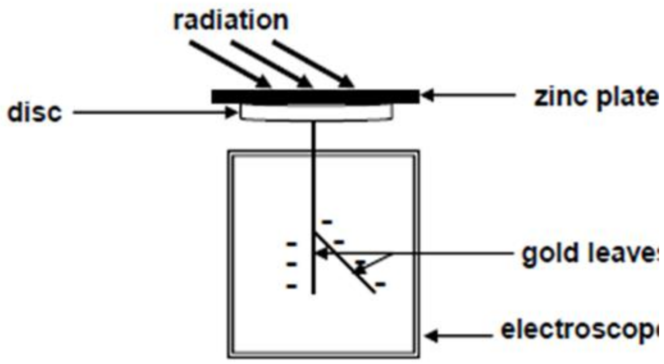
3.1. Calculate the energy of a photon of ultraviolet light. (4)

3.2. Calculate the maximum velocity of the emitted photoelectrons. (4)

[8]

Question 4 *(Taken from DoE Feb – March 2011)*

4.1. A group of learners perform an investigation to compare the effect of two types of radiation on the emission of photoelectrons from zinc. They place a zinc plate on top of the disc of a negatively charged electroscope. Ultraviolet and red light are shone alternately onto the zinc plate as shown below, with the electroscope fully charged in each case.



They record the following observations:

Radiation	Observation
Ultraviolet light	Gold leave collapse
Red light	No effect on the deflection of gold leaves

4.1.1. Write down an investigative question for this investigation. (2)

4.1.2. Explain the observation made for ultraviolet light. (3)

4.1.3. What conclusion can be drawn from this investigation? (2)

4.2. The learners have access to the following information:

Work function of zinc	$6,88 \times 10^{-19}$ J
Frequency of ultraviolet light	$7,89 \times 10^{14}$ Hz
Frequency of red light	$4,39 \times 10^{14}$ Hz

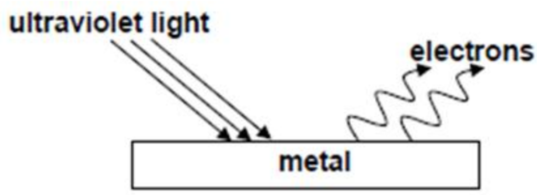
4.2.1. Define the term work function of a metal. (2)

4.2.2. Use a calculation to explain why red light fails to emit photoelectrons from the surface of the zinc plate. (4)

[13]

Question 5 *(Taken from DoE November 2011)*

A metal surface is illuminated with ultraviolet light of wavelength 330 nm. Electrons are emitted from the metal surface. The minimum amount of energy required to emit an electron from the surface of this metal is $3,5 \times 10^{-19}$ J



5.1. Name the phenomenon illustrated above. (1)

5.2. Give one word or term for the underlined sentence in the above paragraph. (1)

5.3. Calculate the frequency of the ultraviolet light. (4)

5.4. Calculate the kinetic energy of a photoelectron emitted from the surface of the metal when the ultraviolet light shines on it. (4)

5.5. The intensity of the ultraviolet light illuminate the metal is now increased. What effect will this change have on the following:

5.1.1. Kinetic energy of the emitted photoelectrons. (Write down only INCREASES, DECREASES or REMAINS THE SAME) (1)

5.1.2. Number of photoelectrons emitted per second (Write down only INCREASES, DECREASES or REMAINS THE SAME) (1)

[12]

Section C: Solutions

Question 1

1.1. Photo electric effect ✓ (1)

1.2. The minimum energy of light needed to emit electrons from a metal ✓✓ (2)

1.3. $W_o = hf_o$ ✓

$= \frac{hc}{\lambda}$ ✓

$= \frac{(6{,}63 \times 10^{-34}) ✓ (3 \times 10^{8})}{555 \times 10^{-9} ✓}$ ✓

$= 3{,}58 \times 10^{-19} J$ ✓ (6)

1.4. Increases ✓

With light of higher intensity more photons strikes the metal surface per second ✓

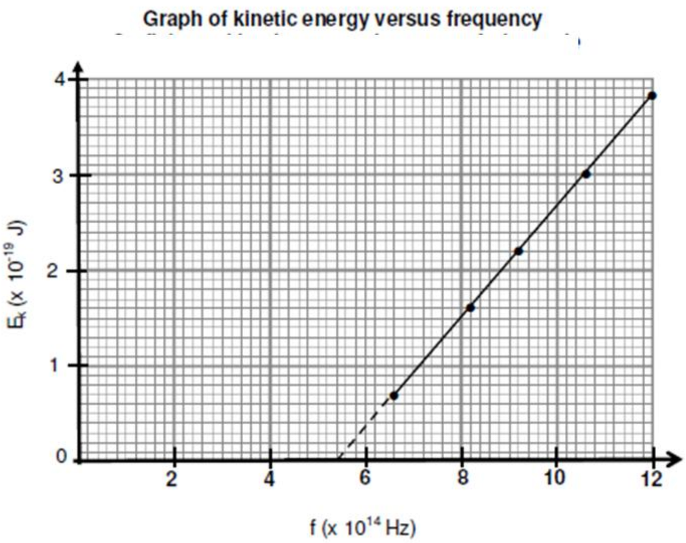
Thus more electrons are emitted per second resulting in a bigger current. ✓ (3)

1.5. Decreases ✓ (1)

Question 2

2.1. Minimum amount of energy needed to remove an electron from the surface of a metal / conducting material. ✓✓ (2)

2.2.



Criteria for graph

- *Relevant heading* ✓
- *Axes labelled correctly with units* ✓
- *Appropriate scale* ✓
- *Plotting all the points* ✓✓
- *Line of best fit* ✓ (6)

2.3.1 $f_o = 5{,}4 \times 10^{14}$ Hz ✓✓ (2)

2.3.2. Cut-off frequency ✓ (1)

2.4. $W_o = hf_o$ ✓

$= (6{,}63 \times 10^{-34})(5{,}4 \times 10^{14})$ ✓

$= 3{,}58 \times 10^{-19}$ J ✓ (3)

Question 3

3.1. $E = \frac{hc}{\lambda}$ ✓

$= \frac{(6,63 \times 10^{-34})(3 \times 10^{8})✓}{(200 \times 10^{9})✓}$

$= 9,95 \times 10^{-19}\ J$ ✓ (4)

3.2. $E = W_o + E_k$ ✓

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

$9,95 \times 10^{-19}$ ✓ $= (3,84 \times 10^{-19}) + \frac{1}{2}(9,11 \times 10^{-31})v^2$ ✓

$(4,555 \times 10^{-31})v^2 = 6,11 \times 10^{-19}$

$\therefore\ v^2 = 1,341 \times 10^{12}$

$\therefore v = 1,16 \times 10^{6}\ m.s^{-1}$ ✓ (4)

Question 4

4.1.1. ***Examples:***

- *Which type of radiation will emit photoelectrons from zinc?*
- *Which one of red light or ultraviolet light will emit photoelectrons from zinc?* (2)

4.1.2. Ultraviolet light emits photoelectrons from the zinc plate. ✓
Electrons in the gold leaves move upward ✓(into the disc of the electroscope due to the shortage of electrons)
Less negative charges in gold leaves ✓(less repulsion between the gold leaves) (3)

4.1.3. Only ultraviolet light will eject photoelectrons from the surface of the zinc ✓✓ (2)

4.2.1. The minimum energy needed ✓by an electron (in a metal) to be emitted from the metal's surface. ✓ (2)

4.2.2. E = hf ✓

$= (6,63 \times 10^{-34})(4,49 \times 10^{14})$ ✓

$= 2,84 \times 10^{-19}$ J ✓

$E < W_o$ therefore no electrons are emitted ✓ (4)

Question 5

5.1. Photoelectric effect ✓ (1)

5.2. Work function ✓ (1)

5.3. $c = f\lambda$ ✓

3×10^{6} ✓$= f(330 \times 10^{-9})$ ✓

$\therefore$ $f = 9,09 \times 10^{14}$ Hz ✓ (4)

5.4.

$$E = W_o + E_{k_{max}} ✓$$

$$hf = W_o + E_{k_{max}}$$

$$(6,63 \times 10^{-34})(9,09 \times 10^{14})✓ = (3,5 \times 10^{-19}) + E_k ✓$$

$$\therefore\ E_k = 2,53 \times 10^{-19} J ✓$$ (4)

5.5.1. Remains the same ✓ (1)

5.5.2. Increases ✓ (1)