Western Cape Government

CTSC
CapeTownScienceCentre

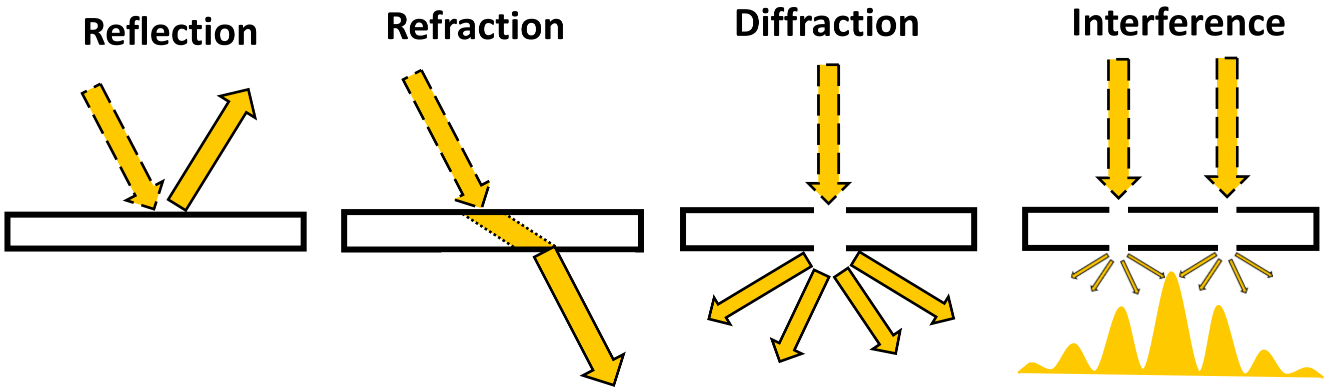
PHOTO-ELECTRIC EFFECT

Developed by the
Cape Town Science Centre

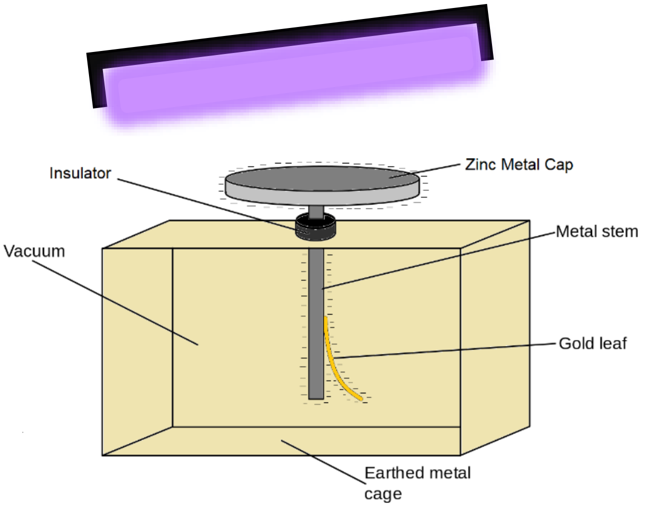
In collaboration with the
Western Cape Education Department

The Dual Nature of Light

In the early 1900s, light was thought to only have a **wave nature**, as it could reflect, refract, diffract and undergo interference.



However this does NOT explain how only certain frequencies of light shone onto a piece of metal would eject electrons.



A gold leaf electroscope, with a zinc metal cap, is given a charge at the beginning of an experiment. This causes the gold leaf to rise.

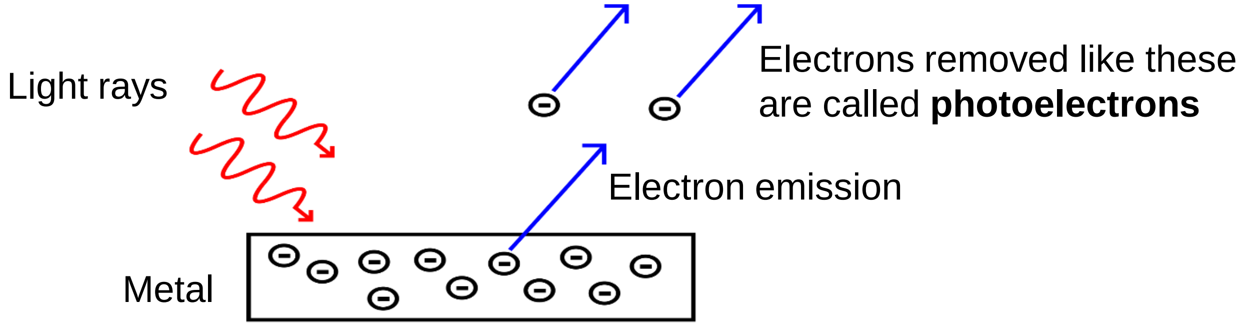
When red and green light is shown onto the zinc plate, no change occurs. However, when a ultraviolet light is shown onto the zinc metal, the gold leaf begins to falls, showing the electroscope is discharging. This is due to electrons being ejected from the zinc plate.

Albert Einstein won the 1921 Nobel Prize in Physics for his discovery of the law of the **Photoelectric Effect** where he presented that light is made up of small '*energy packets'* called **photons**. This showed that light has a **particle nature.**

Therefore light has a **dual nature**. It can be have as **both a particle and as a wave**.

Photoelectric Effect

The process whereby **electrons are ejected from a metal surface** when **light of suitable frequency is incident** on that surface



The photoelectric effect suggested light consists of particles. This changed the scientific understanding of light. It helped to develop the quantum theory of light where light, which consists of photons.

Each photon is a particle which represented quantum of light. They can be though of as '*packets of energy'* called quantum.

The amount of **energy (E)** in a photon is directly proportional to the **frequency (f)** of the light and inversely propotional to the wavelgth of the light (λ) being shown onto the metal .

$$E = hf = h\frac{c}{\lambda}$$

Where

- h is Planck's constant equal to 6,63 x 10^{-34} J.s
- c is the speed of light equal to 3 x 10^{8} m/s

Increasing the intensity (brightness) of the light would only increase the number of photon but not the energy.

The light strikes the metal surface, all the energy is transferred to the atoms in the surface but not all frequencies of light cause electrons to be ejected from the metal surface.

In order for the electron to be released from the atom, the photon must have a minimum amount of energy. This means the light must be of a certain frequency.

The minimum energy that an electron in a metal needs to be emitted from the metal surface is called the **work function (W_O)**

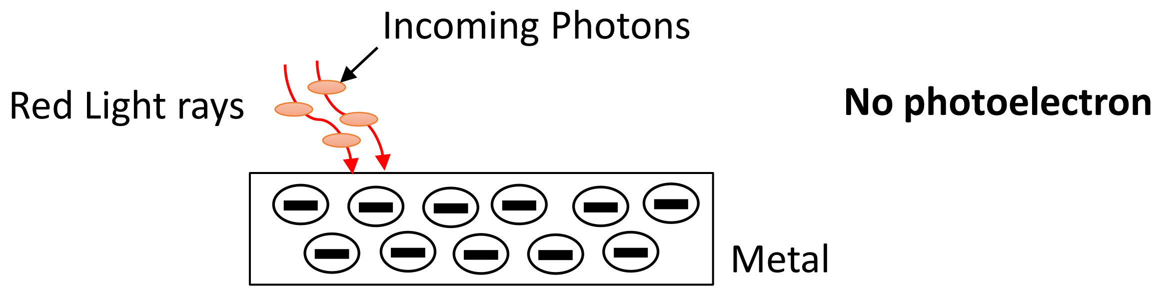
$$W_0 = hf_0$$

The minimum frequency of the incident photon that is required to emit a photoelectron from the surface of the metal is called the **threshold frequency (f_0)**

Photon Energy and Work Function

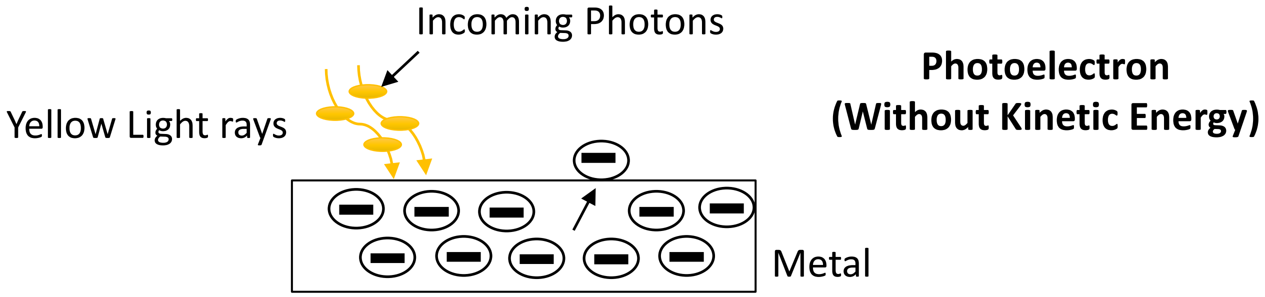
$hf < W_o$

If $hf < W_o$, then the photon does not have enough energy to emit an electron, regardless of the number of photons, their intensity or the duration of exposure, no electron emission would take place.



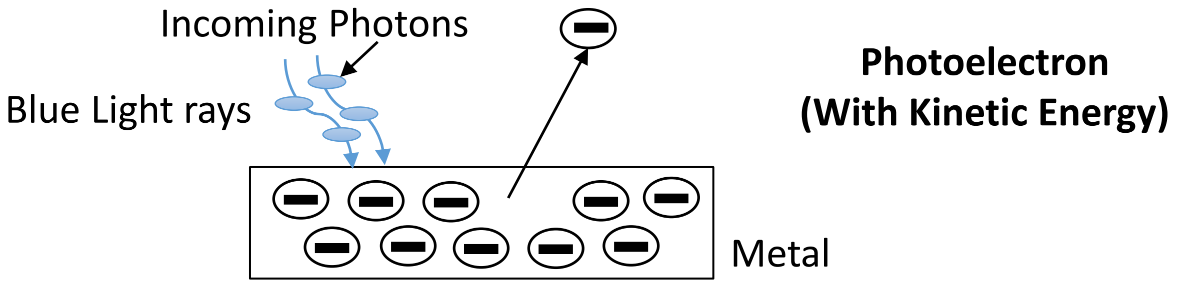
$hf = W_o$

When $hf = W_o$, then an electron will be displaced onto the surface but will not have any kinetic energy. The photoelectron will not move away.



$hf > W_o$

When $hf > W_o$,then the energy transferred to the electron is more than what is needed to emit it. The extra energy is transferred into the kinetic energy of the photoelectron and the photoelectron will move away.



Energy of Photon

The **energy of the photon (E)** can be described using **the threshold energy (W_0)** and the **kinetic energy of the photoelectron (E_k)**. This is because all the energy of the photon is transferred into an electron.

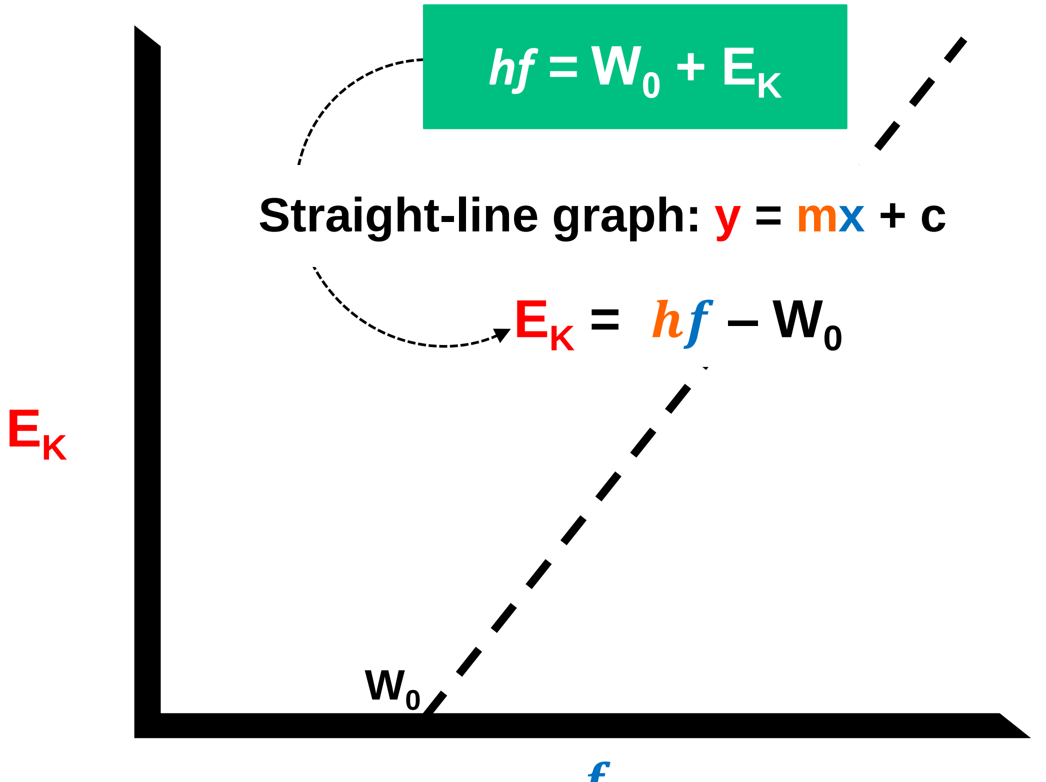
$$E = W_0 + E_K$$

$$hf = W_0 + \frac{1}{2}mv^2$$

Remember

- ***f* is the frequency** which gives the energy of light which is observed as its colour.
- **W_0 is the work-function** which gives the minimum energy needed for the electron to be relsease.
- **E_k is the photoelectron kinetic energy** (max) after the photoelectron has been ejected).

Graphical Representation

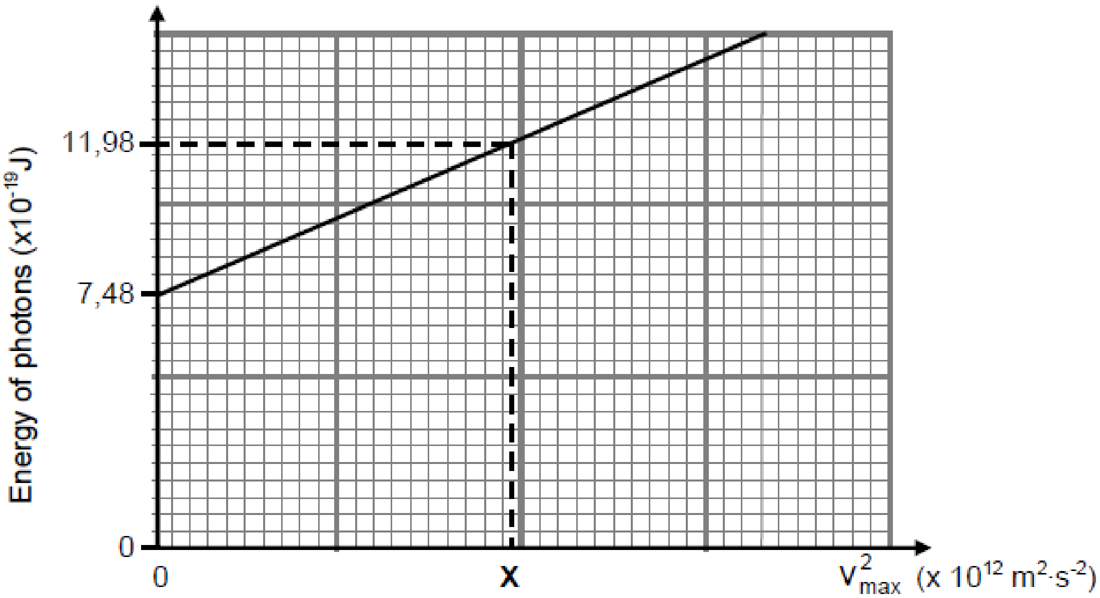


WORKED Exam Question   Paper 1, Oct/Nov 2019, Q.10

During an experiment, light of different frequencies is radiated onto a silver cathode of a photocell and the corresponding maximum speed of the ejected photoelectrons are measured.

A graph of the energy of the incident photons versus the square of the maximum speed of the ejected photoelectrons is shown below.

Graph of energy of photons versus square of maximum speed of photoelectrons



10.1 Define the term *photoelectric effect*.

The process whereby electrons are ejected from a metal / surface when light (of suitable frequency) is incident on that surface.

Use the graph to answer the following questions.

10.2 Write down the value of the work function of silver. Use a relevant equation to justify the answer.

$$E = W_O + E_{K(MAX)} = W_O + \frac{1}{2}mv^2$$

Straight line graph equation: y = mx + c

When v^2 (the x-variable) is zero, then W_o is the y-intercept

Therefore $W_0 = 7{,}48 \times 10^{-19}$ J

10.3 Which physical quantity can be determined from the gradient of the graph?

Mass (of photo-electron)

10.4 Calculate the value of X as shown on the graph.

$E = W_O + \frac{1}{2}mv^2$

$11{,}98 \times 10^{-19} = 7{,}48 \times 10^{-19} + \frac{1}{2}(9{,}11 \times 10^{-31})\,v^2$

$4.5 \times 10^{-19} = 4.56 \times 10^{-31} v^2$

$v^2 = 0{,}9868 \times 10^{12}$

$\therefore X = 0{,}9868$

The experiment above is now repeated using light of higher intensity.

10.5 How will EACH of the following be affected? Choose from INCREASES, DECREASES or REMAINS THE SAME.

10.5.1 The gradient of the graph

Remains the same

10.5.2 The number of photoelectrons emitted per unit time

Increases

PREVIOUS Exam Question — Paper 1, Oct/Nov 2018, Q.11

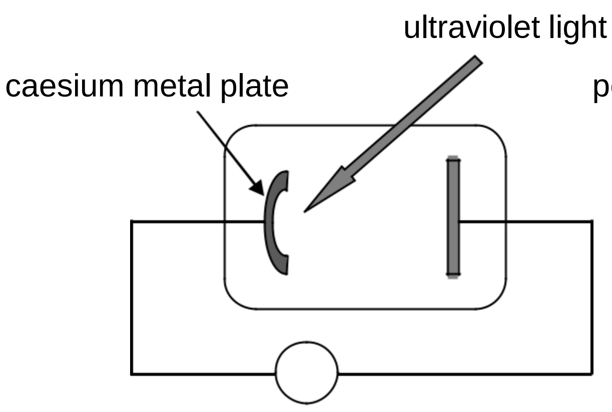
The threshold frequencies of caesium and potassium metals are given in the table below.

METAL	THRESHOLD FREQUENCY
Caesium	$5{,}07 \times 10^{14}$ Hz
Potassium	$5{,}55 \times 10^{14}$ Hz

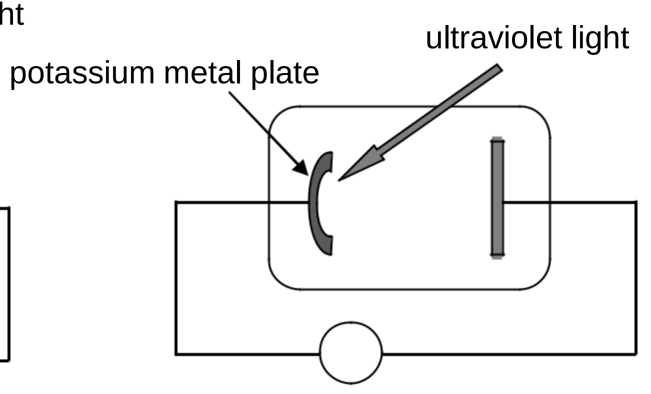
11.1 Define the term *work function* in words. (2)

11.2 Which ONE of the two metals in the table has the higher work function? Give a reason for the answer by referring to the information in the table. (2)

The simplified diagrams below show two circuits, **A** and **B**, containing photocells. The photocell in circuit **A** contains a caesium metal plate, while the photocell in circuit **B** contains a potassium metal plate.



Circuit **A**



Circuit **B**

Ultraviolet light with the same intensity and wavelength of $5{,}5 \times 10^{-7}$ m is incident on the metal plate in EACH of the photocells and the ammeter in circuit **A** registers a current.

11.3 By means of a calculation, determine whether the ammeter in circuit **B** will also register a current. (3)

11.4 Calculate the maximum kinetic energy of an ejected electron in circuit **A**. (5)

11.5 How will the maximum kinetic energy of the ejected electron, calculated in QUESTION 11.4, change when the intensity of the incident light increases?

Choose from: INCREASES, DECREASES or REMAINS THE SAME. (1)

A group of students investigates the relationship between the work function of different metals and the maximum kinetic energy of the ejected electrons when the metals are irradiated with light of suitable frequency.

11.1 Define the term *work function*. (2)

During the investigation ultraviolet rays of wavelength 2 x 10^{-8} m are allowed to fall on different metal plates. The corresponding maximum kinetic energies of ejected electrons are measured.

The data obtained is displayed in the table below.

METAL PLATE USED	MAXIMUM KINETIC ENERGY ($E_{k(max)}$) (x 10^{-18} J)
Lead	9,28
Potassium	9,58
Silver	9,19

11.2 Write down the dependent variable for this investigation. (1)

11.3 Write down ONE control variable for this investigation. (1)

11.4 Using the information in the table, and without any calculation, identify the metal with the largest work function.

Explain the answer. (3)

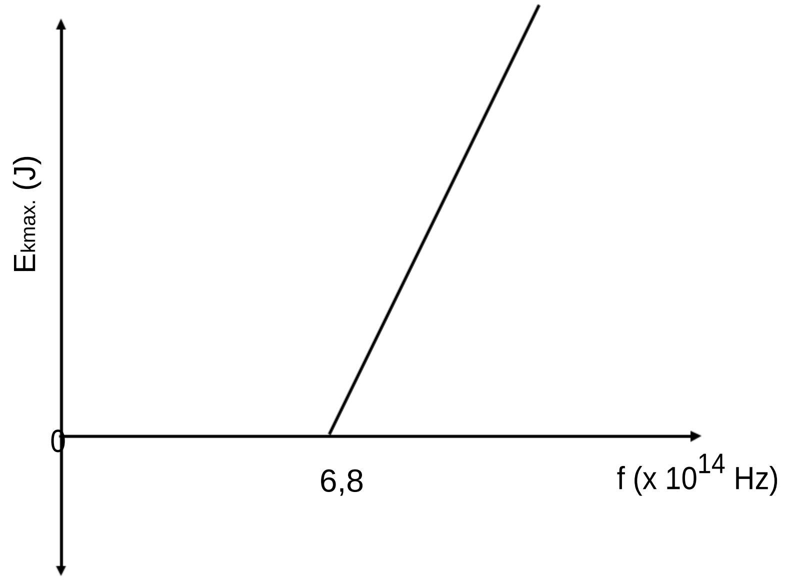
11.5 Use information in the table to calculate the work function of potassium. (4)

11.6 State how an increase in the intensity of the ultraviolet light affects the maximum kinetic energy of the photoelectrons. Choose from: INCREASES, DECREASES, REMAINS THE SAME.

Explain the answer. (3)

PREVIOUS Exam Question — Paper 1, Feb/Mar 2017, Q.10

The graph below is obtained for an experiment on the photoelectric effect using different frequencies of light and a given metal plate.



The threshold frequency for the metal is 6,8 x 10^{14} Hz.

10.1 Define the term *threshold frequency*. (2)

In the experiment, the brightness of the light incident on the metal surface is increased.

10.2 State how this change will influence the speed of the photoelectrons emitted.

Choose from INCREASES, DECREASES or REMAINS UNCHANGED. (1)

10.3 Show by means of a calculation whether the photoelectric effect will be OBSERVED or NOT OBSERVED, if monochromatic light with a wavelength of 6 x 10^{-7} m is used in this experiment. (5)

One of the radiations used in this experiment has a frequency of 7,8 x 10^{14} Hz.

10.4 Calculate the maximum speed of an ejected photoelectron. (5)