Physics Factsheet

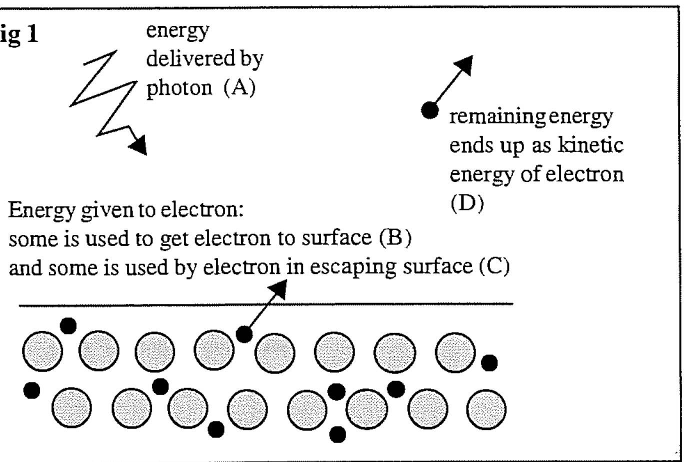
www.curriculum-press.co.uk Number 105

# Calculations on the Photoelectric Effect

**When a metal surface is illuminated with light, electrons can be emitted from the metal surface, provided the frequency of the light is above a certain value. This is called the photoelectric effect.**

*The photoelectric effect is one of the key pieces of evidence that light can behave as a stream of particles called **photons**, rather than as a wave. If light were behaving as a wave, then the emission of electrons would behave very differently. This is beyond the scope of this factsheet.*

**Fig 1**



As you can see in Fig 1, behind the photoelectric effect is a really simple idea:

**Energy delivered by the photon = energy delivered to the electron** (A in the diagram)

Of the energy delivered to the electron:

- some is used in getting electron *to* the metal surface (B in the diagram)
- some is used in getting electron to *escape* the metal surface (C)
- whatever energy remains appears as *kinetic energy* of the electron (D)

So, very simply: A = B + C + D

A : is the energy of the photon. This is proportional to the frequency of the light, such that Energy of photon = $hf$ where h is Planck's constant = $6.63 \times 10^{-34}$ Js

C: is the energy needed for an electron to escape the surface. This is known as the **work function**, and is a constant for a given metal. For example, the work function of zinc is 4.24 eV, and that of caesium is 1.35 eV. The symbol for work function $W$ or $\phi$ .

D is the kinetic energy of the electron and is thus given by: $KE = \frac{1}{2} m v^2$

So: **Energy delivered by the photon = energy delivered to the electron** now turns into:

$$hf = \begin{matrix}\text{energy to get}\\ \text{to surface, B}\end{matrix} + W + \tfrac{1}{2} m v^2$$

The speeds (and energies) of the electrons will depend upon how much of their energy they used getting to the surface. The fastest electrons will be the ones that are already at the surface, so that B is zero. This gives us our final formula, relating only to the fastest electrons, and the one we will use:

$$hf = W + KE_{max}$$

or, $hf = W + \frac{1}{2}mv^2_{max}$

*Exam Hint: when calculating speeds from kinetic energies as we will do later, the KE must be in Joules. However, as you have already seen, the work function and photon energies are often given in electronvolts (eV). It is therefore vital that you:*

- *remember at all times which units you are using*
- *are able to convert between them: 1 eV = $1.6 \times 10^{-19}$ J*

**Worked example**

***A metal surface with a work function of 4.0 electronvolts is illuminated by light of wavelength 200 nm. What is the maximum velocity of the photoelectrons produced?***

***speed of light*** = $3 \times 10^8$ m s$^{-1}$
***Planck's constant*** = $6.6 \times 10^{-34}$ J s
***mass of electron*** = $9.1 \times 10^{-31}$ kg

The first step is to calculate the frequency of the light from its wavelength

v = fλ, so

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8\ \text{m s}^{-1}}{200 \times 10^{-9}\ \text{m}} = 1.5 \times 10^{15}\ \text{Hz}$$

(don't forget the powers of ten when dealing with nano, micro, milli etc)

Now we can use either of the formulas above.
The first ($hf = W + KE_{max}$) will work but requires a two step process – you will have to use $KE = \frac{1}{2} m v^2$ afterwards to convert KE into speed, so we will use the second formula.

$$hf = W + \tfrac{1}{2}mv^2_{max}$$

$$(6.6\times10^{-34}\ \text{J s})\times(1.5\times10^{15}\ \text{s}^{-1}) = (4.0\times1.6\times10^{-19}\ \text{J}) + (0.5\times9.1\text{x}10\text{-}31\ \text{kg}\times v^2)$$

(Notice that I changed the work function into Joules from electronvolts)

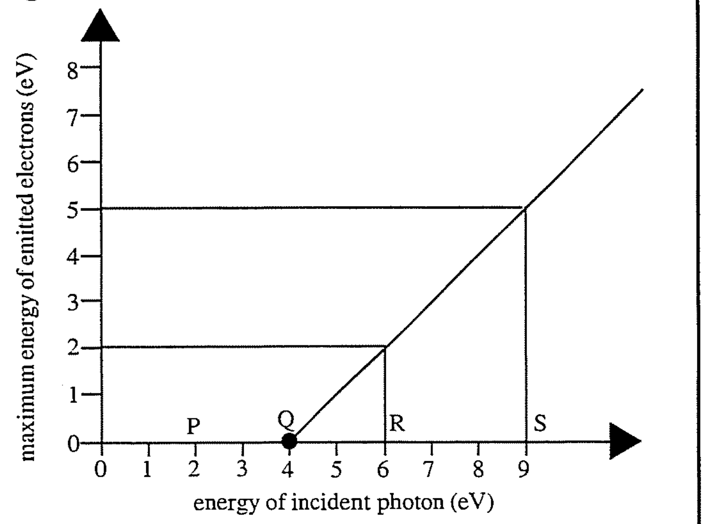
giving $v = 8.8 \times 10^5$ m s$^{-1}$

*Exam Hint: Check you can get this result with your calculator. It is very common for students to do all the hard work and then forget to square-root $v^2$ at the end. Don't fall into this trap!*

## Graphs in the photoelectric effect

The formula $hf = W + KE_{max}$ results in the following graph

**Fig 2**



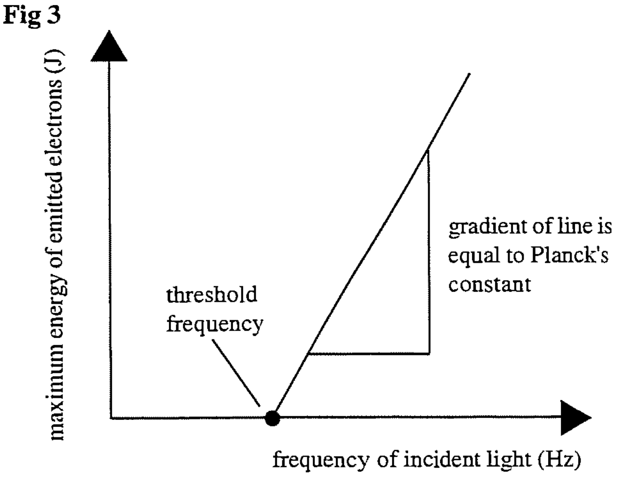
Consider 4 incident photons P, Q, R and S, which have different energies (and frequencies)

- Photon **P** does not have enough energy to cause any **photoemission** of electrons.
- Photon **Q** has *just* enough energy to cause photoemission. There is no 'spare energy' left over, so the photoelectrons have no KE – all the energy went into leaving the surface. This is of course the work function, so the work function of this particular metal is 4 eV.
- Photon **R** had 6 eV. 4 eV of those were used in getting from the surface, so the maximum KE possible is 2 eV.
- Photon **S** had 9 eV. 4 eV of those were used in getting from the surface, so the maximum KE possible is 5 eV
- By considering R and S, you should be able to see that the gradient of the graph is 1, or '45 degrees'.

> *Note that if the energy of the photon is not great enough for an electron to escape the surface, then no electrons will be emitted. This is why there is a threshold frequency: above that frequency electrons are emitted, below it they are not.*

Sometimes this graph is plotted with the *frequency* of the light on the x-axis rather than the *photon energy*. In this case the gradient of the line is not 1.

**Fig 3**



The equation of a straight line is: $y = m\ x + c$

The photoelectric equation can be written $KE = hf - W$

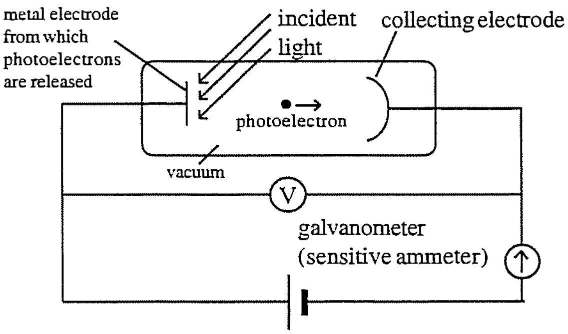
Comparing the two, and looking at Fig 3 shows that:

- the gradient of the line gives a value for Planck's constant
- the threshold frequency, $f_0$, can be read off the x-axis
- the work function can be obtained by continuing the line and reading off the negative y-intercept. Notice that the work function can also be obtained from the threshold frequency: $W = hf_0$

> A photoelectron is not a different particle from an electron. It is just an electron that has been emitted from a metal by a photon. It is still a normal electron!

### Stopping potential

If a negative electrode is placed near the emitting metal surface, then it will repel the photoelectrons. If it is negative enough, then the photoelectrons will not reach it.



The circuit above shows a **photocell**. As the voltage of the supply is increased, more and more electrons are repelled back, and the galvanometer reading falls. Only the fastest electrons reach the collecting electrode. When the supply voltage reaches a value known as the **stopping potential**, even the fastest electrons can not reach the collecting electrode and the current falls to zero.

In energy terms, the electrical potential energy of an electron near the collecting electrode has risen higher than the kinetic energy of the photoelectrons, which therefore cannot reach the electrode. (This is the electrical equivalent of a very simple gravitational idea: if you place a target above you on a wall you may be able to hit it by throwing a ball, but if you raise the target there will come point where you can not give the ball enough KE to reach.)

The electrical energy transferred to an electron crossing from one electrode to the other is $qV$, where $q$ is the charge on an electron and $V$ is the potential difference between the electrodes. At the stopping potential $V_{stop}$, the fastest electrons are *just* prevented from making it, so:

$$qV_{stop} = \frac{1}{2}mv^2_{max}$$

which equals $hf - W$

## Practice Questions

*For the following questions, you may use the data below:*

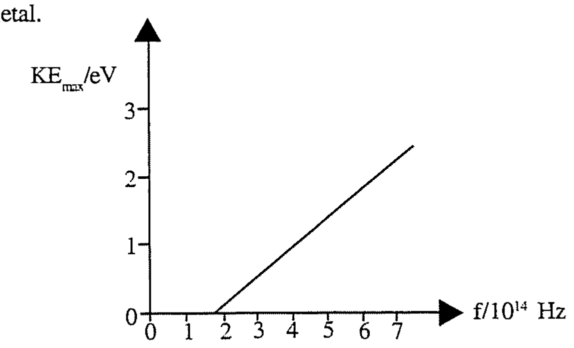
*speed of light* $= 3 \times 10^{8}\ m\ s^{-1}$
*mass of electron* $= 9.1 \times 10^{-31}\ kg$
*charge on electron* $= 1.6 \times 10^{-19}\ C$
*Planck's constant* $= 6.6 \times 10^{-34}\ Js$

1. Light of frequency $9.2 \times 10^{14}$ Hz falls upon a metal with a work function of 2.5 eV.
   (a) Calculate the maximum kinetic energy of the resulting photoelectrons
   (b) Calculate the maximum speed of the resulting photoelectrons
   (c) What is the threshold frequency for photoelectric emission?
   (d) If a nearby electrode is made negative using a potential difference V, what value of V is required to stop any photoelectrons reaching it?

2. The work function of zinc is 4.2 eV. What is the maximum wavelength of light that will cause photoemission of electrons from zinc?

3. Light of wavelength 0.60 µm incident upon a metal surface ejects photoelectrons with kinetic energies up to a maximum value of $2.0 \times 10^{-19}$ J.
   (a) What is the work function of the metal?
   (b) If a beam of light causes no photoelectrons to be emitted, what can you say about its wavelength?

4. The graph below shows how the maximum KE of photoelectrons depends on the frequency of incident radiation for a certain metal.



   (a) Use the graph to estimate the work function of the metal
   (b) Use the graph to obtain a value for Planck's constant (harder)

5. A sample of magnesium is used as an electrode in a photocell. It is illuminated with u-v light of wavelength 225 nm, and a current flows in the photocell. The current can be reduced to zero by making the other electrode negative using a potential difference of 1.4 V. Calculate the work function of magnesium.

6. The work function of caesium is 1.35 eV. A photocell contains a caesium surface that is illuminated with light of wavelength 380 nm. What potential difference must be applied the the cell to just prevent a current passing through it?

7. A metal surface with a work function of 2.9 eV is illuminated with light of wavelength 400 nm. What will be the stopping potential for the photoelectrons?

## Answers

1. (a) $2.1 \times 10^{-19}$ J
   (b) $6.7 \times 10^{5}$ m s$^{-1}$
   (c) $6.1 \times 10^{14}$ Hz
   (d) 1.3 V

2. $2.9 \times 10^{-7}$ m (295 nm)

3. (a) $1.3 \times 10^{-19}$ J (0.81 eV)
   (b) must be greater than $1.5 \times 10^{-6}$ m

4. (a) approx 0.7 eV
   (b) approx $6.7 \times 10^{-34}$ Js

5. $6.6 \times 10^{-19}$ J (4.1 eV)

6. 1.9 V

7. 0.19 V

***Acknowledgements:***
*This Physics Factsheet was researched and written by Michael Lingard*
*The Curriculum Press, Bank House, 105 King Street, Wellington, Shropshire, TF1 1NU*

***ISSN 1351-5136***