AS Level Physics

Chapter 5 – Waves and Particle Nature of Light

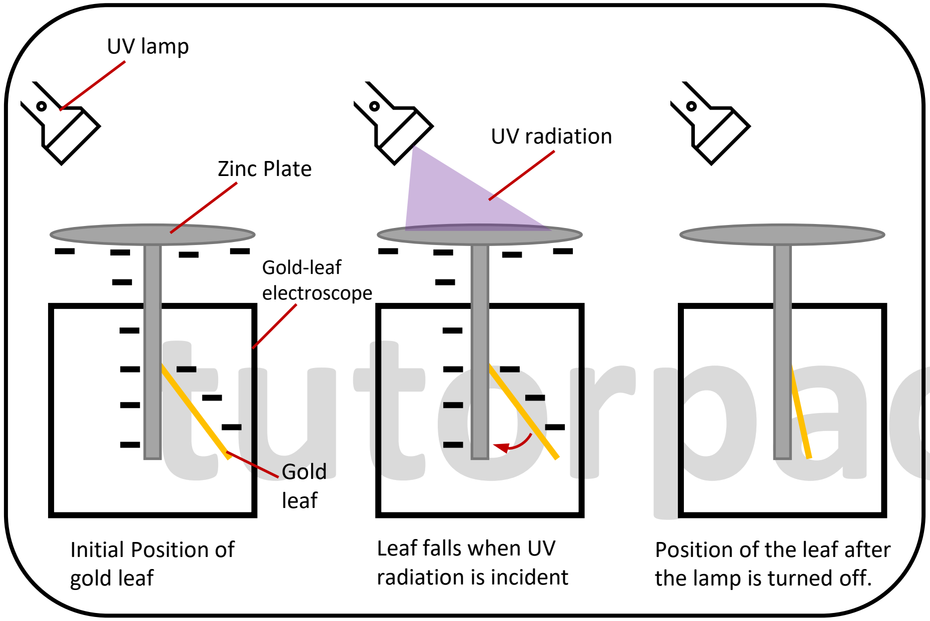
5.7.1 The Photoelectric Effect

Notes

The Photoelectric Effect Experiment

The photoelectric effect is when certain metals are exposed to ultraviolet (UV) radiation, and electrons break free.

A simple experiment can demonstrate the photoelectric effect (see below).



A zinc plate is attached to the top of an electroscope (a box containing a piece of metal with a strip of gold leaf attached).

The zinc plate is charged negatively (which in turn means the metal in the box is negatively charged). The gold leaf is repelled by the negatively charged metal, which causes it to rise.

The zinc plate is then exposed to UV light. Electrons are lost from the zinc plate due to the photoelectric effect, which is caused by the energy of the light. The gold leaf is no longer repelled and falls back down when the zinc plate and metal lose their negative charge.

The Photoelectric Effect Experiment

The leaf will not descend if a glass sheet (which absorbs UV) is placed between the lamp and the zinc plate, indicating that the UV is the cause of the discharge.

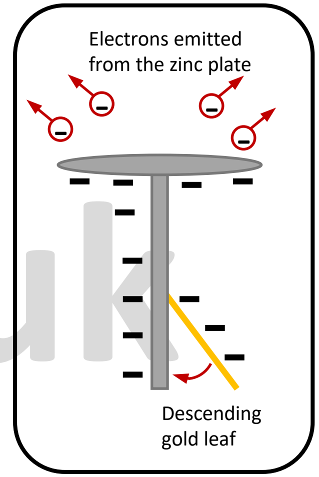
In simpler words:

If you shine a high-frequency light over a metal's surface, it will emit electrons. This frequency is in the UV range for most metals.

1) Free electrons on the metal's surface absorb energy from light and vibrate as a result.

2) When an electron absorbs enough energy, the bonds that hold it to the metal break, releasing the electron.

3) This is known as the photoelectric effect, and the released electrons are referred to as photoelectrons.



The Photoelectric Effect Experiment

Conclusions drawn from the experiment:

Conclusion 1: If the radiation has a frequency below a specific value – called the threshold frequency (f_0) – no photoelectrons are emitted for a given metal.

This means that no electrons are emitted if the incident radiation frequency (f) is less than a certain threshold frequency (f_0), regardless of how intense the radiation is.

Likewise, no electrons are emitted if the wavelength (λ) of the radiation is greater than a specified threshold wavelength (λ_0).

The f_0 and λ_0 values are different for different metals.

Even the brightest industrial laser, for example, cannot cause photoelectric emission from zinc, although a weak UV light will. This is because, while the industrial laser may be bright, no electrons will be released if the frequency of the light is less than the metal's threshold frequency.

For a metal, the **threshold frequency** $(\boldsymbol{f_0})$ is the lowest frequency of electromagnetic (EM) radiation that causes photoelectric emission.

For a metal, the **threshold wavelength** $(\boldsymbol{\lambda_0})$ is the **lowest wavelength** of EM radiation that causes photoelectric emission.

The Photoelectric Effect Experiment

Conclusions drawn from the experiment:

Conclusion 2: The photoelectrons have kinetic energies that range from zero to a maximum value when they are emitted. The maximum kinetic energy increases with the frequency of the radiation and is unaffected by its intensity.

Conclusion 3: The intensity (brightness) of the radiation above the threshold frequency is proportional to the number of photoelectrons emitted per second.

Photoelectric Effect and the Wave Theory

The WAVE theory explained interference and diffraction well, but it failed to explain the photoelectric effect.

Photoelectric emission should occur for all frequencies of incoming radiation, according to the WAVE Theory. This means that for a given frequency of light, each free electron on the metal's surface gains a small amount of energy from each incoming wave. Then each electron would gradually obtain enough energy to escape the metal. However according to experimental proof, photoemission does not occur with incident radiation frequencies less than the threshold frequency.

Furthermore, wave theory suggests that the kinetic energy of the released electrons will increase as the radiation intensity increases. But, the photoelectrons' kinetic energy is unaffected by the intensity of the radiation.

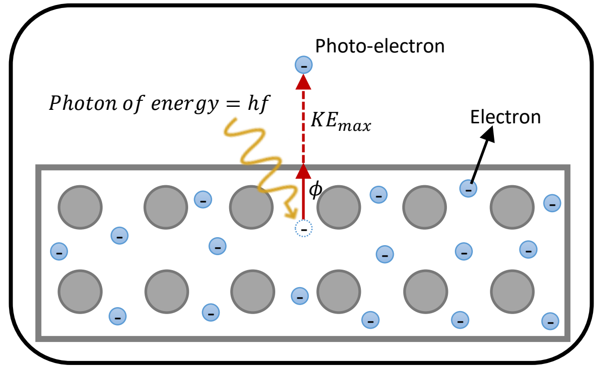
As a result, it was suggested that electromagnetic radiation might have a dual nature. Some of its properties (reflection, refraction, interference, diffraction, and polarisation) may be explained in terms of its wave-like nature, but others, like the photoelectric effect, can only be explained in terms of its particle-like nature.

The first person to explain what was going on was Albert Einstein. He proposed that electromagnetic energy comes in packets or quanta, which we now refer to as photons. So, depending on the circumstances and the effect being observed, light behaves as a wave or as a particle. This concept is now known as wave-particle duality (which we will cover in the next pack).

Work Function (ϕ)

We've observed the photoelectric effect during an experiment and drawn conclusions from it. But, what occurs at the molecular level when high-energy photons are aimed at a metal surface?

A photon with $energy = hf$ is absorbed by an electron on the metal's surface, and the electron is freed and escapes the metal as shown the diagram opposite.

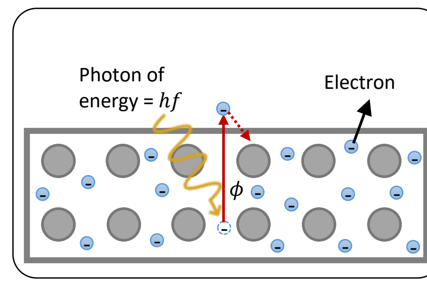


When a **photon of energy (hf)** causes photoemission from a metal surface, some of the photon energy is used to overcome the **work function** (ϕ), while the rest is released as kinetic energy.

The **work function** (ϕ (phi)) is the minimum energy needed for an electron to escape from a metal surface and break the bonds holding the electron there.

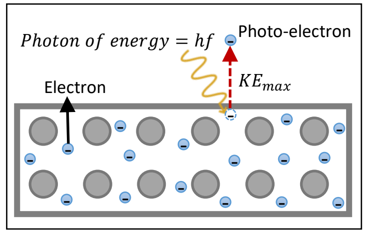
The required **work function** (ϕ) **energy** depends on the metal.

When a photon with $energy = \phi$ interacts with electrons on the surface of a metal, the photon is absorbed and the electron gains enough energy to simply escape from the metal with zero kinetic energy. However, because the electron does not have enough kinetic energy to escape, the electron is sometimes pulled back into the metal.



Work Function (ϕ)

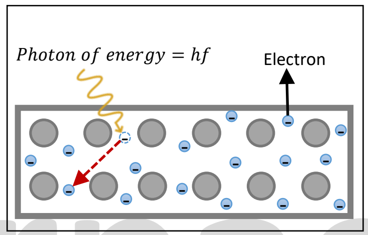
Some photons are absorbed completely by electrons near the metal's surface, and since energy is conserved, when a photon interacts with an electron:



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

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

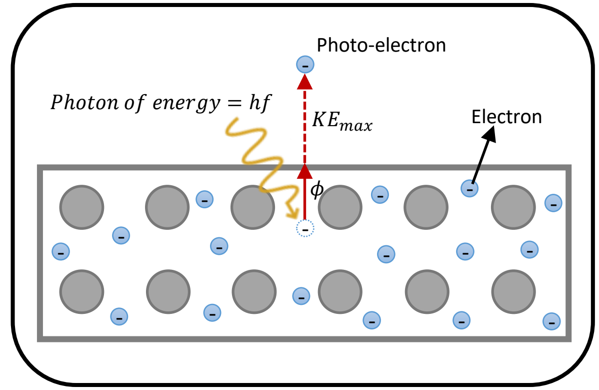
In some situations, electrons gain enough kinetic energy to escape, but they move in the wrong direction, causing the metal to absorb them further.



Einstein's Photoelectric Equation

The following is a summary of Einstein's explanation of the photoelectric effect:

When a photon with $energy = hf$ is captured by an electron in a metal, some of the energy is used to overcome the work function (ϕ), and the remainder is converted to kinetic energy by the electron.



This is expressed mathematically in the equation below:

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

- hf: Energy delivered by a photon of frequency (f)
- ϕ: The minimum amount of energy needed to free the electron from a metal surface.
- KE_{max}: Maximum kinetic energy of the emitted electron

Where:

h = Planck's constant measured in Js ($6.63 \times 10^{-34} Js$),

f = frequency measured in Hz,

ϕ = work function energy measured in J,

KE_{max} = kinetic energy measured in J.

Einstein's Photoelectric Equation

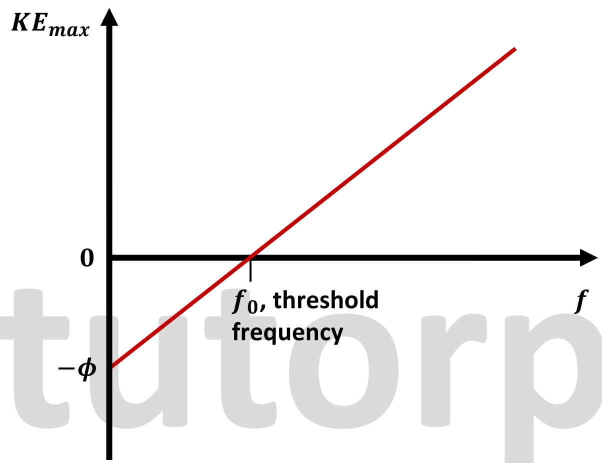
The photoelectric equation is rearranged as follows:

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

Now you can compare it to:

$$y = mx + c$$

And so we can draw a straight-line graph:



Plancks constant, h, is determined by the gradient of a graph of KE_{max} against f . Work function, ϕ, is given by the y-intercept.

Note:

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

Because electrons can only absorb one photon at a time, the electrons' kinetic energy is independent of the intensity.

Increased intensity just implies that incident radiation carries more photons per second, resulting in more photoelectrons per second, but it has no effect on the KE_{max}.

Einstein's Photoelectric Equation

The wavelength (λ) of the incident photons can be used to express the photoelectric equation:

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

But we know that $f = \frac{c}{\lambda}$, so we can substitute that in giving us:

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

Where:

c = speed of light measured in ms^{-1} $(3.0 \times 10^8\ ms^{-1})$,

λ = wavelength measured in m.

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

Note majority of the photoelectrons will have kinetic energy < KE_{max}.

Threshold Frequency

The frequency of the light must be greater than a particular minimum value, known as the threshold frequency, f_0. An individual photon will not have enough energy to let an electron overcome the work function, ϕ, below this value. Therefore:

$$hf_0 = \phi$$

Where:

h = Planck's constant measured in Js,

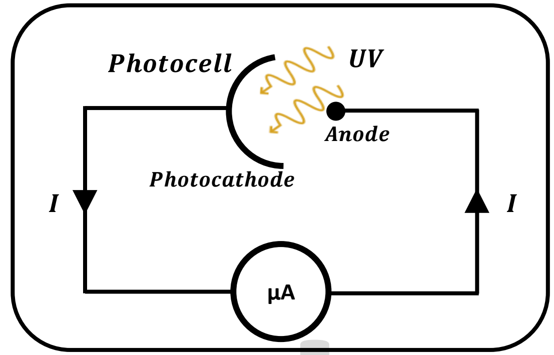
f_0 = threshold frequency measured in Hz,

ϕ = work function measured in J.

The Vacuum Photocell

Vacuum photocells is an evacuated glass bulb, containing a metal electrode (referred to as the Anode) and a metal plate (referred to as the Photocathode).

A photocell is connected in series with a microammeter (μA) as shown in the diagram opposite.



Electrons are emitted from the photocathode and transferred to the anode when electromagnetic radiation with a frequency (f) larger than the threshold frequency (f_0) is shone on it.

The photoelectric current, as measured by the microammeter, is proportional to the number of electrons flowing between the cathode and anode per second. Therefore, a high microammeter value indicates a high number of electrons released per second.

The number of photoelectrons per second (N) emitted by the cathode for a photoelectric current (I) is given by:

$$N = \frac{I}{e} \ (where\ e = electronic\ charge)$$

The Vacuum Photocell

As long as the frequency is greater than the threshold frequency, even a very dim light will suffice for this experiment. But, the brighter the ultraviolet light, the greater the current.

This means that the photoelectric current is proportional to the intensity of the radiation incident on the cathode.

This is because the number of photons per second hitting the cathode is proportional to the intensity. Simply put, as the UV light intensity rises, more photons per second with a frequency larger than the threshold frequency are released, and all those photons strike the cathode.

As a result, more photons can interact with more electrons per second, allowing them to escape, and therefore the number of photoelectrons emitted per second increases (i.e. increasing the photoelectric current).

So:

$$\textit{Photoelectric current} \propto \textit{Intensity}$$

The Vacuum Photocell

But:

The photoelectrons' maximum kinetic energy is independent of the intensity of the incident radiation.

Since each photoelectron gains energy from the absorption of a single photon, the maximum kinetic energy (KE_{max}) is calculated as follows:

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

As a result, the KE is determined by the incident photon energy (hf) and not the intensity, for a given metal. The maximum KE is proportional to the incident photon energy (or its frequency) and has nothing to do with the number of photons that are emitted per second by the UV light hitting the cathode (i.e. intensity) .

Remember increasing the intensity of the UV light does not mean you are increasing the frequency of the individual photons.

Please see **‘5.7.2 The Photoelectric Effect worked examples’** pack for exam style questions.

For more revision notes, tutorials and worked examples please visit **www.tutorpacks.co.uk.**