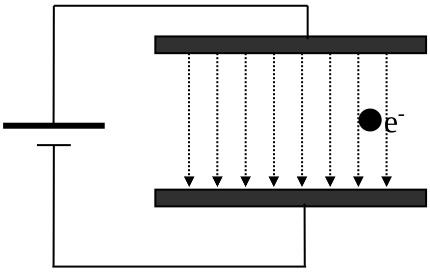
Particle properties of light

Study design:

- **analyse the photoelectric effect with reference to:**
  - **–evidence for the particle-like nature of light**
  - **–experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency**
  - **–kinetic energy of emitted photoelectrons: Ek max = hf – Φ, using energy units of joule and electron-volt**
  - **–effects of intensity of incident irradiation on the emission of photoelectrons**
- **describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect.**

Electric fields (Revision)

In the region between charged plates, the electric field **E** is constant, and so a constant electric force $\mathbf{F}_E$ acts on any electrons between the plates. This causes them to accelerate towards the positive plate. Electrons moving directly between the plates will have a uniform force acting on them. The electric force does work on these electrons and they gain kinetic energy as they move towards the positive plate.



The change in kinetic energy of the electrons is given by:

Work = ΔKE = q. ΔV

Unit of work and energy = joules (J)

Where q = charge of electron (C)

ΔV potential difference electron moves through (V).

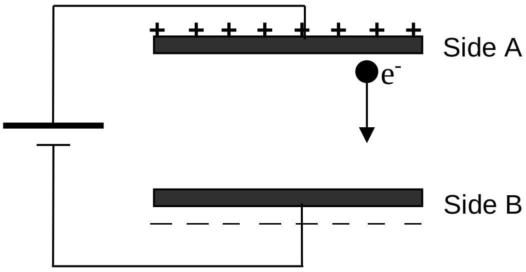
A convenient unit of energy when dealing with electrons is the electron volt (eV).

An electron gains 1eV of energy when it is accelerated across a potential difference of 1 volt.

1 eV = 1.6×10^{-19} J

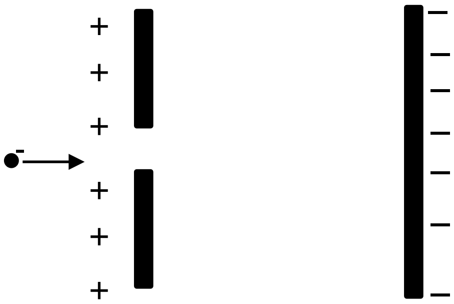
To convert from J to eV, divide the energy (in Joules) by 1.6×10^{-19}.

One application that this is used in is the photoelectric effect. We can use the voltage to stop electrons and thus we would know how much kinetic energy the electrons had. Imagine energy was given to an electron and it came out of side A. Assume it took 2.3 V to stop an electron from travelling from side A to side B. Then the electrons that came out of Side A must have had 2.3 eV of energy.



If an electron is fired through a gap into a region between two plates, then the electric field will oppose its motion. If the electron is travelling relatively slowly, the field may stop the electron before it reaches the other side. The electron will then travel in the opposite direction. If the electron is going fast enough (i.e. has sufficient initial kinetic energy, then it may reach the plate before it slows to a stop.

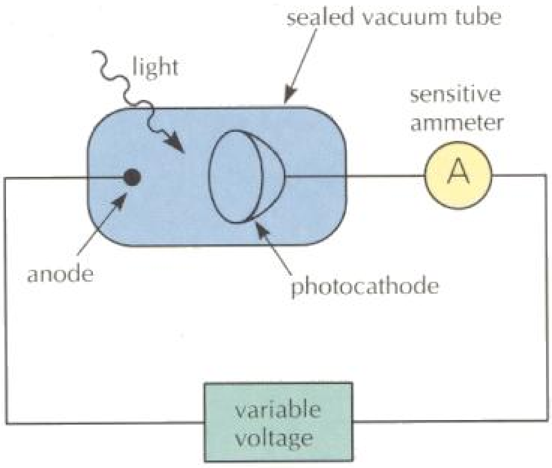
If the field strength is increased then the electron will decelerate more rapidly. It will require a greater initial kinetic energy to make it across to the opposite plate.



The Photoelectric Effect

In 1887, Hertz, while detecting electro-magnetic waves, found that sparks could jump larger gaps if the metal surface was illuminated by ultraviolet light. It was soon shown that the ultraviolet light was liberating negatively charged particles from the metal.
In 1899, J.J. Thomson showed that the charge to mass ratio of these particles was the same as that of cathode rays and they were, in fact electrons. The process by which electrons are ejected from matter by light was named the photoelectric effect.

According to Maxwell's electromagnetic theory, light waves carry energy and so it was conceivable that light falling on a metal surface could supply sufficient energy to eject some of the electrons. However, this model was shown to conflict with the detailed experimental evidence.



Detailed experiment

In 1902, Lenard carried out a detailed study of the photoelectric effect, particularly examining the kinetic energies of the photoelectrons (Electrons that have been emitted from a metal using light). He did this by allowing light of different frequencies to fall on a clean metal surface in a vacuum. Electrons which left the photocathode and reached the anode produced a small current in the ammeter. When the anode was at a sufficiently high positive potential relative to the cathode, all the photoelectrons were collected and the current was a maximum. When the anode potential was zero, the photoelectric current was not zero because many of the electrons were emitted from the cathode with enough kinetic energy to travel to the anode. When the anode potential was made slightly negative with respect to the cathode, the electrons were repelled and only those electrons with sufficiently high kinetic energy could reach the anode. The reverse voltage at which the current is reduced to zero, the 'Stopping potential' V_o, gives a measure of the maximum kinetic energy of the emitted photoelectrons.
$E_{k\ max} = eV_o$

The main experimental results were:

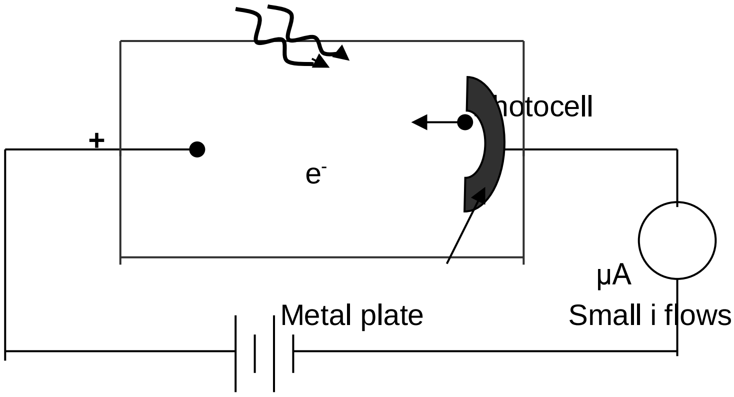
- The rate at which photoelectrons are emitted is proportional to the intensity of the light (for light above the threshold frequency)
- The maximum kinetic energy of the photoelectrons is independent of the intensity of the light.
- The maximum kinetic energy of the photoelectrons depends on the frequency of the light.
- Below a certain frequency, different for different metals, light cannot eject photoelectrons at all. This is called the cut-off or threshold frequency.

The discovery of the photoelectric effect dramatically changed the way scientists were thinking about light. The particle model had lost most of its supporters, especially since Young's double slit interference experiments. In 1897 Heinrich Hertz observed an interaction between light and matter, now known as the photoelectric effect. After further work by Philip Lenard, between 1899 and 1902, led Albert Einstein to conclude that light does in fact behave like a particle. The wave model could not explain the photoelectric effect.

Computer simulation https://phet.colorado.edu/en/simulations/category/physics
Choose Photoelectric effect

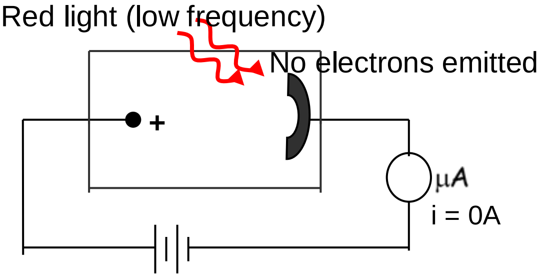
It sometimes happens that when light falls on certain metals, electrons are ejected from the metal. These electrons are known as photoelectrons and can be shown to be electrons by measuring their charge mass ratio. A photocell can be used to investigate the photoelectric effect. Photoelectrons ejected from the cathode are pulled across to the anode. These moving electrons are a current that may be measured by an ammeter.

Dim light

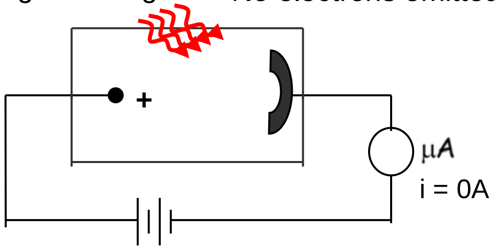


The experiment can be used to show that the number of electrons ejected depends upon the light intensity. As the light intensity increased, so too did the size of the current. More electrons were escaping from the metal when the light was brighter.
When the frequency (i.e. colour) of the light shining on the metal changes, there is a frequency at which the electrons begun to be emitted from the metal. This is called the THRESHOLD or CUT-OFF FREQUENCY (f_c). Below this frequency, no emission occurs, even for very intense light.

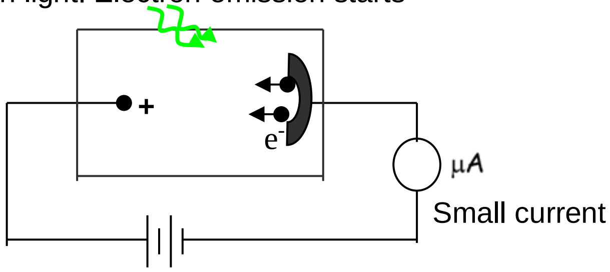
Red light (low frequency)



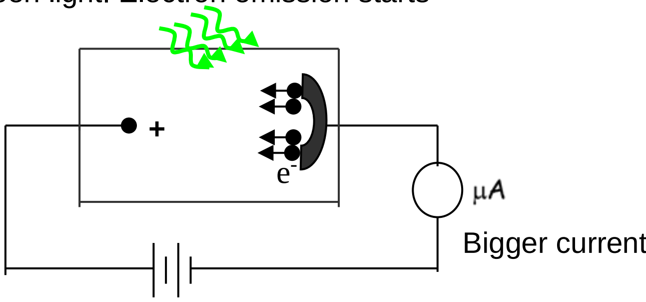
Bright Red light No electrons emitted

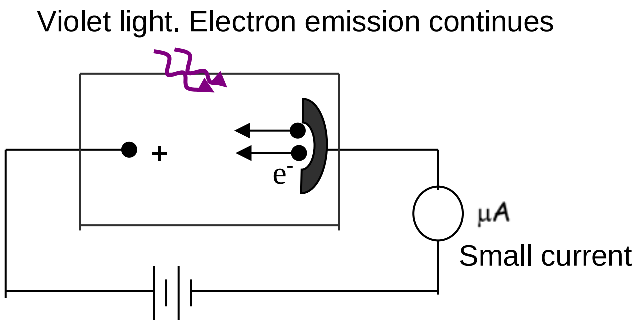


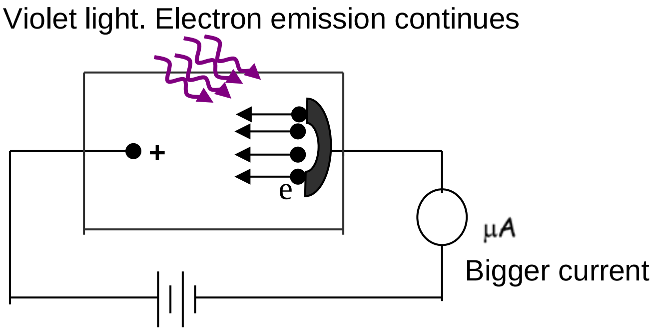
Green light. Electron emission starts



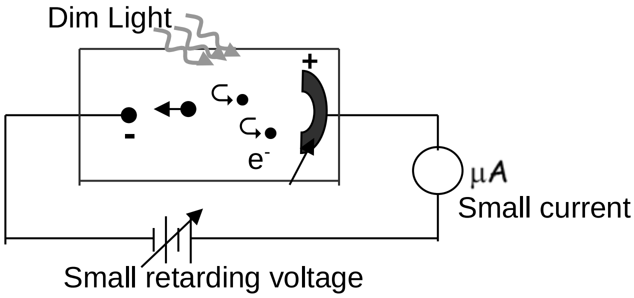
Green light. Electron emission starts

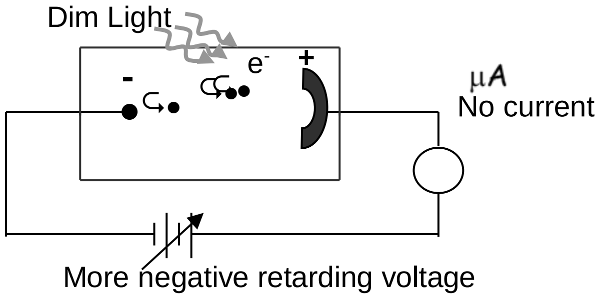




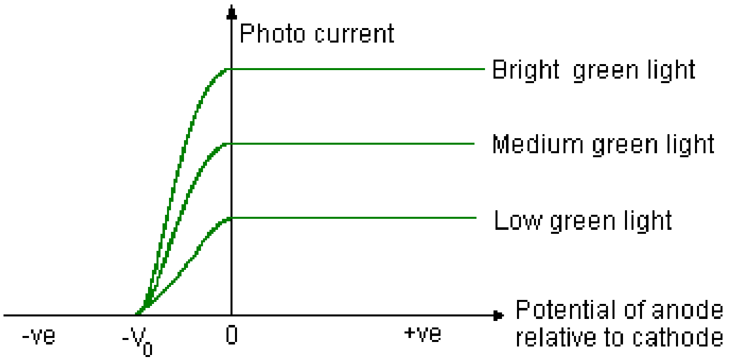


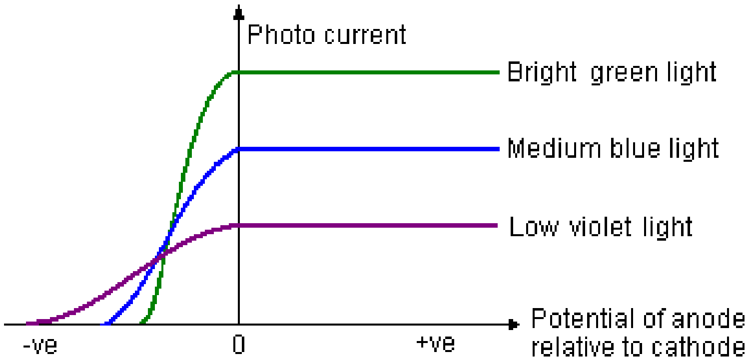
When the battery is reversed, some important results are obtained.





- As the anode is made more negative fewer electrons get across the tube- this means that the ejected electrons must have a range of kinetic energies. Electrons with little or no KE are stopped as soon as the anode becomes negative - those with the most KE being stopped by V_c volts. Energetic electrons come from the surface, less energetic electrons from below the metal surface.
- The value of V_c, the cut off voltage, depends upon the colour, not the intensity of the light. With most metals, low frequency light will not generate electrons.
- The time lag between the light striking the photo-cathode and the emission of electrons is less than 3×10^{-9} secs, even for the lowest light intensity.
- More intense light generates more electrons, but does not increase their energy.





Failure of the wave model to account for the Photoelectric Effect
The electromagnetic wave model describes the energy in the light beam as arriving continuously and uniformly over the metal surface. If the intensity of the light beam in increased, then the energy available to the electrons is also increased and so the maximum kinetic energy available to the electrons is also increased and so the maximum kinetic energy of the photoelectrons should increase. This does not, in fact, happen! The theory also predicts that the energy in a light beam is described entirely by its intensity, so the maximum kinetic energy of the photoelectrons should be independent of the frequency of the light – this again contradicts the facts!
A further difficulty for the wave theory is that the energy in the light beam is delivered in a smooth continuous fashion and is spread out over the whole wave front. Consequently, it should take some appreciable time after the light is turned on, before any one of the electrons absorbs enough energy to escape from the surface. This time delay should be longer for dim light. Experimentally, it turns out that there is no measurable time delay, even with the weakest light source!

The Photon Model
In 1901, Max Planck was attempting to solve a puzzling discrepancy between the observed spectrum of light from a black body and the theoretical predictions of Maxwell's electromagnetic theory. He postulated that electromagnetic energy was emitted and absorbed in packets or quanta, each one carrying a definite amount of energy. The energy was proportional to the frequency, f, and given by the equation: $E = hf$ where h is Planck's constant

Planck's radical suggestion produced a better fit between theory and experiment but was not widely accepted since it disagreed with the essentially continuous nature of radiation as described by Maxwell's theory.

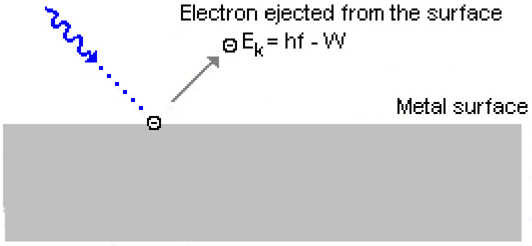
In 1905, Albert Einstein extended Planck's idea and suggested that light was not merely emitted in discrete amounts or quanta, but that it retained its identity, travelled through space as a particle of light energy or photon and was ultimately absorbed by matter as a complete quantum of energy.

So, in the photoelectric effect, one electron could absorb exactly one photon and receive the full quantum of energy, hf. Since it will require a certain minimum amount of energy, W, to remove the electron from the surface, the maximum kinetic energy of the photoelectron will be:

$E_{k\,max}$ = photon energy – minimum energy to remove electron

= *hf* – w

The minimum energy required to remove an electron from the metal is called the work ‘function’ and the symbol W is used for this. Photoelectrons from below the surface will lose further energy by collisions before they escape, so there will be a range of energies for the emitted photoelectrons.



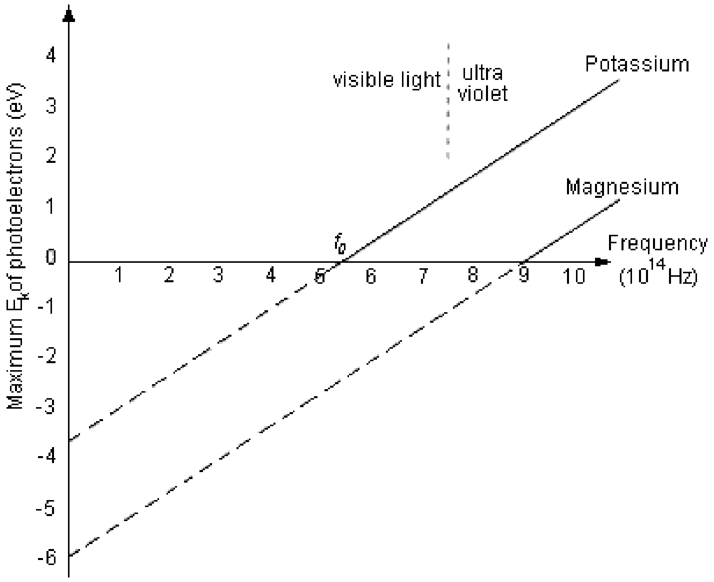
One electron can absorb energy from only one photon

The photon model of light, suggested by Einstein, explained the observed facts:

- Since the photon energy E = *hf*, then the maximum energy of the photoelectron would obviously depend on the frequency of the light, *f*.
- No electron will be emitted until the energy of the incoming photon is at least equal to the work function of the surface. This means that the frequency of the light must be above a minimum value f_o, such that $hf_o = W$. This explains the existence of a threshold frequency – light with lower frequency than the threshold frequency will not eject photoelectrons, no matter how intense the light.
- Increasing the intensity of the light means that the number of photons is increased but the energy of the individual photons is unchanged. So more electrons may be ejected but the maximum energy will be unchanged. A very weak light source with a frequency that is greater than the threshold frequency will eject electrons.

Experimental confirmation of the photon model

In 1916, Robert Millikan published experimental results which completely verified Einstein’s photoelectric theory. He prepared clean surfaces of lithium, sodium, and potassium and measured the maximum energy of the photoelectrons emitted when the surface was exposed to light of different frequencies. The graph of maximum kinetic energy versus frequency for each metal was a straight line, with the same gradient in each case. The intercept of the frequency axis represents the threshold frequency, f_o. The intercept on the energy axis is –W, the negative of the work function. The values were different for each material, though the gradients were the same.



If a graph of the KE of the ejected electrons is plotted against the frequency of the incoming light the following can be deduced:

- There is a threshold frequency below which the electrons are not emitted.
- Different metals have different threshold frequencies
- The gradient of the graph is the same for all metals.
- The equation of the graph, an energy equation, is $E_k = hf - W$ where E_k is the Kinetic Energy of the ejected electrons, h a universal constant and W a constant for the material.
  This can be written as $hf = E_k + W$
- The constant h is called Planck's constant and has the value of 6.626×10^{-34} Js. or 4.136×10^{-15} eVs.
- Other experiments show that photons have a momentum given by $p = \frac{h}{\lambda} = \frac{hf}{c}$
- W is either called the work function or the binding energy of the metal.

G.I. Taylors Experiment

Taylor performed an experiment to determine whether there was a qualitative change in a diffraction pattern when the intensity of the light is reduced greatly.

In other words, did a single photon behave like a wave?

Taylor took photographs of the shadow of a needle, varying the intensity of light by shielding the light source with smoked glass screens. When decreasing the intensity he increased the exposure time to keep the total amount of light on the photograph constant. The longest experiment took three months, corresponding to the intensity of a candle about 2 kilometres away.

Taylor was trying to test for interference with single photons in the apparatus. Since low intensity means very few photons per second, he reduced the intensity until he had only one photon in the apparatus at any-time.

On the screen behind the double slit the photons will pile up in an interference pattern. They cannot interfere with each other. A photon arrives at random on the screen but the probability is greatest that it will arrive where wave behaviour predicts a maximum.

The interference pattern did not change, from very high intensity to very low intensity. Thus both the wave and particle models are needed to explain light behaviour.

The momentum of Photons

Maxwell suggested that photons do have momentum given by

$$p = \frac{E}{c}$$

where c is the speed of light and E is the energy of the photon.

As the energy of the photon is related to its frequency by Planck's equation, and, since $c = f \times \lambda$ for waves, the momentum equation can be written as

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