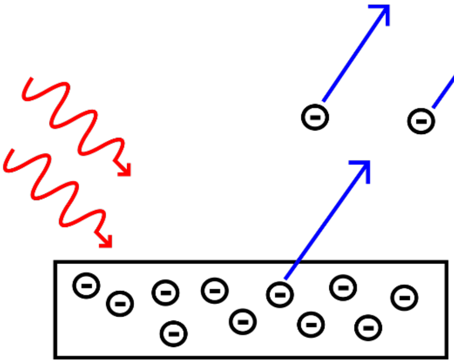
Photoelectric Effect

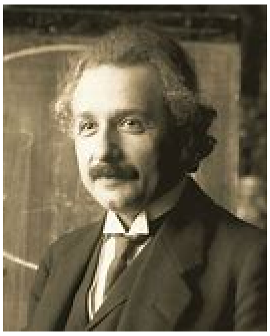
What is the photoelectric effect?

The photoelectric effect is when light falls on/shines on a material and electrons are released from the material. The electrons released are known as **photoelectrons**.



Who discovered the photoelectric effect?

The photoelectric effect was discovered by the German physicist Heinrich Rudolf Hertz, in 1887. Einstein did not discover the photoelectric effect but in 1905 explained the observations, for which he later won the Nobel Prize. The phenomenon could not be explained using classical physics, which described light as electromagnetic wave.



Instead, Einstein used a particle theory of light (corpuscular) in which every particle of light, called a **photon,** carries a certain fixed amount of energy (or quanta) that depends on the frequency of light. Using these hypothesis Einstein was able to explain all observations of the photo-electric effect.

How the photoelectric effect works

The photoelectric effect is only observed above the a minimum frequency, known as threshold frequency, f_o , and below this, no photoelectrons are ejected. This is because each photon needs a minimum amount of energy to release a photoelectron from the metal.

This minimum photon energy required to emit an electron is dependent on the metal and is called the **work function**, W.

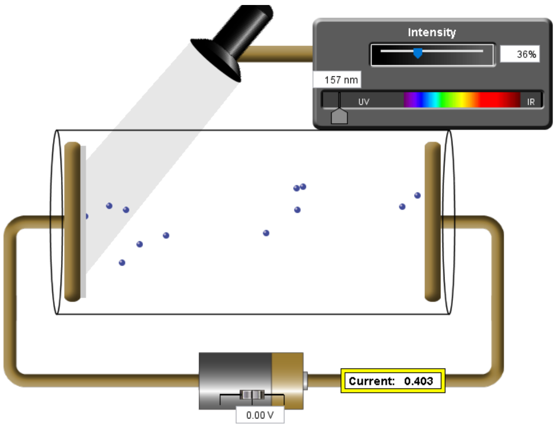
Photon energy is dependent on the frequency of the radiation according to the equation:

$E_p = hf$

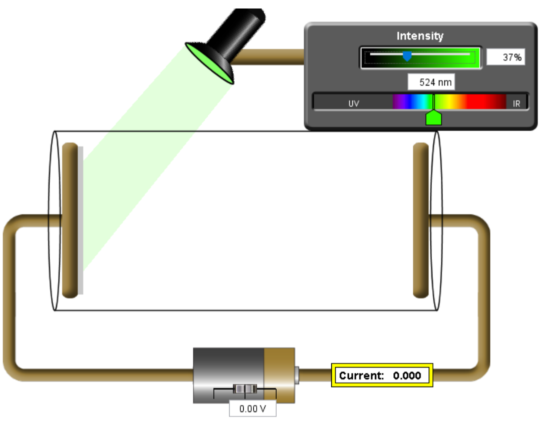
Where E_p is photon energy (Joules), h is Planck constant, 6.63×10^{-34} JS and f is the frequency (Hz)

The photon energy must be at least equal to the work function for electrons to be released.

$hf_o = W$



Photoelectrons emitted when hf is greater or equal to W



Below the threshold frequency, no photoelectrons are emitted because hf < W

Photoelectric effect equation

When radiation of sufficiently high frequency, f, is incident on a metal surface of work function, W. The photon, of energy E_p, is absorbed by the electron. This electron leaves with kinetic energy $K_{max} = E_p - W$

The photon energy $E_p = hf$ and the maximum electron kinetic energy = $\frac{1}{2} mv^2$

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

What does the photoelectric effect prove?

The photoelectric effect proves that energy is quantised. This means that energy arrives in 'lumps' known as quanta. These lumps or packets of energy are called **photons**.

This contradicts the long accepted wave model, where light is considered as an electromagnetic wave, with energy arriving continuously. The photon model was Einstein's explanation of the photoelectric effect.

Why can't photoelectric effect be explained by the wave model?

If the incident light has a frequency lower than the threshold frequency then no photoelectrons are emitted, even if the brightness of the light is cranked right up. This shows that energy is not transferred continuously as predicted by the wave model of light.

With the wave model, it should be possible to increase the intensity of the light or wait for a period of time, until sufficient energy is absorbed by the material to release electrons. This does not happen. There is essentially no delay between absorption of the radiant energy and the emission of photoelectrons.

The wave model, which dates back to Huygens in late 1600's, is still very successful at explaining phenomena such as diffraction (spreading out of light) and interference (overlapping effect of light causing patches of increased/decreased intensity). However, the wave theory cannot explain photoelectric effect.

The maximum kinetic energy of the released electrons does not vary with the intensity of light, as was expected with wave theory, but was instead found to increase with the frequency of light. What the light intensity did was to determine the number of electrons released from the matter, measured as an electric current.

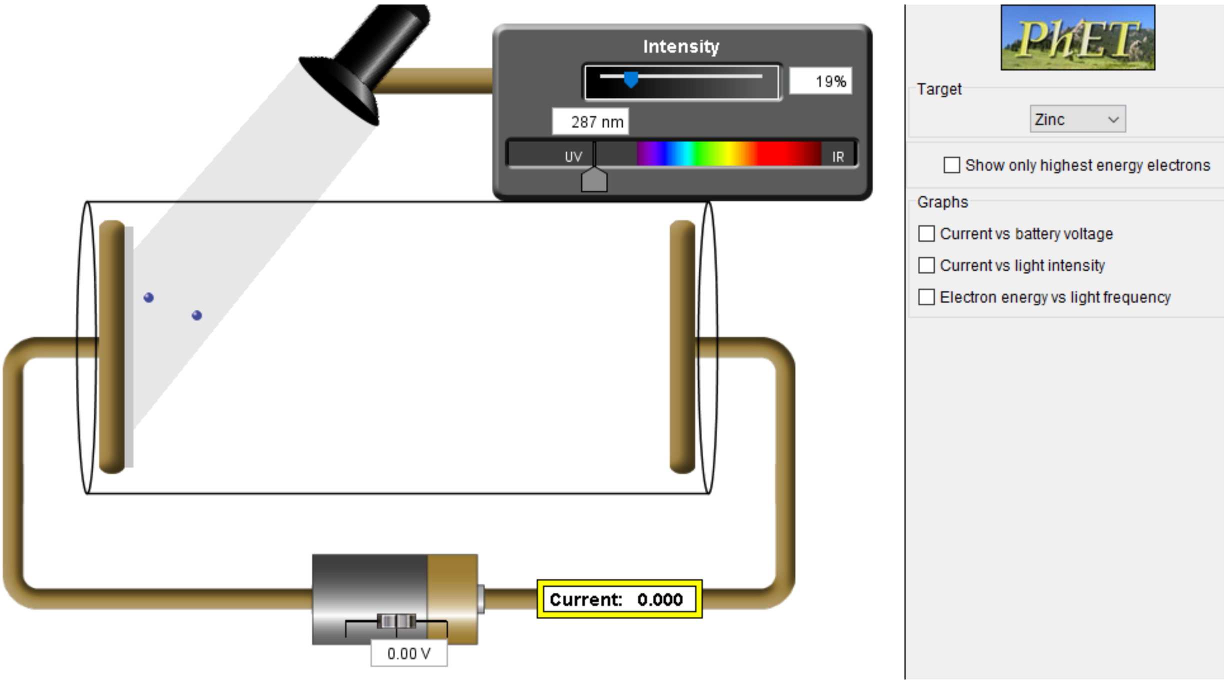
How does photoelectric effect show light is a particle?

For the photon to eject an electron, there must be enough energy in a single photon. You can't use lots and lots of lower energy photons. This proves that photons are discrete packets of energy. In other words, light exhibits a particle nature, where energy arrives in lumps or quanta. Modern physicists have concluded that both the particle theory and the wave theory are simplified explanations for a complex behaviour, known as wave-particle duality.

Which metals exhibit photoelectric effect?

All metals can show the photoelectric effect. Different materials have different workfunctions and threshold frequencies. This means the minimum photon energy required to overcome the workfunction will depend on the material. Most metals have threshold frequencies in the ultraviolet region of the electromagnetic spectrum.

Zinc, for example, has a work function of 4.3eV, which corresponds to a threshold frequency of approximately 1 x 10^{15}Hz (wavelength =287nm), which is in the ultraviolet range.



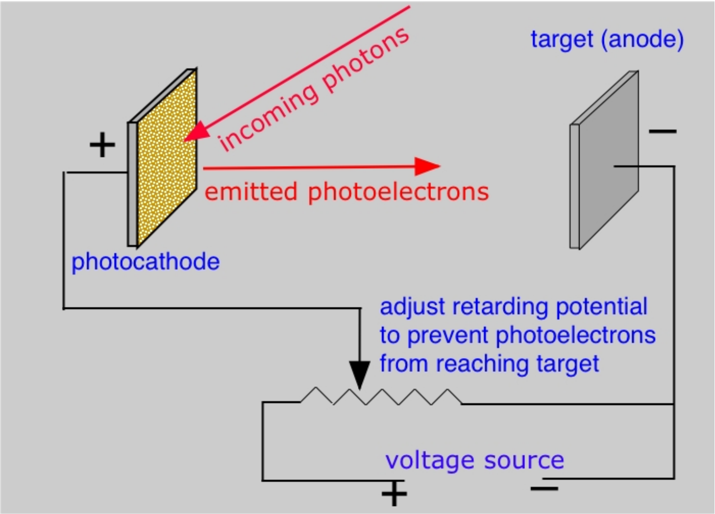
Can non-metals show photoelectric effect?

Non-metals can show the photoelectric effect. With atoms that hold their electrons tightly, a photon is much less likely to be absorbed and release an electron. This is because a greater photon energy is needed to make it happen. The Photoelectric effect can still happen in non-metals, but it is more likely and possible for a wider range of frequencies in a metal.

Metals have a 'sea' of free electrons. It is these spare electrons which are able to be dislodged by passing photons, provided that the photon has sufficient energy. Having said that, some non-metals, mostly in the metalloid group, can exhibit weak photoelectric effects if the energy of the inbound photons is high enough. The photons might need to have a very high frequency, perhaps in the X-rays region. Compounds such as water, are MUCH less likely to show any photoelectric effect, because the electrons are all neatly paired off and bound up in shared electron shells and so on (covalent bonds), reducing the chance of knocking out an electron.

Photoelectric effect experiment

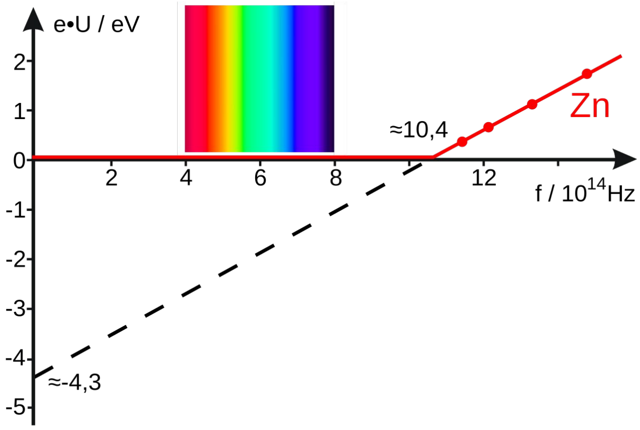
In the classic photoelectric effect experiment, a stopping potential is applied between the metal surface emitting photoelectrons and the target plate. The stopping potential is set so that the electrons are stopped in their tracks. From this the electron energy ½ mv^2 is assumed to be equal to the work done in stopping them, eV_s ($e=1.6 \times 10^{-19}$C, V_s is the stopping potential applied).



The photoelectric effect equation can be written as

$eV_s = hf - W$

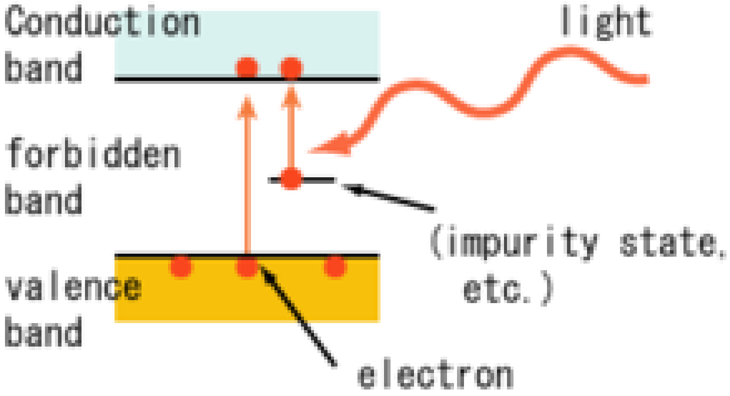
If the experiment is repeated with light of various frequencies above the threshold frequency, a graph is then plotted of electron KE (eVs) vs frequency. The line is extrapolated to find the x and y intercept values.



The gradient of the line gives a value of h (Planck constant). The x intercept is f_0 , the threshold frequency. The y intercept is –W (-work function). The graph shows values for zinc. A similar graph is obtained for all metals with the same gradient (Planck constant) and different values for f_0 and W.

Photoelectric effect in solar cells

Solar Panels usually use semiconductor materials such as silicon or gallium arsenide. The photoelectric effect is observed when a solar cell converts light to electrical energy.



Photons can be absorbed by the semiconductor material. This results in the excitation of an electron from the valence band to the conduction band. Semiconductors, such as silicon, have a different structure to metals. We can't use the work function in the same way to calculate minimum photon energy as we do for metals. Essentially, semiconductors have a filled valence band and an empty conduction band. The photon energy is needed to make an electron move into the conduction band.

It is more difficult to observe the photoelectric effect in insulators, where the electrons are more tightly bound.

The photoelectric effect is best simulated using the Phet simulation.