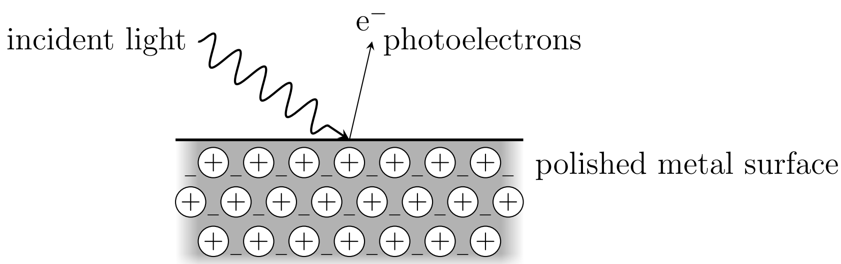
The photoelectric effect

A.C. Norman
anorman@bishopheber.cheshire.sch.uk

The photoelectric effect

Sometimes, visible or ultra-violet light falling on a metal surface can cause electrons to be emitted from the metal. For most metals, ultra-violet light is needed, but some metals will exhibit this phenomenon with visible light, e.g. sodium will emit electons with green light[1]. This phenomenon is known as the *photoelectric effect*.

Metals have high electrical conductivity, and usually one or two electrons per atom are free to move about, termed the 'conduction electrons'. Our best picture of a metal structure is of a regular array of positive ions in a more-or-less uniform sea of negative charge caused by the conduction electrons. Light cannot turn into electrons (charge must be conserved!) so the light must be giving electrons in the metal enough energy to escape from the electrostatic attraction of the metal nuclei:



The classical picture of light as a wave in the electric and magnetic fields would explain the photoelectric emission of electrons as a result of the electrons gaining enough energy to escape the metal surface from being shaken by the electric and magnetic field disturbances of the light wave. As the light is made brighter, these disturbances are greater, since the light wave has greater amplitude.

However, Einstein realized in 1905 that this picture could not fully explain the experimental observations of the photoelectric effect. In particular:

[1] This works with visible light for the other alkali metals too, and there are even semi-conductors with special coatings that will emit electrons all the way through the visible spectrum and into the infra-red.

- as the light intensity is turned down, there is no threshold intensity below which no electrons are emitted: they continue being emitted (albeit less often) no matter how dim the light is, and indeed some may be emitted *as soon as the light is turned on*!

- as the light intensity is increased, the electrons which are emitted do not get more energetic. There are more of them, but their (kinetic) energy remains the same.

- if the frequency of the light is changed, there is a certain frequency below which no electrons will be emitted *no matter how intense the light is made.*

This led Einstein to relate these results to Planck's hypothesis that matter can only accept or emit radiation in *quanta* of size $E = hf$, and postulate that light comprises a finite number of individual packets of energy (which we now call *photons*) which carry an energy hf and transfer all their energy to the photoelectrons during a collision.

The photoelectrons need a certain minimum energy ϕ to escape from the metal, known as the *work function*, so the minimum frequency f_0 of photon that can give rise to photoelectrons must have this energy $hf_0 = \phi$, where h is Planck's constant, $6.64 \times 10^{-34}\,\mathrm{J\,s}$.

The kinetic energy $\frac{1}{2}m_\mathrm{e}v^2$ of a photoelectron leaving the metal surface also comes from the energy given to it by the photon that it absorbed: any extra energy above the minimum required that the incoming photon has—once the energy of the work function has been used to escape from the metal—goes into the photoelecton's kinetic energy:

$$\frac{1}{2}m_\mathrm{e}v^2 = hf - \phi.$$

In this way, Einstein was able to explain all of the experimental results in a simple theory, and his equation for the kinetic energy above was verified experimentally in 1912[2], but one which was at odds with many other extremely wide ranging experiments which had lead scientists to the conclusion that light is a form of wave motion.

[2]Following the publication for an accurate value for the mass of the electron produced by using Millikan's oil drop experiment and earlier measurements of the electron specific charge.