NCEA Level 3 Physics (Modern Physics)

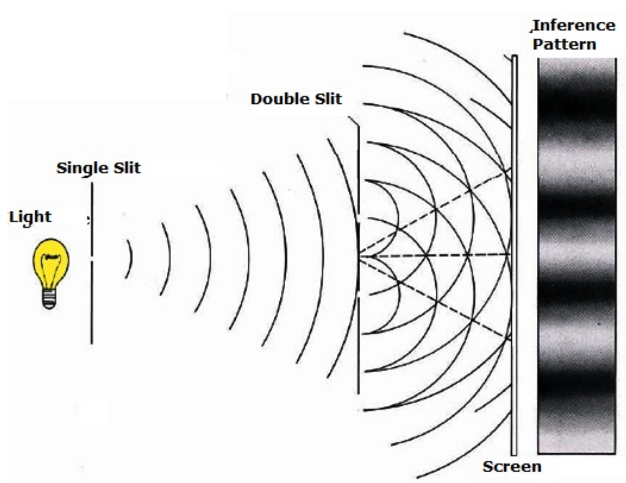
Heinrich Hertz was a German physicist who was the first to conclusively prove the existence of electro-magnetic waves (light). In 1887, he observed an interesting phenomenon: when light strikes a metal surface, electrons are emitted. This is known as the *photoelectric effect*.

The photoelectric effect

When UV light falls on a sheet of metal, its energy is absorbed and some is transferred to electrons which are ejected as fast-moving particles (photoelectrons). A certain amount of energy must be transferred to an electron before it can be emitted; this amount is dependent on the type of metal and is known as the *work function* ϕ of the metal. This energy is quite small in absolute terms, and can easily be provided by electro-magnetic waves. However, some observations surrounding the photoelectric effect cannot be explained by treating light as a wave, and seem to suggest that light in fact acts as a particle!

Predicted by the wave theory	**Observed phenomena**
A brighter light would cause electrons to have greater kinetic energy when released.	Brighter light caused **more** electrons of the **same** kinetic energy to be released.
If a dim light were used, electrons would need to accumulate energy to overcome the work function and so would not be emitted instantaneously.	When UV light was used, even the faintest light caused instant electron emission.
The frequency of light would not cause any change in observations.	A higher frequency of light caused electrons to have a higher kinetic energy. Below a certain frequency, no electrons were emitted.

On the other hand, from experiments like Young's double-slit experiment, we know that light can sometimes act as a wave!



Albert Einstein, a German physicist, discussed the photoelectric effect in 1905 using the idea of *quantization* that was put forward by Max Plank. In essence, it was proposed that electro-magnetic radiation comes in packets (quanta) of fixed size known as *photons*; the energy of an individual photon is directly proportional to the frequency of light, with a constant of proportionality $h \approx 6.63 \times 10^{-34}\,\mathrm{J\,s}$ known as *Plank's constant*:

$$E = hf.$$

If we apply this to the photoelectric effect, we find that the energy of emitted photoelectrons when light of frequency f is incident can be found (and recalling that ϕ is the work function of the metal).

$$E = hf - \phi$$

This allows us to calculate the *critical frequency* of the metal — the frequency f_0 which is at the threshold of electron emission. If the frequency of incident light is less than f_0, no light is emitted.

$$0 = hf_0 - \phi \implies f_0 = \frac{\phi}{h}$$

We can easily see the effects of the photoelectric effect by examining a photoelectric cell. Recall that voltage is simply $V = \frac{E}{q}$, and so $E = qV$. Hence, if an electron of charge $e = 1.6 \times 10^{-19}\,\mathrm{C}$ is emitted from the cell then the cell must lose an energy eV; since energy is conserved, this energy must have gone to the emitted electron.

Questions

Useful data: $c \approx 2.99 \times 10^8\,\mathrm{m\,s^{-1}}$, $h \approx 6.63 \times 10^{-34}\,\mathrm{J\,s}$, $e \approx 1.6 \times 10^{-19}\,\mathrm{C}$, $1\,\mathrm{eV} \approx 1.6 \times 10^{-19}\,\mathrm{J}$

1. The frequency of a photon of red light is $4.57 \times 10^{14}\,\mathrm{Hz}$. Calculate the energy of the photon.
2. Calculate the energy of a photon of blue light with a wavelength of $4.0 \times 10^{-7}\,\mathrm{m\,s^{-1}}$.
3. Consider the following properties of light; which are better explained by a wave theory of light, and which by a particle theory?
   (a) Reflection
   (b) Diffraction
   (c) Interference
   (d) The photoelectric effect
4. A metal plate has a work function of $\phi = 5\,\mathrm{eV}$. If EM radiation with a wavelength of $\lambda = 2 \times 10^{-7}\,\mathrm{m}$ falls on the plate, what is the energy of the emitted photons?
5. In an experiment, blue light of frequency $7 \times 10^{14}\,\mathrm{Hz}$ shines on a photoelectric cell and produces a cutoff voltage of $1.63\,\mathrm{V}$.
   (a) What is the energy of a photon of blue light?
   (b) What is the maximum kinetic energy of the ejected electrons?
   (c) What is the work function of the metal?
   (d) What is the threshold frequency of the metal?
6. What does the maximum kinetic energy of photoelectrons emitted from a particular metal depend on?