# Quantum Behaviour

Photons appear to be random – they hit a camera screen in random places (this can be seen on a short exposure camera film). This randomness can be calculated using probabilities.

An electron becomes excited and jumps to a higher orbital. It is unstable here so it drops down to a lower orbital, emitting a photon of light, equivalent to the energy put in ($E_{IN}$ = hf). This means that they emit discrete wavelengths of light.

*Evidence for Quantum Phenomena*

**The Photoelectric Effect**

The photoelectric effect provides evidence that electromagnetic waves have particle-like behaviour which is more pronounced at the **short-wavelength** end of the spectrum. In the photoelectric effect, electrons are emitted from a metal surface when it absorbs electromagnetic radiation.

The results of photoelectricity experiments show that:

- There is no emission of electrons below a certain frequency, called the **threshold frequency, $f_0$,** which differs for each metal.
- Above this frequency, electrons are emitted with a range of kinetic energies up to a maximum ($\frac{1}{2} mv^2)_{max}$.
- Increasing the **frequency** of the radiation causes and increase in the maximum kinetic energy of the emitted electrons, but has no effect on the photoelectric current, i.e. the rate of emission of electrons.
- Increasing the **intensity** of the radiation has **no effect** if the frequency is below the threshold frequency. For frequencies above the threshold, it causes an **increase** in the photoelectric current, so the electrons are emitted at a greater rate.

The wave model cannot explain this behaviour; if electromagnetic radiation is a continuous stream of energy then radiation of all frequencies should cause photoelectric emission. It should only be a matter of time for an electron to absorb enough energy to be able to escape from the attractive forces of the positive ions in the metal.

The explanation of the photoelectric effect relies on the concept of a photon, a quantum packet of energy. A quantum refers to the smallest amount of quantity that can exist.

The relationship between the energy, E, of a photon of electromagnetic radiation and its frequency, f, is:

$$E = hf$$

Where *h* is **Planck's constant, 6.626 $10^{-34}$ Js**.

The energy of a photon can be measured in either joules or **electronvolts**. One electronvolt is the energy transfer when an **electron** moves through a **potential difference of 1 volt.**

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

The threshold wavelength, $\lambda_0$, is the wavelength of the waves that have the threshold frequency.

$$\lambda_0 = c / f_0$$

*Einstein's Theory of Photoelectric Emission*

- An electron needs to absorb a minimum amount of energy to escape from a metal. This minimum amount of energy is a property of the metal and if called the **work function, ϕ** .
- If the photons of the incident radiation have energy *hf* less than ϕ, then there is no emission of electrons.
- Emission becomes just possible when hf = ϕ.
- For photons with energy greater than φ, the electrons emitted have a range of energies, those with the maximum energy being the ones that needed the maximum energy to escape.
- Increasing the intensity of the radiation increases the number of photons incident each second. This causes a greater emission of electrons, but does not affect their maximum kinetic energy,

Einstein's photoelectric equation related the maximum kinetic energy of the emitted electrons to the work function and the energy of each photon:

$$K.E._{max} = hf - \phi$$

Where ϕ is the work function.

At the threshold frequency, the minimum frequency that can cause photoelectric emission from a given metal, $(\frac{1}{2} mv^2)_{max}$ is zero, and so the equation becomes $hf_0 = \phi$.

*Particles or Waves*

Waves can show particle-like behaviour in photoelectric emission. Similarly, particles can show wave-like behaviour if they diffract or superpose (properties unique to waves). All particles have an associated wavelength called the **de Broglie wavelength:**

The wavelength, λ, of a particle is related to its momentum, *p*, by the de Broglie equation:

$$\lambda = h/p = h/mv$$

Where *h* is Planck's constant.

There are two separate models of how matter behaves. The particle model explains such phenomena as ionisation and photoelectricity, while the wave model explains superposition and diffraction. Other particles such as protons and neutrons also show wave-like behaviour.

One revolution of a phasor arrow is the distance of one wavelength. We can use T = 1/f to work out the time period.

Photons do not necessarily travel in straight lines, but go in every imaginable direction. There is just a higher probability from summing up all of the individual probabilities.

e.g. Angle or reflection:

Angle of incidence = angle of reflection. This is due to a higher probability.

The sum of the phasor arrows that reflect off the surface either side of the centre will be zero, or negligible. This is because they will be pointing in lots of different directions and hence will add up to almost nothing.

When the light reflects from the centre of the material, the phasor arrows are approximately in phase when they reach the receiver. This is where we expect reflection to be the most, i.e. where i = r.

The photons of light bombard the mirror with energy hf. The atoms in the mirror absorb this energy and re-emit the same energy due to electron excitation. These can be emitted in any direction but there is a higher probability that they will reach the receiver in phase if they emitted from the centre of the material. No matter which direction they travel in, i.e. not necessarily in straight lines, this will be true.

*Calculating probability of quantum events*

To calculate the probability of an event happening you square the resultant amplitude of the phasors.

*Combining relativity and Quantum Ideas*

Louis de Broglie thought that electrons have a wavelength and a frequency. The diffraction gratings at the time were not small enough so he used the atomic spacing in materials. This gave a diffraction pattern of the Airy disc. This has a circular aperture with a bright region in the centre, surrounded by concentric circles.

$E = mc^2$, $E = hf$

$mc^2 = hf$
$v = f\lambda$; $f = v / \lambda$
$mc^2 = hv / \lambda$ (c's cancel as electromagnetic radiation travels at c).
$mc = h / \lambda$

$$\boldsymbol{\lambda = h / mv = h / p}$$

Where $p$ is the momentum, and $h$ is Planck's constant. This is known as the **de Broglie wavelength**.

We can conclude that photons and electrons must have momentum. This is odd as photons have no mass, but **momentum = mass x velocity**.

**p = mv (mass of electron = $10^{-31}$kg)**

Macroscopic objects also have these wavelengths, but we cannot observe the wavelength because our mass is so large compared to *h.* So our momentum is very large, and *h* is very small. This means the wavelength we have is infinitesimally small to be noticeable.

A phasor rotates at the following speed:

$$\mathbf{f = E_{kinetic} / h}$$

$V = J / Q$
Energy = charge X voltage
Hence, $E = eV$
Hence, $eV = hf$
$h = eV / f$
$h = 1.6 \times 10^{-19} \times$ voltage needed to get red LED to light up / $5 \times 10^{14}$ (frequency of red light)