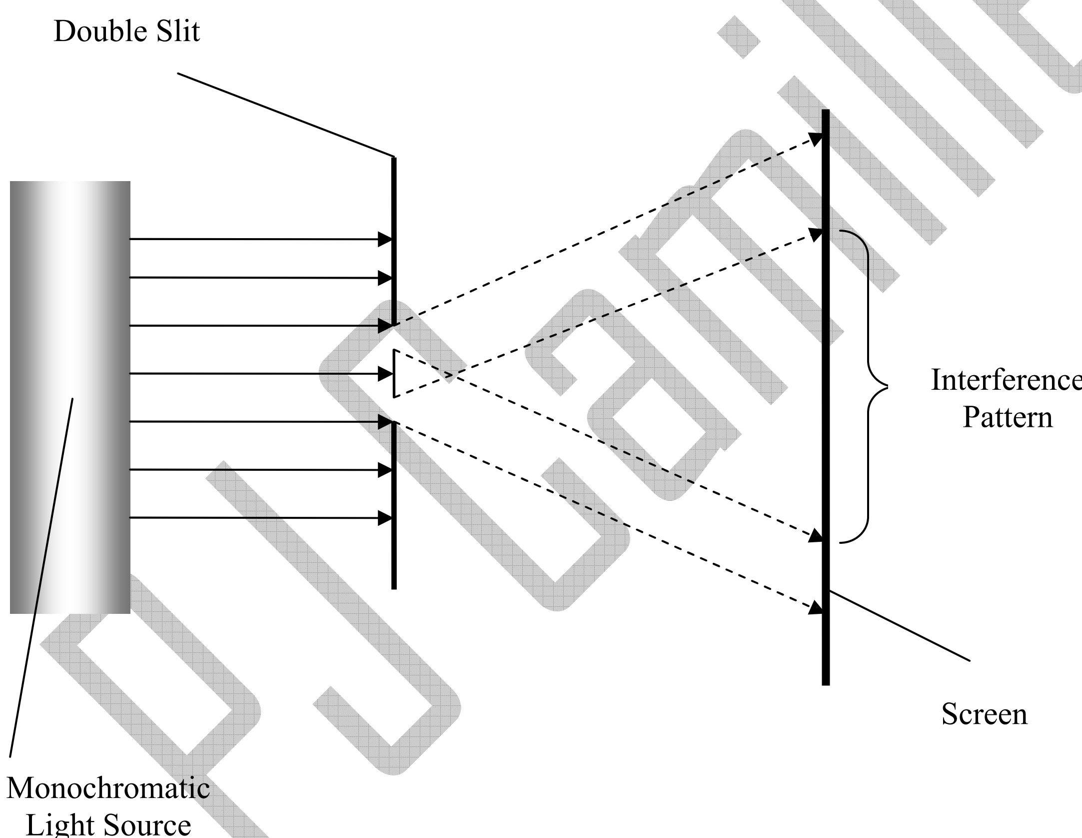
The Photoelectric Effect. The Wave particle duality of light

Light, like any other E.M.R (electromagnetic radiation) has got a dual nature. That is there are experiments that prove that it is made up of waves while other experiments prove that it is made up of particles.

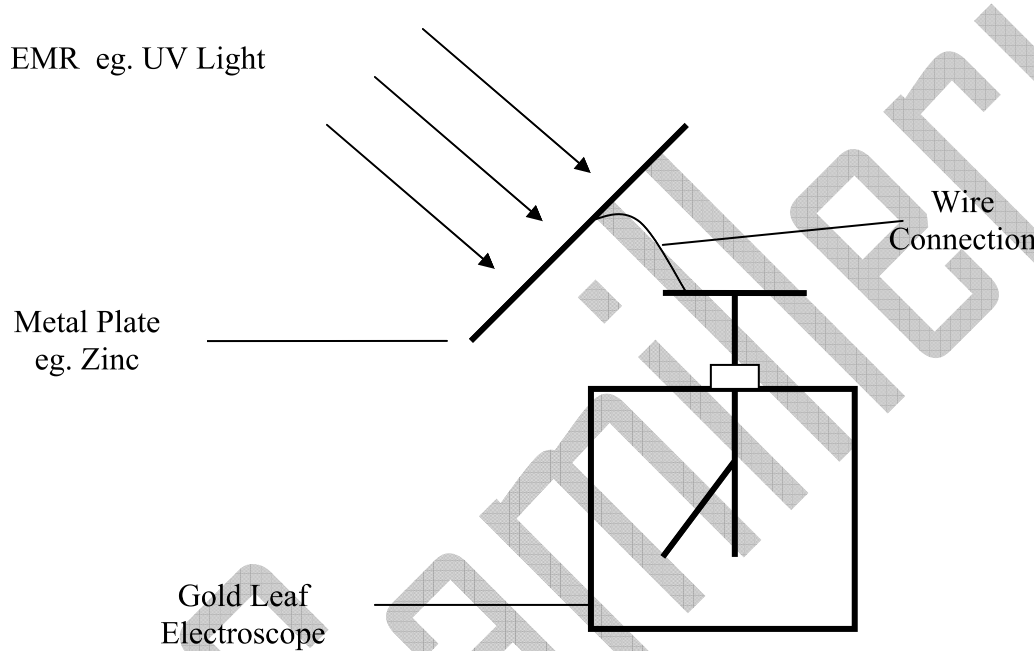
- The experiment that proves that light is made up of waves is the Diffraction of Light experiment. (Refer to diffraction of light by a single slit, double slit or diffraction grating.



- The experiment that proves that light is particulate in nature is the Photoelectric Effect.

The Phenomenon of Photoelectric Emission:

EMR incident on a metal surface can cause electrons to be emitted from the surface.



Observations:

When UV light is radiated onto an uncharged zinc plate it is observed that **instantaneously** a divergence is noted on the gold leaf electroscope. Further experimentation shows that the electroscope has attained a positive charge.
This phenomenon is not repeated at any frequency of emr.

Conclusions drawn:

1. Emission only occurs if the frequency of the incident radiation is above some minimum **threshold frequency** and depends on the particular metal being irradiated. That is, NOT all metals are excited by the same minimal threshold frequency. For instance the threshold frequency of sodium is in the yellow region while that of zinc is in the UV.
2. Emission commences instantaneously with the irradiation of the surface.
3. If the incident radiation is of a single frequency (above the threshold frequency) the number of electrons emitted per second is proportional to the intensity of the radiation.
4. The emitted electrons have various KEs, ranging from zero to a maximum. Increasing the frequency of the incident radiation increases the energies of the emitted electrons and the particular the maximum KE.

5. Intensity of light has no effect on the KEs off the electrons but on the quantity.

The Inability of the Wave Theory of light to explain the observations:

In the photoelectric effect, the currently outer electrons orbiting a nucleus would absorb the energy provided by the emr and gain sufficient KE to break away from the nuclear attraction. As an effect the electron becomes free from nuclear attraction and achieve infinity, simultaneously causing the atom involved to gain a positive charge.

If light is made up waves then it should be expected that the energy content of light is continuous. This would imply that

- It would be a matter of time before an electron would acquire enough energy to become free from nuclear attraction. This does not occur. In fact unless emission occurs instantaneously and simultaneously with the irradiation of light it would not occur at all.
- Emission would occur at any frequency. In fact it does not. Emission would occur solely if the minimal requirement of the electron considered are being met. Therefore emission is frequency related.
- Increasing the frequency will not increase the number of electrons emitted but would increase the maximum KE threshold.
- On the basis of the wave theory energy is distributed uniformly on the wave front. Therefore each electron in the surface of the metal concerned should receive the same amount of energy. On the basis of this opinion then it would be expected that in the consequence that the intensity of the light is low no emission would occur. Still from observations it is seen that using the right frequency of light, emission would still be obtained.

Einstein's Theory of the Photoelectric Effect. The Particulate nature of light.

Einstein proposed light to be made up of quantised packets of energy (Planck's Theory) which he referred to as photons. Accordingly these photons had an energetic content related to the frequency. That is the higher the frequency the higher would be the energetic content.

- Einstein proposed that an electron would be emitted only if it is hit by a photon and the energy of the photon is absorbed. In the consequence of a collision the electron would absorb all of the energy of the photon or none at all.

- Energy cannot be shared between electrons.

- Consequently the amount of emitted electrons is proportional to the intensity or number of incident photons.

- The energy of a photon is constant but any number of photons may spread out in space. Thus even though the intensity of light may decrease accordingly to

Newton's Inverse Square Law, the energy per photon would remain constant and unaffected by distance.

The relation between Frequency and Energy in the Photon

$$E=hf$$

h is a constant referred to as Planck's Constant.

f is the frequency of the emr being irradiated on the surface.

Einstein reasoned that the energy provided by the photon is initially utilised to allow the electron to break free from the nuclear attraction.
Any extra remaining energy would be manifested by the electron as KE.

This is summed up in Einstein's Photoelectric Equation.

$$hf = W + \tfrac{1}{2} mv^2$$

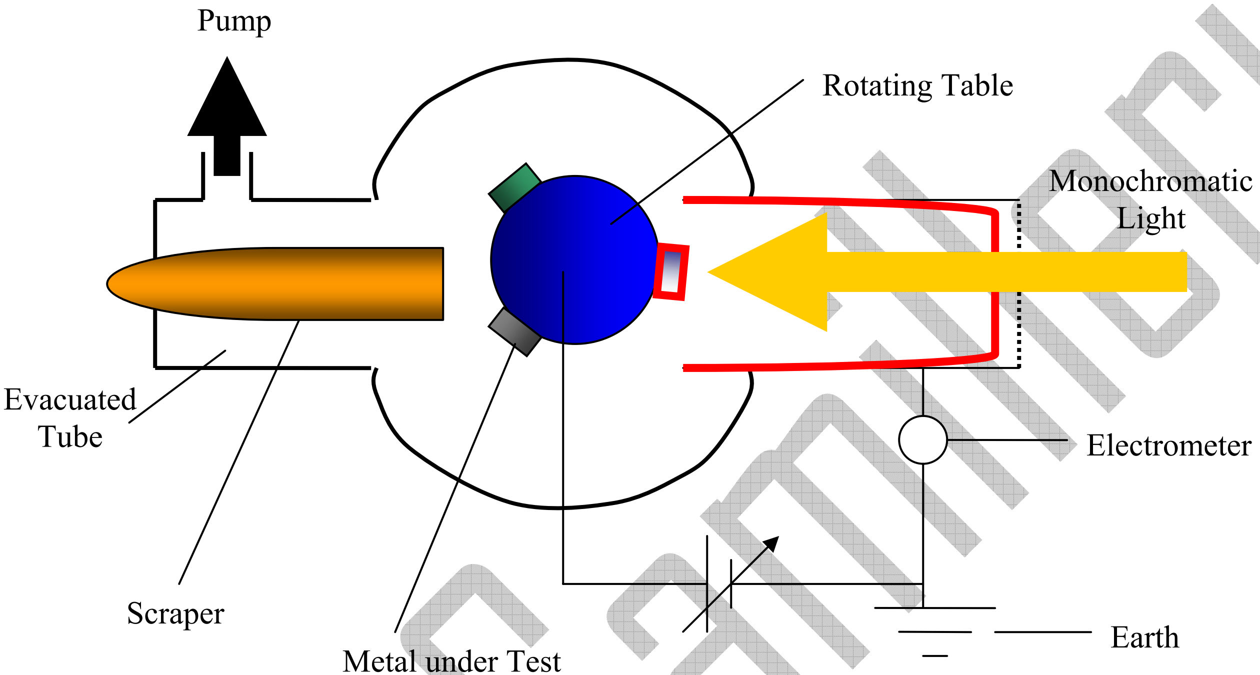
hf= the energy of each incident measured in Joules
W = The Work Function of the surface that is the minimum amount of energy that has to be given to an electron to release it from the surface.
$\frac{1}{2} mv^2$ = The maximum kinetic energy of the emitted electrons.

NB. There is a minimum frequency at which emission would just occur. This frequency is referred to as the **threshold frequency** represented by $\mathbf{f_0}$. Thus the work function has an energetic value proportional to the threshold frequency.

Thus $W = hf_o$.

$$hf = hf_o + \tfrac{1}{2} mv^2$$

Millikan's Experiment on the verification of Einstein's Photoelectric equation and measurement of h



Method:
The metal under test is fitted on a rotating table as shown.
Prior to being placed to receive emr, its surface is scraped clean by a scraper.
Then it is irradiated with a chosen frequency of light.
If electron emission occurs it is captured by the electrode and transferred to earth via an electrometer that registers its emission by a steady current in the region of milliamperes.

The potential difference between the metal and the rotating table is increased until no more current is registered on the meter. This potential difference would be equivalent to the stopping potential of the metal.
The work done by an electron in moving against a stopping potential is give by the equation:

$$eV = \frac{1}{2} mv^2$$

Where eV is the energy of the electron in electronvolts.
Incidentally e is the electronic charge of 1.6×10^{-19}C.
$\frac{1}{2} mv^2$ is the maximum kinetic energy of an emitted electron.

By the photoelectric equation:

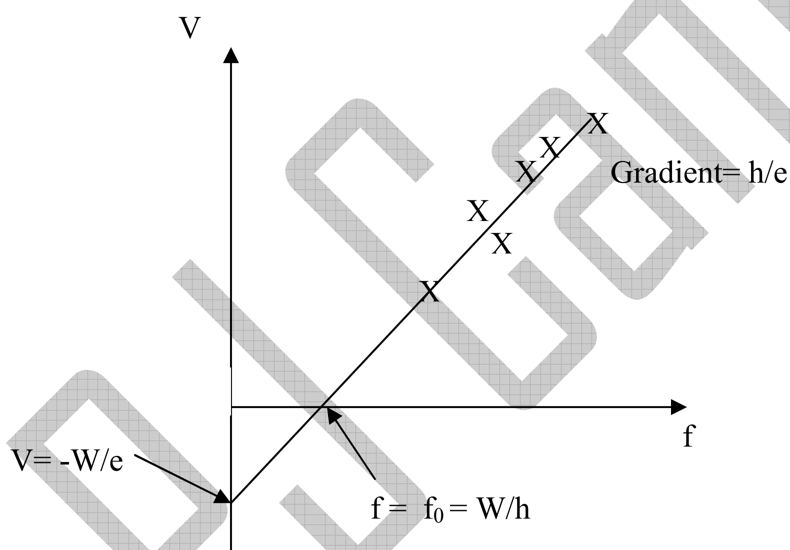
$$hf = W + \tfrac{1}{2}mv^2$$

Thus

$$hf\uparrow = W + eV\uparrow$$

i.e $$V\uparrow = (hf\uparrow)/e - W/e$$

Therefore for any given range for the specific metal involved plot a graph of V against f.
A linear relationship is obtained.
Thus the value of Planck's constant may be measured.



NB: Changing the metal target would give rise to the same gradient.
The intercepts would be different depending on the work function of the metal involved. The more tightly held the outer electrons are the larger would be the value of the work function thus the larger the threshold frequency would have to be.

Wave-Particle Duality

The idea that light may have a wavelike or particulate nature are just two notions that express the behaviour of light under different circumstances.

De Broglie stated that matter might also have a dual nature. He proposed that any particle of momentum p has an associated wavelength λ referred to as de Broglie wavelength.

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

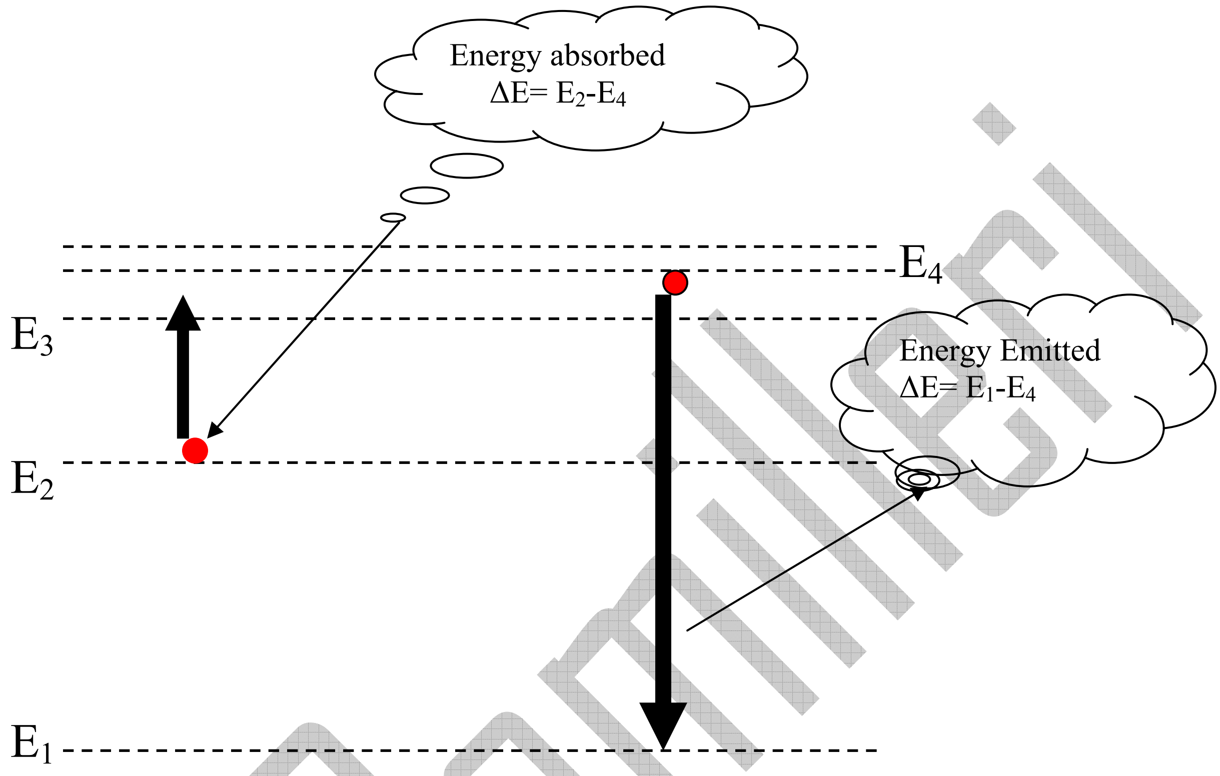
The Atomic Structure and Energy Levels

The alpha scattering experiment proved that the atom is composed of a central highly compact positive nucleus with a cloud of orbiting negative electrons. These electrons being negative could only exist away from the nucleus only if being potentially stable at specific distances from the nucleus referred to as electron shells, electron orbitals or energy levels.

Bohr's proposals:

1. The angular momenta of the electrons are whole multiples of h/2π. Meaning that the energy of the lectrons is not continous but quantised and that they can exist at certain fixed distances from the nucleus. Therefore electrons can only have certain values of energy, thus the energy levels.

2. An electron can jump from an orbit to another prescribed energy level if it gains or looses a specified amount of energy. Thus if it jumps to a level which is nearer to the nucleus it looses or dissipates an amount of energy equivalent to the energetic difference between the levels considered. On the other hand if it jumps to a level which is further out from he nucleus it would require to absorb an amount of energy equivalent to the difference between the energy levels considered.



In any situation the change in energy $\Delta E = hf$.
The larger ΔE is the larger f absorbed or emitted would be.
In this situation as f increases the wavelength λ would decrease.

Absorption and emission spectra.

Ionization and Excitation Potentials

The minimum amount of energy required to ionise an atom which is in its ground state that is to remove the most loosely bound electron is referred to as the 1st ionisation energy of the atom.
This would be equivalent to the work function of the atom considered. Any energy above the work function would cause the electron to gain KE.
The ionisation potential is measured in Volts.

Thus for instance the ionisation potential of hydrogen (hydrogen contains one electron only) is equivalent to 13.6V.

The energy required to allow an electron to become free in the hydrogen atom is equivalent to QV.

Thus: Work = QV = 1 electronic charge X 13.6 V = 13.6 eV

$$13.6\text{eV} = 1.6 \times 10^{-19}\ \text{C} \times 13.6\text{V} = 2.178 \times 10^{-18}\ \text{J}$$

The minimal frequency that it would be requiring just to become free from the ground state can be calculated as follows.

$$13.6eV = 2.178 \times 10^{-18}\ J = hf \quad (h = 6.64 \times 10^{-34})$$

$$\text{Thus } 2.178 \times 10^{-18}\ J / h = f = 3.28 \times 10^{15}\ Hz$$

Therefore in other words, in order for the electron just to become free, it must be irradiated with a frequency of light with a minimal value of 3.28×10^{15} Hz. This would be equivalent to he ABSORBTION SPECTRA for hydrogen.

On the other hand if the electron were to fall from infinity to the lowest possible level it would emit the same frequency giving rise to EMISSION SPECTRA.

Types of Spectra

Spectra are of two basic types:

Emission spectra: These occur when a heated substance emits specific waves that are synonymous with that particular material. Usually the waves obtained are quantified by passing the emr through a diffraction grating or prism. Usually a grating is preferred as in the case of the prism there are diverse optical aberrations including the distortion of the waves.

Emission spectra fall in two categories.

Line spectra: These arise when the substance involved is usually made up of one single element therefore emitting single specific waves.

Band Spectra: Arise when the material under test is usually composed of two or more elements all of which emit their specific waves producing lines that are either very close to each other or even he same.

In the case of the sun, it emits white light. White light from the sun is the emission spectrum consisting of all the possible wavelengths of emr.

The Absorption Spectrum:

When light passes through a vaporised material some parts of the spectrum whose frequencies would be equivalent to the energy requirements of the substance would be absorbed. Thus the resultant spectrum obtained will have specific lines missing.

Line absorption spectrum arise when only specific wavelengths would be missing from the resultant light. These usually arise when the light is being passed through on single element.

Band absorption spectra arise when white light is incident on a compound usually made up of two or more elements.