WJEC (Wales) Physics A-level

Topic 3.4: Photons

Notes

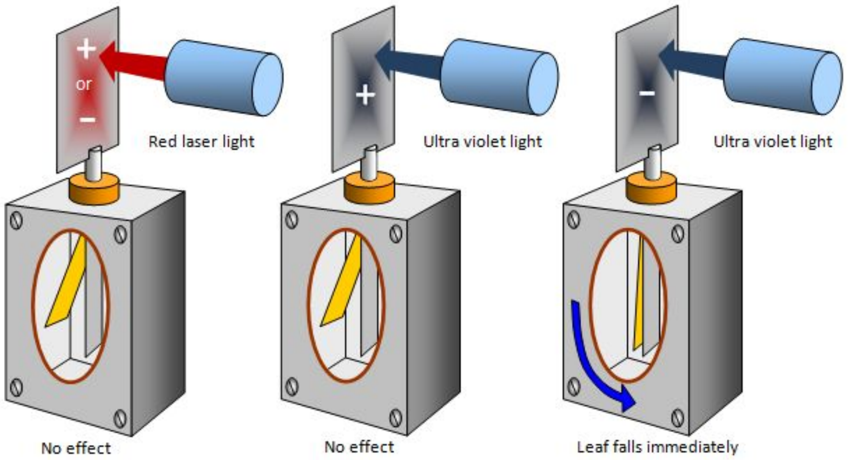
The Nature of Light

There are two key experiments which show what appear to be contradicting statements about the nature of light. The first is Young's double slit experiment which shows that light interferes just like waves do to produce an interference pattern. The second experiment is an experiment based on the photoelectric effect. This effect demonstrates that light also behaves like a particle.

These particles have been shown to be discrete packets of energy called **photons**.

Photoelectric Effect

You can demonstrate the photoelectric effect using a gold leaf electroscope.



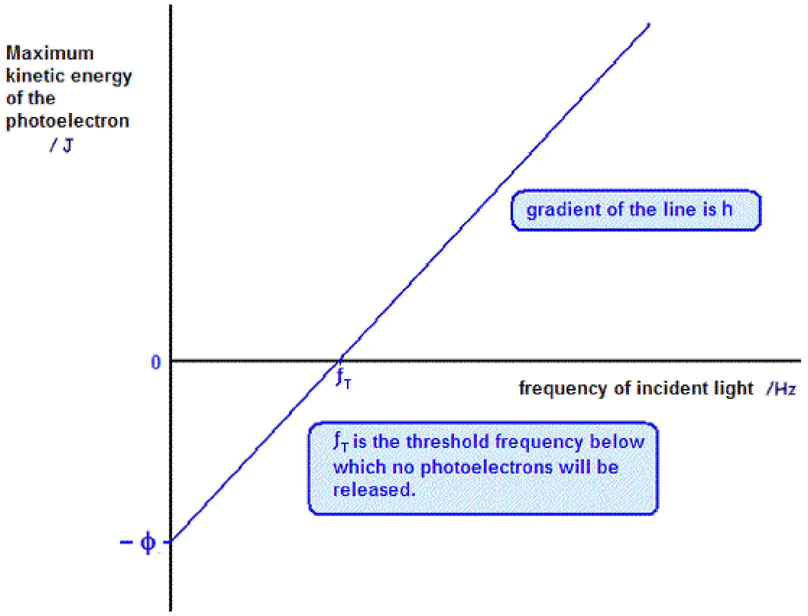
http://www.schoolphysics.co.uk/age16-19/Quantum%20physics/text/Photoelectric_effect/index.html?PHPSESSID=b8fa1ac4f3073e77ff1cc2039741676b

To observe the effect, you need the plate and metal insides to be negatively charged. As the gold leaf is free to move, it will repel the metal rod on the inside (because like charges repel) and move away. When light of a high enough energy is shone onto the plate, it **ejects some electrons**. This reduces the negative charge in the electroscope and so the repulsive force on the gold foil reduces. Therefore, it falls down.

The ejection of electrons is the photoelectric effect.

Graph

https://www.cyberphysics.co.uk/topics/atomic/Photoelectric_effect/Photoelectric_effect_graph.htmhttps:/bit.ly/2wYcDSP



Using a gold leaf electroscope, we can see that there is a minimum energy of light for emission of electrons to occur. The energy of light is **directly proportional to the frequency of that light**. However, the minimum energy for emission suggests there is some energy that must be overcome in order to eject electrons. This is called the **work function** and is given the symbol ϕ.

The energy of a light photon is given by the relationship:

$$E = hf$$

E is the energy, h is a constant of proportionality called the Planck constant, and f is the frequency of the light.

Therefore, if a photon is incident on a piece of metal, which has a work function ϕ, the energy left over is:

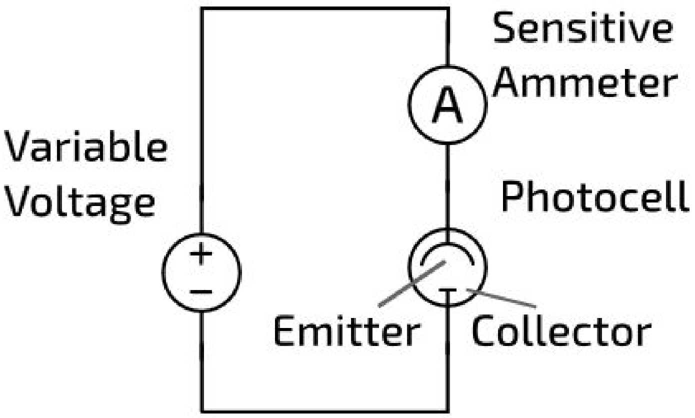
$$E_{kmax} = hf - \phi$$

This is the maximum kinetic energy of the ejected electrons. If we look at the graph above, we can see that this matches. The threshold frequency f_T, is when the maximum kinetic energy is zero. Hence:

$$0 = hf_T - \phi$$

$$f_T = \frac{\phi}{h}$$

Vacuum Photocell



https://isaacphysics.org/concepts/cp_photoelectric_effect

A vacuum photocell is a device which can be used to measure the maximum kinetic energy of electrons. Light of a known frequency/wavelength is shone onto a photosensitive cathode. Due to this, electrons are ejected from the cathode. This will create a current in our circuit. Then, using a variable voltage source, the voltage is increased. This will mean electrons will have to overcome an **electrostatic repulsion** to get to the collector and provide a current.

Eventually, when the voltage is raised high enough, no electrons reach the collector and there is zero current in the circuit. This is at the **stopping voltage**. As the electrons near the collector, their kinetic energy is turned into potential energy which is given by:

$$E = eV$$

V is the stopping voltage and e is the electron charge. Therefore the kinetic energy of those electrons is equal to eV . If the stopping voltage is 3V, then the maximum kinetic energy of the electrons is 3 electron-volts and $3\times\left(1.6\times10^{-19}\right) = 4.8\times10^{-19}$ joules.

In a vacuum photocell, **not all the electrons have the maximum kinetic energy** because some lose energy during collisions with the metal atoms in the container or with air molecules inside if the vacuum is not perfect. However, the maximum kinetic energy of electrons will be the few remaining electrons which cause the current to drop to zero which corresponds with the stopping voltage. Therefore, the stopping voltage provides you with the maximum kinetic energy of ejected electrons.

You can plot maximum kinetic energy against the frequency of light on a graph (see above) to calculate threshold frequency, work function and the Planck constant.

Electromagnetic Spectrum

The visible range is from 400nm to 700nm approximately. The 400nm end is for violet light and the 700nm end is for red light.

Order of magnitude approximations for the wavelengths and typical photon energies of the other parts of the spectrum are given here:

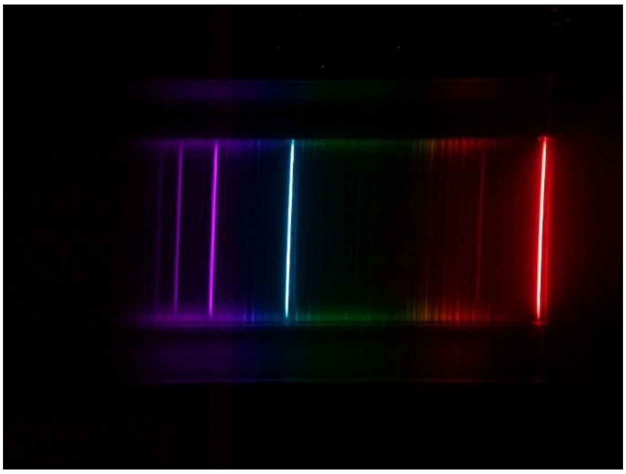
Region	Wavelength (order of magnitude)	Typical photon energies
Radio	$10^{3}\ m$	$10^{-9}\ eV$
Microwave	$10^{-2}\ m$	$10^{-4}\ eV$
Infrared	$10^{-5}\ m$	$10^{-1}\ eV$
Ultraviolet	$10^{-8}\ m$	$10^{2}\ eV$
X-rays	$10^{-10}\ m$	$10^{4}\ eV$
Gamma rays	$10^{-12}\ m$	$10^{6}\ eV$

Vapour Lamps – Emission and Absorption Lines

Vapour lamps are tubes containing a gas. A **high voltage source** is used to provide electrons with energy which then transfer some of their energy to the gas atoms. This excites electrons within the atoms causing them to rise to higher energy states. They then fall back down to the lower energy state (from which they came) **releasing a photon**. Because there are multiple energy states within atoms, photons of different energies are released. You, therefore, would see a combination of the colours from the lamp.

To separate the colours you can put the light through a **prism**. By refracting it, the **colours separate** (due to varying wavelengths) and provide you with the emission spectrum.

You can also pass this light through a **diffraction grating and it will show you the individual colours** separated out. This is what it will look like (this example is hydrogen):

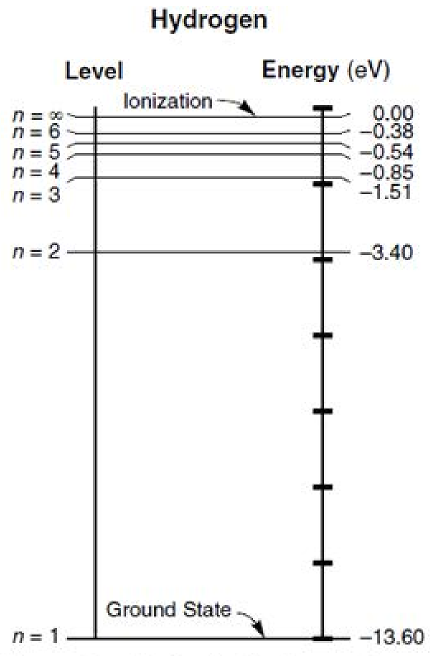


http://astro.psu.edu/public-outreach/fireworks-masks-1/sample-spectra-of-gases

Because the emission spectrum is a characteristic of the atoms' energy levels, the absorption spectrum is the **'opposite'** because the energy difference between levels is exactly the same independent of absorption or emission.

Energy Level Diagrams

These diagrams can help us to show, visually, why there are thin, discrete, emission and absorption lines.



Energy Levels for the Hydrogen Atom

The coloured lines we see above arise from electrons falling between some of these states shown to the left. All transitions will emit a photon of some type of electromagnetic radiation, however, only four of the emissions are visible.

To calculate the wavelengths of the emissions we need to know the energy difference between the states and convert this into a wavelength using:

$$\Delta E = hf = \frac{hc}{\lambda} \quad \Rightarrow \lambda = \frac{hc}{\Delta E}$$

https://aplusphysics.com/courses/regents/modern/regents_modern_atomic_models.html

Starting from the red end of the spectrum, our transitions are:

n = 3 to n = 2

n = 4 to n = 2

n = 5 to n = 2

n = 6 to n = 2

For the transition n = 3 to n = 2

$$\Delta E = -1.51 - (-3.40) = 1.89\ eV$$

$$\lambda = \frac{(6.6\times10^{-34})(3.0\times10^{8})}{(1.89)(1.6\times10^{-19})} = 656\ nm$$

This wavelength corresponds to the red light we see in the spectrum.

The same idea applies to absorption except the photons are absorbed instead of emitted. Therefore the electron rises to a higher energy state.

Ionisation Energy

The ionisation energy is the energy an electron requires to escape an atom leaving it as an ion. This requires the electron to be moved up through all of the energy states until the state with zero energy. The negative sign for the energies means the electron is **bound** to the atom. When the energy becomes zero, the electron escapes.

To find the ionisation energy, you need to work out the energy difference between ground state and zero energy ($n = \infty$) state. For the hydrogen atom, you can see the ionisation energy is 13.60eV.

Electron Diffraction

After the photoelectric effect had shown that light behaves as a wave and a particle, people wondered whether other particles could behave like waves, such as the electron.
An electron gun (a high voltage accelerator) rapidly increases the speed of electrons and directs them through what is often a very thin slice of carbon. The atomic spacings act as the slits, producing a diffraction pattern. The pattern is made up of alternating bright and dark circles centred on a common point in front of the electron gun. This suggests that the electrons have interfered like waves do to produce the bright and dark areas.

Therefore, it was concluded that particles also have wave-like properties.

De Broglie Wavelength

The De Broglie wavelength is the ‘wavelength’ of a particle. You can calculate it if you know the momentum of the particle, p. The reason why we do not notice wave-like effects in everyday objects is that their wavelength is so very small that the size of the gap required to diffract them would not be possible to achieve.

$$\lambda = \frac{h}{p}$$

This can also be used for calculating the momentum of photons just by rearranging and substituting in the wavelength of the photons/light. Photons have a momentum but no mass hence you cannot calculate their momentum in the usual $(p = mv)$ way.

Radiation Pressure

Radiation pressure is when there is a **change in momentum of electromagnetic radiation** which causes a pressure to be exerted on a surface.

To calculate the pressure exerted on a surface you first need to calculate the force which is given by the rate of change of momentum and then divide by the cross-sectional area of the surface.

An example calculation is given below:

2000 photons strike and reflect off a panel of surface area $4\ m^2$ every second. They have a frequency of $10^{18}\ Hz$. Calculate the pressure exerted on the panel.

Step 1)

The change in momentum of each photon is equal to $\Delta p = 2p_0$ because they are reflected.

$$\Delta p = 2\frac{hf}{c} = \frac{2(6.6\times10^{-34})(10^{18})}{(3.0\times10^{8})} = 4.4 \times 10^{-24}\ kgm/s$$

Therefore, the change in momentum of all incident photons within one second equals $4.4\times10^{-24}\times2000 = 8.8\times10^{-21}\ kgm/s$.

Step 2)

The force on the panel is therefore $F = \frac{\Delta p}{\Delta t} = 8.8 \times 10^{-21}\ N$.

Step 3)

Pressure, $P = \frac{F}{A} = \frac{8.8\times10^{-21}}{4} = 2.2 \times 10^{-21}\ Pa$.