AS Level Physics

Chapter 11 – Quantum Physics

11.1.1 Photons

Notes

Light.

Light, as we know, is an electromagnetic (EM) wave that travels roughly at $3 \times 10^8\ ms^{-1}$.

We know this because light travels from the Moon to the Earth in approximately 1.25 seconds. The average distance between the Moon and the Earth is $3.8 \times 10^8\ m$. Therefore using:

$$speed = \frac{distance}{time}$$

We get:

$$speed\ of\ light, \mathbf{c} = \frac{3.8 \times 10^8\ m}{1.25\ s} = \mathbf{3 \times 10^8\ ms^{-1}\ (2\ s.f.)}$$

Light. A Wave or Particle?

If you asked a scientist in the late 1800s what light was, they would gladly show you dozens of neat experiments demonstrating that light must be a wave.

Experiments would reveal that light has properties like interference, diffraction, and polarisation that can only be explained if light is thought to be made up of waves (i.e. use a WAVE MODEL).

Then there was the **photoelectric effect**, which could only be explained if light behaved like a particle called a photon (we will discuss this in greater depth in a later pack).

So is light (and all other electromagnetic radiation) a wave or a particle?

Both notions are essentially different ways of explaining how EM radiation behaves in different situations; neither is a complete or a perfect description.

Photons

When Max Planck was researching black body* radiation, he proposed that electromagnetic waves can only be released in discrete packets known as Quanta. A quantum is a single packet of electromagnetic energy.

This simply means that electromagnetic radiation is emitted in short 'bursts' or 'packets' of energy.

The energy carried by one of these wave-packets is proportional to the frequency, according to Max Planck:

$$\boldsymbol{E \propto f}$$

And because they're proportional, he needed a constant, which he named Planck's constant (h). As a result, the energy carried by one of these wave-packets had to be:

$$\boldsymbol{E = hf}$$

Where:

E = Energy emitted measured in Joules, J,

h = Planck's constant (= $6.63 \times 10^{-34} Js$),

f = Frequency of the radiation measured in hertz, Hz.

Therefore, the greater the EM radiation's frequency, the more energy its wave-packets carry.

The Planck's constant unit Js is equivalent to 'joules per hertz ($J\ Hz^{-1}$)'. Each wave packet carries more joules as the hertz (or frequency) increases.

Photons

We can take it a step further. We know, $f = \frac{v}{\lambda}$, and that all EM waves travel at the speed of light, c, we can substitute $f = \frac{c}{\lambda}$ into $E = hf$ to get:

$$\boldsymbol{E = \frac{hc}{\lambda}}$$

Where:

c = speed of light in a vacuum measured in ms^{-1} ($\approx 3 \times 10^8\ ms^{-1}$)

λ = Photon wavelength measured in metres, m.

Albert Einstein went even further a few years later, claiming that EM waves (and the energy they carry) can only exist in discrete packets. He called these wave-packets photons.

He believed that a photon acts as a particle, and when a photon interacts with another particle, like an electron, it transfers all or none of its energy.

* The Sun can be assumed to be a black body. It absorbs nearly all of the light that strikes it and releases the most powerful radiation in the visible range (i.e. yellow region) of the EM spectrum. No light reflects off a black body. In a later pack, we'll talk more about black bodies.

The Electronvolt (eV)

When dealing with photons, the energies involved are so little that it makes sense to use a unit other than the Joule, J. When dealing with photon energy, you can use the electronvolt (eV) as a more convenient unit.

1 electronvolt (eV) is the energy transferred by an electron when it moves between two points by a potential difference (p.d.) of 1 Volt.

The kinetic energy (E) gained by an electron (with charge, $Q = e = 1.6 \times 10^{-19} C$) moving through a p.d. of $1\ V$ is given by:

$$E = QV = (1.6 \times 10^{-19}\ C) \times (1\ V)$$

Hence,

$$1\ eV = 1.6 \times 10^{-19}\ J$$

To convert from J to eV: divide by $1.6 \times 10^{-19}\ J$

To convert from eV to J: multiply by $1.6 \times 10^{-19}\ J$

Kinetic Energy and eV

When an electron is accelerated between two electrodes, some electrical potential energy (eV) is converted into kinetic energy (KE).

Consider an electron with a charge (e) and mass (m) that is initially at rest before being accelerated through a p.d. (V) to a final speed (v).

Then:

The KE energy gained by an electron is equal to the work done on it by the accelerating p.d. so:

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

Where:

m = mass of electron measured in kg

v = speed of electron measured in ms^{-1}

e = electron charge measured in C

V = potential difference measured in volts, V

Rearranging the above formula, we get the following equation for electron speed (v):

$$v = \sqrt{\frac{2eV}{m}}$$

Note:

These equations apply to any charged particle.

When the accelerating p.d. is large, the equations are invalid. This is because the charged particles' speeds could approach the speed of light (c), requiring consideration of the relativistic effect of mass increase (i.e. mass is no longer constant).

Light Emitting Diode (LED)

A simple experiment with LEDs can be used to determine Planck's constant.

However, before we talk about the experiment, you should be aware of the following characteristics of the LED.

An LED will allow current to flow through it when:

- It is forward biased (i.e., when it is connected to a supply as shown in the diagram opposite. In this set-up the P-side of the diode is connected to the positive terminal, while N-side is connected to the negative terminal of the battery).

- The applied p.d. is greater than or equal to the threshold voltage (V_0) (the minimum voltage required to allow current to flow).

Different colours of LEDs have different threshold voltages for conducting and emitting light. A blue LED has a higher threshold voltage and emits higher energy photons than a red LED.

We can say that when an LED conducts and emits photons:

The energy lost by an electron as it passes through the LED is equal to the energy of the emitted photon.

$$eV_0 = \frac{hc}{\lambda}$$

Where:

V_0 = threshold frequency measured in volts, V

h = Planck's Constant

Therefore, finding the threshold voltage for a particular wavelength of an LED, you are able to calculate Planck's constant:

$$h = \frac{(eV_0)\lambda}{c}$$

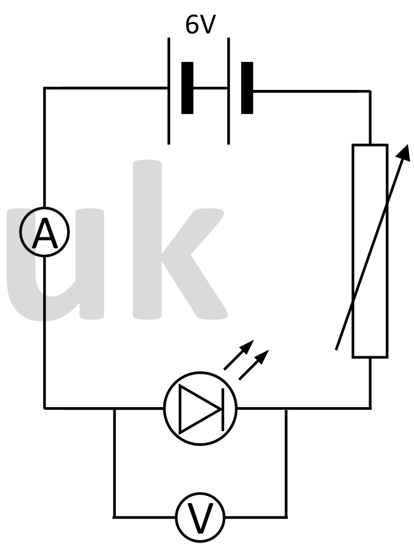
Experimentally Obtaining Planck's Constant

Apparatus:

- Set of four coloured LEDs
- 6V Battery
- Voltmeter
- Ammeter
- Variable resistor

Method:

1) Connect an LED of known wavelength in the electrical circuit shown opposite.
2) Start with no current flowing through the circuit and adjust the variable resistor until a current just starts to flow. This is the threshold voltage (V_0).
3) Record the LEDs threshold voltage (V_0) and the wavelength of light it emits.
4) Repeat steps 1 to 3 with a different LEDs emitting different optical wavelengths.
5) Then Plot a graph of threshold voltage (V_0) against $\frac{1}{\lambda}$ (where λ is the wavelength of light emitted by the LED in metres).
6) You should obtain a straight-line graph where the gradient is equal to $\frac{hc}{e}$, which you can then use to find the value of h.



Light Emitting Diode (LED)

Analysis:

$$eV = \frac{hc}{\lambda}$$

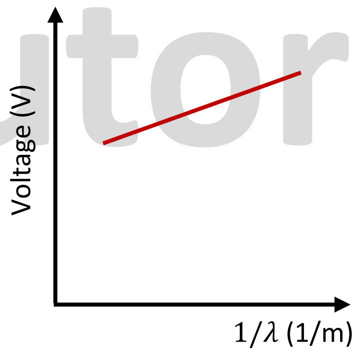
$$\therefore V = \left(\frac{hc}{e}\right) \times \frac{1}{\lambda}$$

Comparing with: $y = mx$

Therefore: $gradient = \frac{hc}{e}$

Rearranging the above you can calculate Planck's constant:

$$h = gradient \times \frac{e}{c}$$



Improvements:

- Use a black viewing tube in a dark room to make it easier to see when the LED light turns on.
- Use a resistor to limit the current flow through the LED to ensure the LED isn't destroyed by exceeding the limit.

Please see '11.1.2 Photons worked examples' pack for exam style questions.

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