1.3 Photons

Learning objectives:
- What is a photon?
- What is the energy of a photon?
- How many photons does a light source emit every second?

Specification reference: 3.1.1

Electromagnetic waves

Light is just a small part of the spectrum of electromagnetic waves. Our eyes cannot detect the other parts. The world would appear very different to us if they could. For example, all objects emit infrared radiation. Infrared cameras enable objects to be observed in darkness.

In a vacuum, all electromagnetic waves travel at the speed of light, c, which is $3.0 \times 10^8\,\mathrm{m\,s^{-1}}$. As you know from GCSE, the wavelength λ of electromagnetic radiation of frequency f in a vacuum is given by the equation

$$\lambda = \frac{c}{f}$$

Note that we often express light wavelengths in nanometres (nm), where 1 nm = 0.000000001 m = 10^{-9} m.

The main parts of the electromagnetic spectrum are listed in Table 1.

Table 1 *The main parts of the electromagnetic spectrum*

type	radio	microwave	infrared	visible	ultraviolet	X-rays	gamma rays
wavelength range	> 0.1 m	0.1 m to 1 mm	1 mm to 700 nm	700 nm to 400 nm	400 nm to 1 nm	< 1 nm	< 1 nm

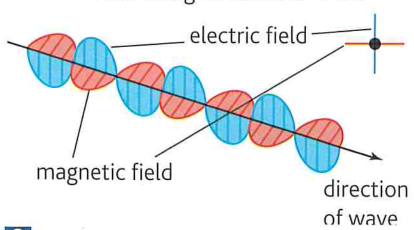

Figure 1 *Electromagnetic waves*

As shown in Figure 1, an electromagnetic wave consists of an electric wave and a magnetic wave which travel together and vibrate:

- at right angles to each other and to the direction in which they are travelling,
- in phase with each other. As you can see the two waves reach a peak together so they are in step. When waves do this we say they are 'in phase'.

Photons

Electromagnetic waves are emitted by a charged particle when it loses energy. This can happen when:

- a fast-moving electron is stopped (for example, in an X-ray tube) or slows down or changes direction,
- an electron in a shell of an atom moves to a different shell of lower energy.

Electromagnetic waves are emitted as short 'bursts' of waves, each burst leaving the source in a different direction. Each burst is a packet of electromagnetic waves and is referred to as a **photon**. The photon theory was established by Einstein in 1905, when he used his ideas to explain **photoelectricity**. This is the emission of electrons from a metal surface when light is directed at the surface. We will consider photoelectricity and the photon theory in more detail in Topic 3.1.

Einstein imagined photons to be like 'flying needles' and he assumed that the energy E of a photon depends on its frequency f in accordance with the equation:

$$\text{photon energy } E = hf$$

where h is a constant referred to as the Planck constant. The value of h is 6.63×10^{-34} J s.

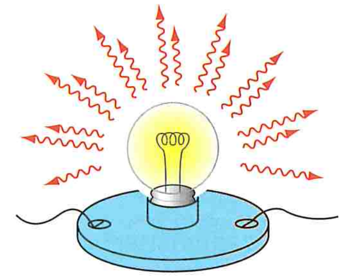
Figure 2 *Emitting photons*

Worked example:

Calculate the frequency and the energy of a photon of wavelength 590 nm.

$h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$

Solution

To calculate the frequency, use $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{590 \times 10^{-9}} = 5.08 \times 10^{14}$ Hz

To calculate the energy of a photon of this wavelength, we use $E = hf$

$E = hf = 6.63 \times 10^{-34} \times 5.08 \times 10^{14} = 3.37 \times 10^{-19}$ J

Laser power


Figure 3 *A laser at work*

A laser beam consists of photons of the same frequency. The power of a laser beam is the energy per second transferred by the photons. For a beam consisting of photons of frequency f,

$$\text{the power of the beam} = nhf$$

where n is the number of photons in the beam passing a fixed point each second. This is because each photon has energy hf. Therefore, if n photons pass a fixed point each second, the energy per second (or power) is nhf.

Summary questions

$c = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$
$h = 6.63 \times 10^{-34}$ J s

1. a List the main parts of the electromagnetic spectrum in order of increasing wavelength.
   b Calculate the frequency of i light of wavelength 590 nm, ii radio waves of wavelength 200 m.
2. With the aid of a suitable diagram, explain what is meant by an electromagnetic wave.
3. Light from a certain light source has a wavelength of 430 nm. Calculate:
   a the frequency of light of this wavelength,
   b the energy of a photon of this wavelength.
4. a Calculate the frequency and energy of a photon of wavelength 635 nm.
   b A laser emits light of wavelength 635 nm in a beam of power 1.5 mW. Calculate the number of photons emitted by the laser each second.