

# Workshop Tutorials for Introductory Physics

## Solutions to Q11: **Photons**

### A. Review of Basic Ideas:

#### **Light, photons and the electromagnetic spectrum**

In the 18<sup>th</sup> and 19<sup>th</sup> centuries it was believed that light was a **wave**. Many experiments provided evidence for the wave model of light since they showed that light could refract, **reflect** and interfere. However, there were other experiments that couldn't be explained by the wave model of light. In 1900 Max Planck proposed that when light was absorbed or emitted it only came in **discrete** amounts. The particles of light in this model became known as **photons**.

These photons have no **mass**, and no charge, but they do have **energy**. In fact they can have a huge range of energies, and the light that we can see is only a very small part of the **spectrum**. Photons are made up of a combination of an electric field and magnetic field which travel around together, and so we call the entire range the **electromagnetic** spectrum. Photons are the "particles" associated with electromagnetic **radiation**.

One of the interesting things about photons of a given wavelength is that they always travel at the **same** speed in a given medium, e.g. air. Other particles, like electrons, travel faster or slower depending on how much **kinetic** energy they have, but photons always travel at the speed of light,  $c = 3 \times 10^8 \text{ ms}^{-1}$  in vacuum or in air.

Even though light behaves like particles, it still behaves like **waves**! When you do some experiments, the light behaves like particles, while during other experiments it behaves like waves. This is a great mystery. Other particles with **mass** like electrons and protons, and even whole atoms, also behave like waves. This is called wave-particle **duality**, and is one of the biggest mysteries of modern physics. For any wave, there is a relationship between the speed, **frequency** and wavelength given by  $c = \lambda \times f$ . Usually you need to know two of these to find the third. However, with light, because the speed is always the same, knowing the frequency will tell you the wavelength and vice versa.

#### **Discussion questions**

Photoelectric Effect: Ejected photoelectrons are emitted immediately if they are to be emitted at all. This can be explained if photons are particles having an energy related to their frequency. A wave model of light would suggest that the electrons would be ejected only after some time for low intensity light.

There are many experiments which show the wave nature of light, such as diffraction and interference experiments. An example is the twin slit experiment where light from the two slits interferes to give a pattern of fringes. This is a result of the wave nature of light, allowing it to pass through both slits at once.

### B. Activity Questions:

#### **1. Wave and particle nature of light 1- interference pattern**

This demonstrates the wave nature of light. A particle could only pass through one slit or the other. However, a wave can pass through both slits simultaneously and interfere with itself.

#### **2. Wave and particle nature of light 2- emission spectra**

If you accept that the spectral lines result from transitions of electrons from one energy level to another, then the excess energy of an electron when it jumps down from one energy level to another is released as a photon. These lines have discrete colours (frequencies) and correspond to photons of different energies.

### C. Qualitative Questions:

#### 1. Light as a wave and particle.

	Wave Model	Particle Model
Brightness	square of wave amplitude	number of photons (flux density)
Colour	frequency or wavelength	energy of photons

#### 2. Humans see from blue (around 400 nm wavelength) to red (around 700 nm).

- Blue photons have shorter wavelength,  $\lambda$ , therefore they have higher frequency,  $f$ , as  $c = \lambda f$  and  $c$  is constant (the speed of light). Energy is proportional to frequency, hence blue light has higher energy per photon than red light.
- X-rays have much higher frequency than radio-waves, and have much higher energy.
- X-rays have much higher frequency and energy than visible light, and hence are more penetrating. This allows them to be used to see inside things which visible light cannot penetrate, such as the body.
- The depletion of the ozone layer is a concern because it absorbs a lot of UV light. Without it much more UV will get through.
- Ultraviolet light is much more dangerous than infrared because it has much higher energy, and is more penetrating. It can break bonds in DNA and that can lead to skin cancer.

### D. Quantitative Question:

An enzyme called luciferase is used by many animals that produce light, for example fireflies. Fireflies produce a yellow light (with wavelength  $\sim 500$  nm) which they flicker and flash to attract a mate. Many marine organisms produce a green or blue light.

- a. Use  $E = hf$  and  $c = \lambda f$ .

$$f = c / \lambda = 3 \times 10^8 / 500 \times 10^{-9} = 6 \times 10^{14} \text{ Hz.}$$

$$E = hf = 6.63 \times 10^{-34} \times 6 \times 10^{14} = 4.0 \times 10^{-19} \text{ J.}$$

Jellyfish produce higher energy (shorter wavelength) photons.

- b.  $0.1 \text{ mW} = 0.1 \times 10^{-3} \text{ J/s}$ . Each photon has  $4.0 \times 10^{-19} \text{ J}$ .

so they are producing

$$0.1 \times 10^{-3} \text{ Js}^{-1} / 4.0 \times 10^{-19} \text{ J.photon}^{-1} = 2.5 \times 10^{14} \text{ photons per second for 10 fireflies.}$$

So each produces  $2.5 \times 10^{13}$  photons per second.

- The colour (frequency and energy) is the same, but the intensity is greater for more fireflies.
- Higher energy photons would be shorter wavelength, so green or blue rather than yellow.