OCR A Physics A-level

Topic 4.5: Quantum physics

Notes

Photons

The photon model

Electromagnetic radiation travels through space as a **continuous wave**, with properties such as diffraction and interference providing evidence for this model. However, when electromagnetic radiation interacts with matter, it interacts as **discrete energy quanta** ('packets') called **photons**.

The **energy**, E, of a photon is directly proportional to the **frequency**, *f,* of the electromagnetic radiation

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

where *h* is the Planck constant 6.63×10^{-34}. The equation can also be rewritten by using the wave equation $v = f\lambda$, with *v* as the speed of light, *c*.

The electronvolt

The energy of a photon is very small when measured in joules, so the **electronvolt** (eV) is a more appropriate unit of energy to use for photons. 1 electronvolt is defined as the energy transferred when an electron travels through a potential difference of 1 volt.

Using the formula W=VQ, the work done is equal to the charge on an electron multiplied by the p.d., 1 volt, so an electronvolt $= 1.60 \times 10^{-19}$ joules.

Using LEDs to estimate the value of the Planck constant

We can use LEDs to determine the Planck constant experimentally. LEDs only emit light when the potential difference across them **exceeds the threshold p.d.** required. A potential divider is set up to vary the voltage through the LED. A small black tube is placed over the LED, to make it obvious when the LED has lit up. By varying the p.d. across the LED, we can determine the threshold p.d., V, required to turn it on. As the LED produces light of a specific colour, we know the wavelength of the light. Each photon from the LED is emitted when a single electron loses energy. By **equating the energy** of an individual electron in the LED with an individual photon produced, we can use the equation $eV = hc/\lambda$ to determine the Planck constant.

To improve the accuracy of this estimate, the experiment can be repeated with a variety of **different coloured LEDs**, which each emit **different wavelengths** of light. The values of wavelength and threshold p.d. for each can be recorded, and a graph drawn of V against $1/\lambda$. The gradient of this graph will be equal to hc/e. As the speed of light and the electron charge are known constants, we can calulcate the value of h from this.

The photoelectric effect

The photoelectric effect

When electromagnetic radiation is shone on to a metal, **electrons are released** from the surface of the metal. This is known as the **photoelectric effect**.

The photoelectric effect can be demonstrated using a **gold leaf electroscope** – a zinc plate on top of a negatively charged stem, with a negatively charged piece of gold leaf attached to the stem. Initially, the gold lead and the stem have the same charge, so they repel each other. If UV light is shone on to the zinc plate, free electrons will be released from the surface of the plate, and the negative charge will slowly be lost, so the gold leaf will gradually **fall back to the stem**.

When the gold leaf electroscope experiment is carried out, several observations can be made when the type of electromagnetic radiation shone on to the plate is varied. When **visible light** is used, it does not matter how intense the radiation is, **no electrons** will be removed from the plate. When **UV light** is used, even if it is a very low intensity, electrons **are instantaneously removed** from the plate. These observations are a result of the particulate nature of photons, and cannot be explained by the wave model of electromagnetic radiation.

Each electron on the surface of the metal requires a certain amount of energy to escape. Each photon incident on the surface can transfer its **exact energy** to one electron, with any excess energy above the energy required to escape becoming kinetic energy of the electron. The **work function**, ϕ, of a metal is the **minimum energy** required to **free an electron** from the surface of the metal. Each photon must have energy at least as great as the work function to release an electron. As the photon's energy is directly proportional to its frequency, there is **a threshold frequency** for the electromagnetic radiation, which is the minimum frequency required to free electrons from the surface of the metal. UV light has a higher frequency than visible light, which is why it produces the photoelectric effect in the gold leaf electroscope experiment, but visible light does not.

Einstein's photoelectric equation

During the photon-electron interaction, energy must be conserved. Einstein equated the energy of the incident photon with the energy required to release the electron, to produce **the photoelectric equation**

$$hf = \phi + KE_{max}$$

where ϕ is the work function of the metal, and KE_{max} is the **maximum** kinetic energy of the released electron. It is a maximum because some electrons may be closer to the nucleus, requiring more energy than the work function amount to be released, leaving less energy left over as kinetic energy. For the equation to work, all three quantities must be given in the same unit – when completing calculations, ensure that all values have been correctly converted.

Whether or not electrons are released from the metal's surface is **not related to the intensity** of the radiation. If the incident radiation has frequency below the threshold frequency, then no

electrons will be released, regardless of how high the intensity of the radiation is. However, if the frequency is above the threshold frequency, then increasing the intensity of the radiation will increase the **rate of electron emission**. This is because the increase in intensity increases the number of photons available to interact with the electrons. The only way to increase the **kinetic energy** of the electrons is to **increase the frequency** of radiation further above the threshold frequency, so there is more energy left over to be converted to kinetic energy.

Wave-particle duality

The de Broglie equation

Diffraction and superposition of light relies on the radiation acting as a wave, but the photoelectric effect relies on it acting as discrete photons. This is the result of electromagnetic waves having a dual nature – **wave-particle duality**. De Broglie realised that **all matter** can exhibit both wave and particle properties, and that the wavelength associated with a particle is inversely proportional it its momentum, p. This relationship is given by the **de Broglie equation**

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

This equation can be applied to all particles with mass. As the mass of the particle increases, their wavelength decreases, so it becomes harder to observe wavelike properties.

Evidence for wave-particle duality

The dual nature of electromagnetic radiation has already been covered, however **electrons** can also be used as evidence for wave-particle duality. Electrons are classified as particles, with mass and charge. They can be accelerated and deflected by magnetic and electric fields, which is behaviour associated with particles. However, they can also be made to diffract. When a beam of electrons is fired at a thin piece of polycrystalline graphite (a material containing carbon atoms spread over many layers) the electrons are **diffracted by the gaps between atoms**, and produce a diffraction pattern when they hit a screen. This diffraction is a property of waves.