Chapter 28

Quantum physics

LEARNING INTENTIONS

In this chapter you will learn how to:

- understand that electromagnetic radiation has a particulate nature
- understand that a photon is a quantum of electromagnetic energy
- recall and use $E = hf$
- use the electronvolt (eV) as a unit of energy
- understand that a photon has momentum and that the momentum is given by $p = \frac{E}{c}$
- understand that photoelectrons may be emitted from a metal surface when it is illuminated by electromagnetic radiation
- understand and use the terms threshold frequency and threshold wavelength
- explain photoelectric emission in terms of photon energy and work function energy
- recall and use $hf = \Phi + \frac{1}{2}mv_{max}{}^2$
- explain why the maximum kinetic energy of photoelectrons is independent of intensity, whereas the photoelectric current is proportional to intensity
- understand that the photoelectric effect provides evidence for a particulate nature of electromagnetic radiation, while phenomena such as interference and diffraction provide evidence for a wave nature
- describe and interpret qualitatively the evidence provided by electron diffraction for the wave nature of particles
- understand the de Broglie wavelength as the wavelength associated with a moving particle
- recall and use $\lambda = \frac{h}{p}$
- understand that there are discrete electron energy levels in isolated atoms (such as atomic hydrogen)
- understand the appearance and formation of emission and absorption line spectra

- recall and use the relation $hf = E_1 - E_2$.

BEFORE YOU START

- The principle of conservation of energy is an important idea in physics. Write down some examples of this from several topics in physics. Share your list with a partner.
- In pairs, discuss the concepts of momentum and kinetic energy.

WHAT IS LIGHT?

When the first laser was made in 1960, it seemed like a clever idea, but it was a long time before it found any useful application. Today, lasers are everywhere – in CD and DVD machines, computer disc drives, supermarket barcode scanners–there are probably more lasers than people. Figure 28.1 shows a patient undergoing laser eye surgery.

The invention of the laser was only possible when scientists had cracked the mystery of the nature of light.

You already know that light is a wave. What experimental evidence is there for the wave-like behaviour of such waves? You will see in this chapter that electromagnetic waves have a dual nature – they interact with matter as 'particles' and propagate through space as a wave.

Figure 28.1: This patient is undergoing laser eye surgery, which improves the focusing of the eye by modifying the shape of the surface of the eyeball.

28.1 Modelling with particles and waves

In this chapter, we will study two very powerful scientific models – particles and waves – to see how they can help us to understand more about both light and matter. First, we will take a closer look at each of these models in turn.

Particle models

In order to explain the properties of matter, we often think about the particles of which it is made and the ways in which they behave. We imagine particles as being objects that are hard, have mass and move about according to the laws of Newtonian mechanics (Figure 28.2). When two particles collide, we can predict how they will move after the collision, based on knowledge of their masses and velocities before the collision. If you have played snooker or pool, you will have a pretty good idea of how particles behave.

Particles are a macroscopic model. Our ideas of particles come from what we observe on a macroscopic scale–when we are walking down the street, or observing the motion of stars and planets, or working with trolleys and balls in the laboratory. But what else can we explain using a particle model?

The importance of particle models is that we can apply them to the microscopic world, and explain more phenomena.

We can picture gas molecules as small, hard particles, rushing around and bouncing haphazardly off one another and the walls of their container. This is the kinetic model of a gas that we studied in depth in Chapter 20. We can explain the macroscopic (larger scale) phenomena of pressure and temperature in terms of the masses and speeds of the microscopic particles. This is a very powerful model, which has been refined to explain many other aspects of the behaviour of gases.

Table 28.1 shows how, in particular topics of science, we can use a particle model to interpret and make predictions about macroscopic phenomena.

Figure 28.2: Pool balls provide a good model for the behaviour of particles on a much smaller scale.

Topic	Model	Macroscopic phenomena
electricity	flow of electrons	current
gases	kinetic theory	pressure, temperature and volume of a gas
solids	crystalline materials	mechanical properties
radioactivity	nuclear model of the atom	radioactive decay, fission and fusion reactions
chemistry	atomic structure	chemical reactions

Table 28.1: Particle models in science.

Wave models

Waves are something that we see on the sea. There are tidal waves, and little ripples. Some waves have foamy tops, others are breaking on the beach.

Physicists have an idealised picture of a wave – it is shaped like a sine graph. You will not see any waves quite this shape on the sea. However, it is a useful picture, because it can be used to represent some simple phenomena. More complicated waves can be made up of several simple waves, and physicists can cope with the mathematics of sine waves. (This is the principle of superposition, which we looked at in detail in Chapter 13.)

Waves are a way in which energy is transferred from one place to another. In any wave, something is changing in a regular way, while energy is travelling along. In water waves, the surface of the water moves up and down periodically and energy is transferred horizontally.

Table 28.2 shows some phenomena that we explain in terms of waves.

Phenomenon	Varying quantity
sound	pressure (or density)
light (and other electromagnetic waves)	electric field strength and magnetic flux density
waves on strings	displacement

Table 28.2: Wave models in science.

The characteristic properties of waves are that they all show reflection, refraction, diffraction and interference. Waves themselves do not have mass or charge. Since particle models can also explain reflection and refraction, it is **diffraction** and **interference** that we regard as the defining characteristics of waves. If we can show diffraction and interference, we know that we are dealing with waves (Figure 28.3).

Figure 28.3: A diffraction grating splits up light into its component colours and can produce dramatic effects in photographs.

Waves or particles?

Wave models and particle models are both very useful. They can explain a great many different observations. But which should we use in a particular situation? And what if both models seem to work when we are trying to explain something?

This is just the problem that physicists struggled with for over a century, in connection with light. Does light travel as a wave or as particles?

For a long time, Newton's view prevailed–light travels as particles. This was set out in 1704 in his famous book *Opticks*. He could use this model to explain both reflection and refraction. His model suggested that light travels **faster** in water than in air. In 1801, Thomas Young, an English physicist, demonstrated that light showed diffraction and interference effects. Physicists were still very reluctant to abandon Newton's particle model of light. The ultimate blow to Newton's model came from the work carried out by the French physicist Léon Foucault in 1853. His experiments on the speed of light showed that light travelled more **slowly** in water than in air. Newton's model had at last been tested and it was in direct contradiction with experimental results. Most scientists had to accept that light travelled through space as a wave.

28.2 Particulate nature of light

We expect light to behave as waves, but can light also behave as particles? The answer is yes, and you are probably already familiar with some of the evidence.

If you place a Geiger counter next to a source of gamma radiation, you will hear an irregular series of clicks. The counter is detecting γ-rays (gamma-rays). But γ-rays are part of the electromagnetic spectrum. They belong to the same family of waves as visible light, radio waves, X-rays and so on.

So, here are waves giving individual or discrete clicks, which are indistinguishable from the clicks given by γ-particles (alpha-particles) and γ-particles (beta-particles). We can conclude that γ-rays behave like particles when they interact with the gas particles within a Geiger counter.

This effect is most obvious with γ-rays, because they are at the most energetic end of the electromagnetic spectrum. It is harder to show the same effect for visible light.

Photons

The **photoelectric effect**, and Einstein's explanation of it, convinced physicists that light could behave as a stream of particles. Before we go on to look at this in detail, we need to see how to calculate the energy of photons.

Newton used the word **corpuscle** for the particles that he thought made up light. Nowadays, we call them **photons** and we believe that all electromagnetic radiation consists of photons. A photon is a 'packet of energy' or a quantum of electromagnetic energy. Gamma-photons (γ-photons) are the most energetic. According to Albert Einstein, who based his ideas on the work of another German physicist, Max Planck, the energy E of a photon in joules (J) is related to the frequency f in hertz (Hz) of the electromagnetic radiation of which it is part, by the equation:

$$E = hf$$

The constant h has an experimental value equal to 6.63×10^{-34} J s.

This constant h is called the **Planck constant**. It has units of joule seconds (J s), but you may prefer to think of this as 'joules per hertz'. The energy of a photon is directly proportional to the frequency of the electromagnetic waves, that is:

$$E \propto f$$

Hence, high-frequency radiation means high-energy photons.

Notice that the equation $E = hf$ shows us the relationship between a particle-like property (the photon energy E) and a wave-like property (the frequency f). It is called the **Einstein relation** and applies to all electromagnetic waves.

The frequency f and wavelength λ of an electromagnetic wave are related to the wave speed c by the wave equation $c = f\lambda$, so we can also write this equation as:

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

where h is the Planck constant, f is frequency and λ is wavelength.

KEY EQUATION

Einstein relation:

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

It is worth noting that the energy of the photon is inversely proportional to the wavelength. Hence the short-wavelength X-ray photon is far more energetic than the long-wavelength photon of light.

Now, we can work out the energy of a γ-photon. Gamma-rays typically have frequencies greater than 10^{20} Hz. The energy of a γ-photon is therefore greater than $(6.63 \times 10^{-34} \times 10^{20}) \approx 10^{-13}$ J. This is a very small amount of energy on the human scale, so we don't notice the effects of individual γ-photons. However, some astronauts have reported seeing flashes of light as individual cosmic rays, high-energy γ-photons, passed through their eyeballs.

The energy of individual photons can be quite small, but the rate at which photons emitted by a source can be enormous. This is illustrated in Worked example 1 for a light-emitting diode.

WORKED EXAMPLE

1 A light-emitting diode (LED) emits light of wavelength 670 nm. The radiant power of the light from the LED is 50 mW.

Calculate the rate at which photons are emitted from this LED.

Step 1 Calculate the energy E of a single photon.

$$E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3.00\times10^{8}}{670\times10^{-9}} = 2.97\times10^{-19}\,\text{J}$$

(Note: 1 nm = 10^{-9} m)

Step 2 Calculate the rate of photons emitted.

The rate at which the photons are emitted is the equivalent to the number of photons emitted per second.

$$\text{rate of photon emission} = \frac{\text{power}}{\text{energy of a single photon}} = \frac{50\times10^{-3}}{2.97\times10^{-19}} = 1.68\times10^{17}\,\text{s}^{-1}$$

(Note: 1 mW = 10^{-3} W)

In one second, there are about 1.7×10^{17} photons emitted by the LED.

Questions

To answer questions 1 to 7 you will need these values:

speed of light in a vacuum $c = 3.00 \times 10^8$ m s^{-1}

Planck constant $h = 6.63 \times 10^{-34}$ J s

1 Calculate the energy of a high-energy γ-photon, of frequency 1.0×10^{26} Hz.

2 Visible light has wavelengths in the range 400 nm (violet) to 700 nm (red). Calculate the energy of a photon of red light and a photon of violet light.

3 Determine the wavelength of the electromagnetic waves for each photon, a to e. Then use Figure 28.4 to identify the region of the electromagnetic spectrum to which each belongs.

The photon energy is:

a 10^{-12} J

b 10^{-15} J

c 10^{-18} J

d 10^{-20} J

e 10^{-25} J

4 A 1.0 mW laser produces red light of wavelength 6.48×10^{-7} m. Calculate how many photons the laser produces per second.

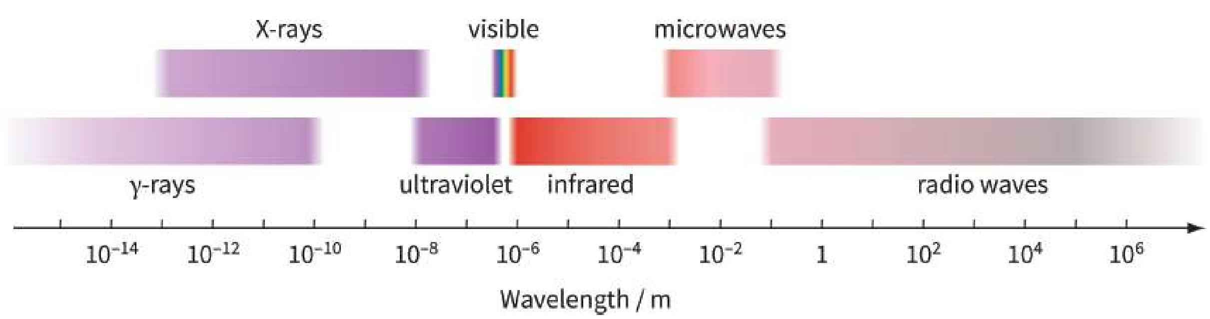

Figure 28.4: Wavelengths of the electromagnetic spectrum. The boundaries between some regions are fuzzy.

The electronvolt (eV)

The energy of a photon is extremely small and far less than a joule. Hence, the joule is not a very convenient unit for measuring photon energies. You may remember from Chapter 15 that we use another energy unit, the **electronvolt (eV)**, when considering amounts of energy much smaller than a joule.

To recap from Chapter 15: when an electron travels through a potential difference, energy is transferred. If an electron, which has a charge of magnitude 1.60×10^{-19} C, travels through a potential difference of 1 V, its energy change W is given by:

$$W = QV = 1.60 \times 10^{-19} \times 1 = 1.60 \times 10^{-19}\ \text{J}$$

We can use this as the electronvolt:

One electronvolt (1 eV) is the energy gained by an electron travelling through a potential difference of one volt.

Therefore:

$$1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$$

So when an electron moves through 1 V, 1 eV of energy is gained or transferred to the electron. When one electron moves through 2 V, 2 eV of energy is gained. When five electrons move through 10 V, a total of 50 eV is transferred and so on.

- To convert from eV to J, multiply by 1.60×10^{-19}.
- To convert from J to eV, divide by 1.60×10^{-19}.

Question

5 An electron travels through a cell of e.m.f. 1.2 V.

Calculate the energy is transferred to the electron. Give your answer in both eV and J.

6 Calculate the energy in eV of an X-ray photon of frequency 3.0×10^{18} Hz.

7 With the help of a calculation, identify the region of the electromagnetic spectrum (Figure 28.4) a photon of energy 10 eV belongs.

When a charged particle is accelerated through a potential difference V, its kinetic energy increases. For an electron (charge e), accelerated from rest, we can write:

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

We need to be careful when using this equation. It does not apply when a charged particle is accelerated through a large voltage to speeds approaching the speed of light c. For this, we would have to take account of relativistic effects. (The mass of a particle increases as its speed gets closer to $3.00 \times 10^8\ \text{m s}^{-1}$.)

Rearranging the equation gives the electron's speed:

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

This equation applies to any type of charged particle, including protons (charge $+e$) and ions.

Question

8 A proton, initially at rest, is accelerated through a potential difference of 1500 V. A proton has charge $+1.60 \times 10^{-19}$ C and mass 1.67×10^{-27} kg.

Calculate:

a its final kinetic energy in joules (J)

b its final speed.

PRACTICAL ACTIVITY 28.1

Estimating the Planck constant *h*

You can obtain an estimate of the value of the Planck constant h by means of a simple experiment. It makes use of light-emitting diodes (LEDs) of different colours (Figure 28.5). You may recall from Chapter 10 that an LED conducts in one direction only (the forward direction) and that it requires a minimum voltage, the **threshold voltage**, to be applied in this direction before it allows a current. This experiment makes use of the fact that LEDs of different colours require different threshold voltages before they conduct and emit light.

- An LED giving light of red colour emits photons that are of low energy. It requires a low threshold voltage to make it conduct.
- An LED giving light of blue colour emits higher-energy photons. It requires a higher threshold voltage to make it conduct.

What is happening to produce photons of light when an LED conducts? The simplest way to think of this is to say that the electrical energy of a single electron passing through the diode is transferred to the energy of a single photon.

Figure 28.5: Light-emitting diodes (LEDs) come in different colours.

Hence, we can write:

energy transferred by electron = energy of photon

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

where V is the threshold voltage for the LED. The values of e and c are known. Measurements of V and λ will allow you to calculate h. So the measurements required are:

- V – the voltage across the LED when it begins to conduct (its threshold voltage). It is found using a circuit like the one shown in Figure 28.6a.
- λ – the wavelength of the light emitted by the LED. This is found by measurements using a diffraction grating or from the wavelength quoted by the manufacturer of the LED.

If several LEDs of different colours are available, V and λ can be determined for each and a graph of V against $\frac{1}{\lambda}$ drawn (see Figure 28.6b). The graph passes through the origin and has gradient $\frac{hc}{e}$ and, hence, h can be estimated.

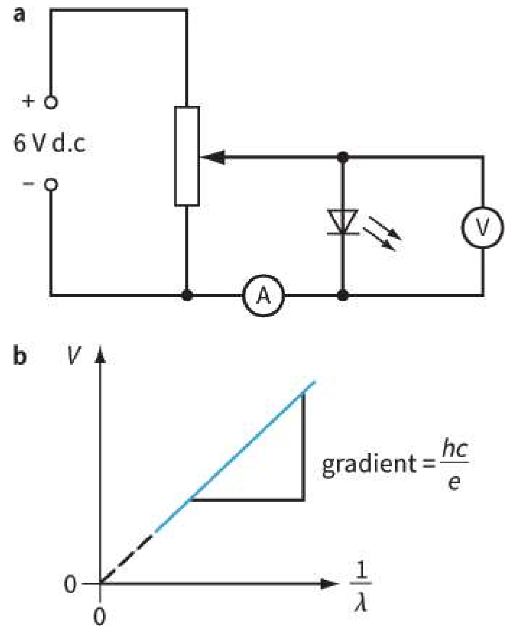

Figure 28.6: a A circuit to determine the threshold voltage required to make an LED conduct. An ammeter helps to show when this occurs. **b** The graph used to determine *h* from this experiment.

Question

9 In an experiment to determine the Planck constant *h*, LEDs of different colours were used. The p.d. required to make each conduct was determined, and the wavelength of their light was taken from the manufacturer's catalogue. The results are shown in Table 28.3. For each LED, calculate the experimental value for *h* and, hence, determine an average value for the Planck constant.

Colour of LED	**Wavelength / 10^{-9} m**	**Threshold voltage / V**
infrared	910	1.35
red	670	1.70
amber	610	2.00
green	560	2.30

Table 28.3: Results from an experiment to determine *h*.

28.3 The photoelectric effect

In the photoelectric effect, light shines on a metal surface and electrons are released from it. The Greek word for light is photo, hence, the word ‘photoelectric’. The electrons removed from the metal plate in this manner are often known as photoelectrons.

The apparatus used to observe the photoelectric effect is shown in Practical Activity 28.2. Light from a lamp is shone onto a negatively charged metal plate and some of the electrons in the metal are emitted. A simple explanation is that light is a wave that carries energy and this energy releases electrons from the metal. However, detailed observations of the effect at first proved difficult to explain, in particular, that there is a minimum threshold frequency of light below which no effect is observed.

PRACTICAL ACTIVITY 28.2

Observing the photoelectric effect

You can observe the photoelectric effect yourself by fixing a clean zinc plate to the top of a gold-leaf electroscope (Figure 28.7). Give the electroscope a negative charge and the leaf deflects. Now, shine electromagnetic radiation from a mercury discharge lamp on the zinc and the leaf gradually falls. (A mercury lamp strongly emits ultraviolet radiation.) Charging the electroscope gives it an excess of electrons. Somehow, the electromagnetic radiation from the mercury lamp helps electrons to escape from the surface of the metal.

Placing the mercury lamp closer causes the leaf to fall more rapidly. This is not very surprising. However, if you insert a sheet of glass between the lamp and the zinc, the radiation from the lamp is no longer effective. The gold leaf does not fall. Glass absorbs ultraviolet radiation and it is this component of the radiation from the lamp that is effective.

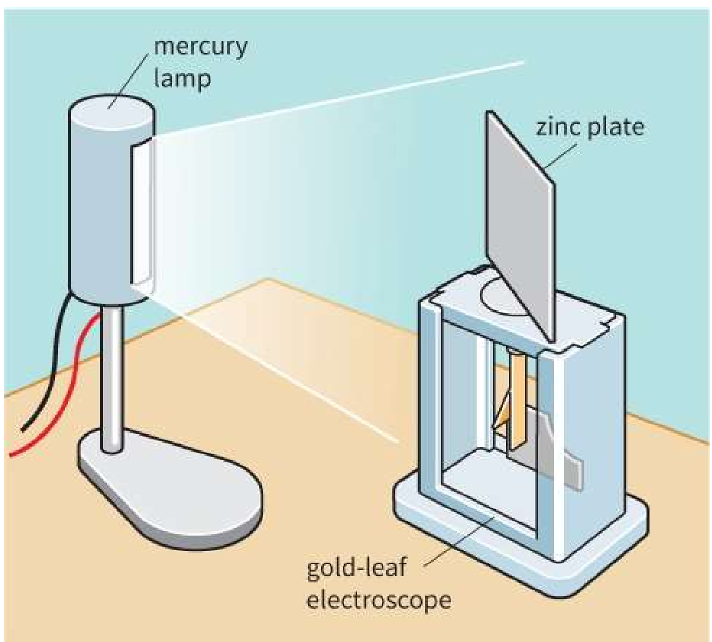

Figure 28.7: A simple experiment to observe the photoelectric effect.

28.4 Threshold frequency and wavelength

If you try the experiment described in Practical Activity 28.2 with a bright filament lamp, you will find it has no effect. A filament lamp does not produce ultraviolet radiation. There is a minimum frequency that the incident radiation must have in order to release electrons from the metal. This is called the **threshold frequency**. The threshold frequency is a property of the metal plate being exposed to electromagnetic radiation.

The threshold frequency is defined as the minimum frequency required to release electrons from the surface of a metal.

Since $c = f\lambda$, this implies that the threshold frequency has an equivalent longest wavelength for the liberation of electrons from the surface of a metal. This is called the **threshold wavelength**.

Threshold wavelength is the longest wavelength of the incident electromagnetic radiation that would eject electrons from the surface of a metal.

Physicists found it hard to explain why weak ultraviolet radiation could have an immediate effect on the electrons in the metal, but very bright light of lower frequency had no effect. They imagined light waves arriving at the metal, spread out over its surface and they could not see how weak ultraviolet waves could be more effective than the intense visible waves. In 1905, Albert Einstein came up with an explanation based on the idea of photons.

Metals (such as zinc) have electrons that are not very tightly held within the metal. These are the conduction electrons, and they are free to move about within the metal. When photons of electromagnetic radiation strike the metal, some electrons break free from the surface of the metal (Figure 28.8). They only need a small amount of energy (about 10^{-19} J) to escape from the metal surface.

We can picture the electrons as being trapped in an energy 'well' (Figure 28.9). A single electron requires a minimum energy Φ (Greek letter phi) to escape the surface of the metal. The **work function energy**, or simply **work function**, of a metal is the minimum amount of energy required by an electron to escape its surface. Energy is needed to release the surface electrons because they are attracted by the electrostatic forces due to the positive metal ions.

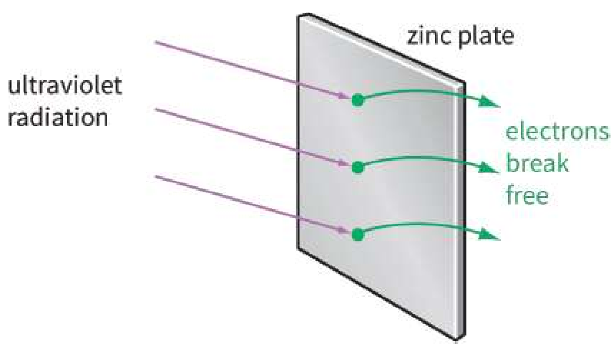

Figure 28.8: The photoelectric effect. When a photon of ultraviolet radiation strikes the metal plate, its energy may be sufficient to release an electron.

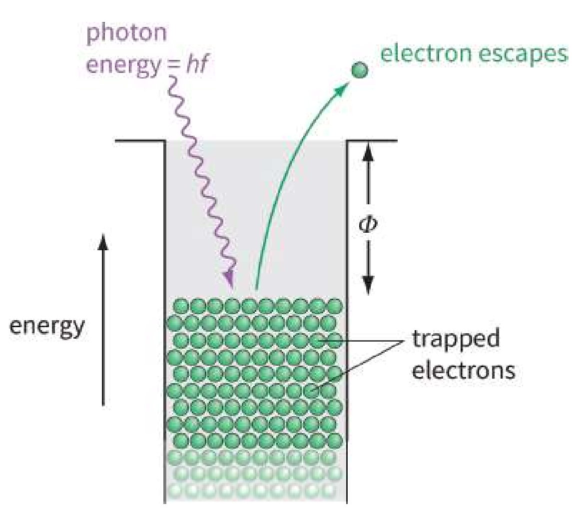

Figure 28.9: A single photon may interact with a single electron to release it.

Einstein did not picture electromagnetic waves interacting with all of the electrons in the metal. Instead, he suggested that a single photon could provide the energy needed by an individual electron to escape. The photon energy would need to be at least as great as Φ. By this means, Einstein could explain the threshold frequency. A photon of visible light has energy less than Φ, so it cannot release an electron from the surface of zinc.

When a photon arrives at the metal plate, it may be captured by an electron. The electron gains all of the photon's energy and the photon no longer exists. Some of the energy is needed for the electron to escape from the energy well; the rest is the electron's kinetic energy.

Now we can see that the photon model works because it models electromagnetic waves as concentrated 'packets' of energy, each one able to release an electron from the metal.

Here are some rules for the photoelectric effect:

- Electrons from the surface of the metal are removed.
- A single photon can only interact, and hence exchange its energy, with a single electron (one-to-one interaction).
- A surface electron is removed **instantaneously** from the metal surface when the energy of the incident photon is greater than, or equal to, the work function Φ of the metal. (The frequency of the incident radiation is greater than, or equal to, the threshold frequency of the metal. Alternatively, the wavelength of the incident radiation is less than, or equal to, the threshold wavelength of the metal.)
- Energy must be conserved when a photon interacts with an electron.
- Increasing the intensity of the incident radiation does not release a single electron when its frequency is less than the threshold frequency. The intensity of the incident radiation is directly proportional to the **rate** at which photons arrive at the plate. Each photon still has energy that is less than the work function.

Photoelectric experiments showed that the electrons released had a range of kinetic energies up to some maximum value, k.e.$_{\text{max}}$. These fastest-moving electrons are the ones that were least tightly held in the metal.

Imagine a single photon interacting with a single surface electron and freeing it. According to Einstein:

$$\begin{aligned}\text{energy of photon} &= \text{work function} + \text{maximum kinetic energy of electron}\\ hf &= \Phi + \text{k.e.}_{\text{max}}\\ hf &= \Phi + \tfrac{1}{2}mv_{\text{max}}{}^2\end{aligned}$$

where hf is the energy of the photon, Φ is the work function of the metal and $\frac{1}{2}mv_{\text{max}}{}^2$ is the maximum kinetic energy of the emitted photoelectron.

This equation, known as **Einstein's photoelectric equation**. It can also be written as:

$$\frac{hc}{\lambda} = \Phi + \frac{1}{2}mv_{\text{max}}{}^2$$

KEY EQUATION

Einstein's photoelectric equation:

$$hf = \Phi + \frac{1}{2}mv_{\text{max}}{}^2 \text{ or } \frac{hc}{\lambda} = \Phi + \frac{1}{2}mv_{\text{max}}{}^2$$

The photoelectric equation can be understood as follows:

- We start with a photon of energy hf.
- It is absorbed by an electron.
- Some of the energy (Φ) is used in escaping from the metal. The rest remains as kinetic energy of the electron.
- If the photon is absorbed by an electron that is lower in the energy well, the escaping electron will have less kinetic energy than k.e.$_{\text{max}}$ (Figure 28.10).

What happens when the incident radiation has a frequency equal to the threshold frequency f_0 of the metal?

The kinetic energy of an electron is zero. Hence, according to Einstein's photoelectric equation:

$$hf_0 = \Phi$$

Hence, the threshold frequency f_0 is given by the expression:

$$f_0 = \frac{\Phi}{h}$$

and, the threshold wavelength γ_0 is given by the expression:

$$\lambda_0 = \frac{hc}{\Phi}$$

What happens when the incident radiation has frequency less than the threshold frequency? A single photon can still give up its energy to a single electron, but this electron cannot escape from the attractive forces of the positive metal ions. The energy absorbed from the photons appears as kinetic energy of the electrons. These electrons lose their kinetic energy to the metal ions when they collide with them. This warms up the metal. This is why a metal plate placed close to a table lamp gets hot.

Different metals have different threshold frequencies, and hence different work functions. For example, alkali metals such as sodium, potassium and rubidium have threshold frequencies in the visible region of the electromagnetic spectrum. The conduction electrons in zinc are more tightly bound within the metal and so its threshold frequency is in the ultraviolet region of the spectrum.

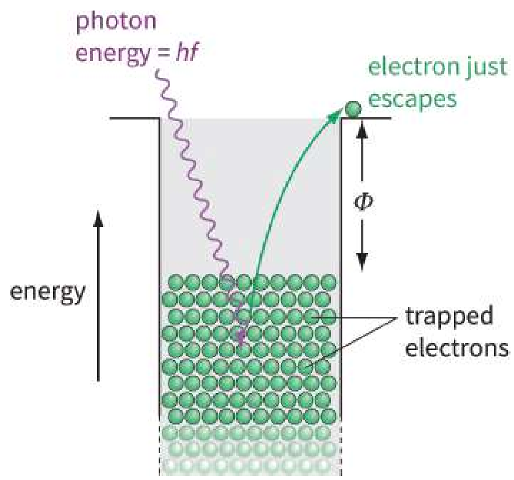

Figure 28.10: A more tightly bound electron needs more energy to release it from the metal.

Table 28.4 summarises the observations of the photoelectric effect.

Observation	**Comments**
Emission of electrons happens as soon as the electromagnetic radiation is incident on the metal.	A single photon interacts with a single electron. If the energy of the incident photon is equal to, or greater than, the work function of the metal, the electrons will be ejected instantaneously.
Even weak (low-intensity) electromagnetic radiation is effective.	Low-intensity means smaller rate of photons incident on the metal surface. The energy of each photon depends on the frequency or wavelength – not the intensity. As long as each photon has energy equal to, or greater than, the work function of the metal, the electrons will be ejected. Low intensity would imply smaller rate of emission of electrons.
Increasing intensity of electromagnetic radiation increases rate at which electrons leave metal.	Greater intensity means greater rate of photons incident on the metal surface. If the electrons are collected as part of an external circuit, then the photoelectric current would be directly proportional to the intensity of the incident radiation – this is provided the threshold frequency of the metal has been exceeded.

Increasing intensity has no effect on kinetic energies of electrons.	Greater intensity does not mean more energetic photons, so electrons cannot have more kinetic energy. The maximum kinetic energy of the electrons is given by $\mathrm{k.e.}_{\max} = hf - \Phi$; it is independent of intensity.
A minimum threshold frequency is needed for the emission of electrons.	Electrons will be emitted from the metal surface when the incident radiation has frequency equal to or greater than the threshold frequency.
Increasing frequency of electromagnetic radiation increases maximum kinetic energy of electrons.	Higher frequency means more energetic photons; so electrons gain more kinetic energy and can move faster. Once again, you can use $\mathrm{k.e.}_{\max} = hf - \Phi$ to explain the observation.

Table 28.4: The success of the photon model in explaining the photoelectric effect.

Questions

You will need these values to answer questions 10 to 13:

speed of light in a vacuum c = 3.00 × 108 m s^{-1}

Planck constant h = 6.63 × 10^{-34} J s

mass of electron m_e = 9.11 × 10^{-31} kg

elementary charge e = 1.60 × 10^{-19} C

10 Photons of energies 1.0 eV, 2.0 eV and 3.0 eV strike a metal surface whose work function is 1.8 eV.

- **a** State which of these photons could cause the release of an electron from the metal.
- **b** Calculate the maximum kinetic energies of the electrons released in each case. Give your answers in eV and in J.

11 Table 28.5 shows the work functions of several different metals.

- **a** State which metal requires the highest frequency of electromagnetic waves to release electrons.
- **b** State which metal will release electrons when the lowest frequency of electromagnetic waves is incident on it?
- **c** Calculate the threshold frequency for zinc.
- **d** Calculate the threshold wavelength for potassium.

Metal	**Work function Φ / J**	**Work function Φ / eV**
caesium	3.0 × 10^{-19}	1.9
calcium	4.3 × 10^{-19}	2.7
gold	7.8 × 10^{-19}	4.9
potassium	3.2 × 10^{-19}	2.0
zinc	6.9 × 10^{-19}	4.3

Table 28.5: Work functions of several different metals.

12 Electromagnetic waves of wavelength 2.4 × 10^{-7} m are incident on the surface of a metal whose work function is 2.8 × 10^{-19} J.

- **a** Calculate the energy of a single photon.
- **b** Calculate the maximum kinetic energy of electrons released from the metal.
- **c** Determine the maximum speed of the emitted photoelectrons.

13 When electromagnetic radiation of wavelength 2000 nm is incident on a metal surface, the maximum kinetic energy of the electrons released is found to be 4.0 × 10^{-20} J.

Calculate the work function of the metal in joules (J).

28.5 Photons have momentum too

Figure 28.11: Comet Hyakutake. The tail of a comet is evidence that photons of sunlight have momentum.

The photoelectric effect provides evidence for the particle-like behaviour of photons. Is there any other evidence for this type of behaviour of electromagnetic radiation? In 1619, German mathematician and astronomer Johann Kepler suggested that the long tail of a comet points away from the Sun because sunlight exerts pressure on this tail. Figure 28.11 shows the tail of the Comet Hyakutake in the night sky.

Kepler was almost correct. In 1905, Albert Einstein, as part of his Special Theory of Relativity, showed that a photon travelling in a vacuum has momentum, even though it has no mass. The steady stream of momentum-carrying photons in sunlight is responsible for exerting pressure (or force) on objects in space. Satellites orbiting the Earth – or space probes sent to explore the planets in our Solar System – have to take account of tiny pressures exerting by colliding photons. A satellite orbiting the Earth would experience a pressure of about 9 μN m^{-2} from sunlight.

Einstein showed that the momentum p of a photon is related to its energy E by the equation:

$$p = \frac{E}{c}$$

where c is the speed of light in a vacuum.

The energy E of a photon can be written either as:

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

Worked example 2 shows how you can **estimate** the pressure exerted by photons hitting a metal plate.

WORKED EXAMPLES

2 A 2.0 mW laser beam is incident normally on a fixed metal plate. The cross-sectional area of the beam is 4.0×10^{-6} m^2. The light from the laser has frequency 4.7×10^{14} Hz.

Calculate the momentum of the photon, and the pressure exerted by the laser beam on the metal plate. You may assume that the photons are all absorbed by the plate.

Step 1 Calculate the momentum of each photon.

$$\begin{aligned} p &= \frac{E}{c} \\ &= \frac{hf}{c} \\ &= \frac{6.63\times10^{-34}\times4.7\times10^{14}}{3.0\times10^{8}} \\ &= 1.04\times10^{-27}\,\text{Ns} \end{aligned}$$

(Note: the units can either be written as kg m s^{-1} or N s.)

Step 2 Calculate the number of photons incident on the plate per second.

$$\text{number of photons per second} = \frac{\text{power}}{\text{energy of each proton}} = \frac{0.002}{hf} = \frac{0.002}{6.63\times10^{-34}\times4.7\times10^{14}} = 6.42 \times 10^{15}\,\text{s}^{-1}$$

Step 3 Calculate the force exerted on the plate by assuming we can use Newton's second law. Consider a time interval of 1.0 s.

$$\begin{aligned}\text{force} &= \text{rate of change of momentum of the photons}\\ &= \text{number of photons per second} \times \text{momentum of each photon}\\ &= 6.42 \times 10^{15} \times 1.04 \times 10^{-27}\\ &= 6.68 \times 10^{-12}\,\text{N}\end{aligned}$$

Step 4 Calculate the pressure.

$$\text{pressure} = \frac{\text{force}}{\text{area}} = \frac{6.68\times10^{-12}}{4.0\times10^{-6}} = 1.7 \times 10^{-6}\,\text{Pa}$$

This is a tiny pressure and would not be noticeable on the fixed metal plate. However, if this plate was in deep-space, it would, over a period of time, show some movement.

28.6 Line spectra

We will now look at another phenomenon that we can explain in terms of light as photons. We rely a great deal on light to inform us about our surroundings. Using our eyes we can identify many different colours. Scientists take this further by analysing light, by splitting it up into a spectrum. The technical term for the splitting of light into its components is **dispersion**. You will be familiar with the ways in which this can be done, using a prism or a diffraction grating (Figure 28.12).

The spectrum of white light shows that it consists of a range of wavelengths, from about 400 nm (violet) to about 700 nm (red), as in Figure 28.13. This is a **continuous spectrum**.

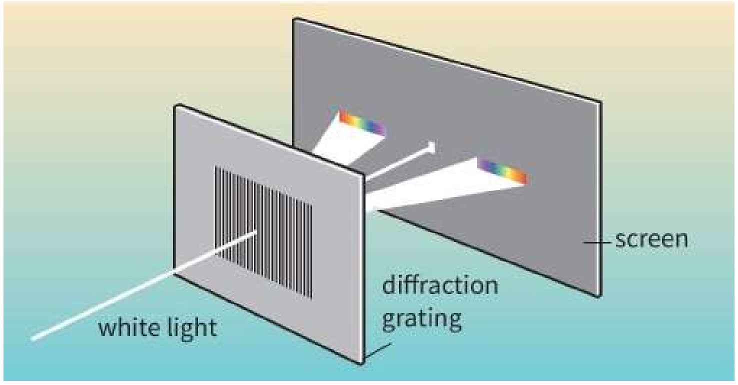

Figure 28.12: White light is split up into a continuous spectrum when it passes through a diffraction grating.

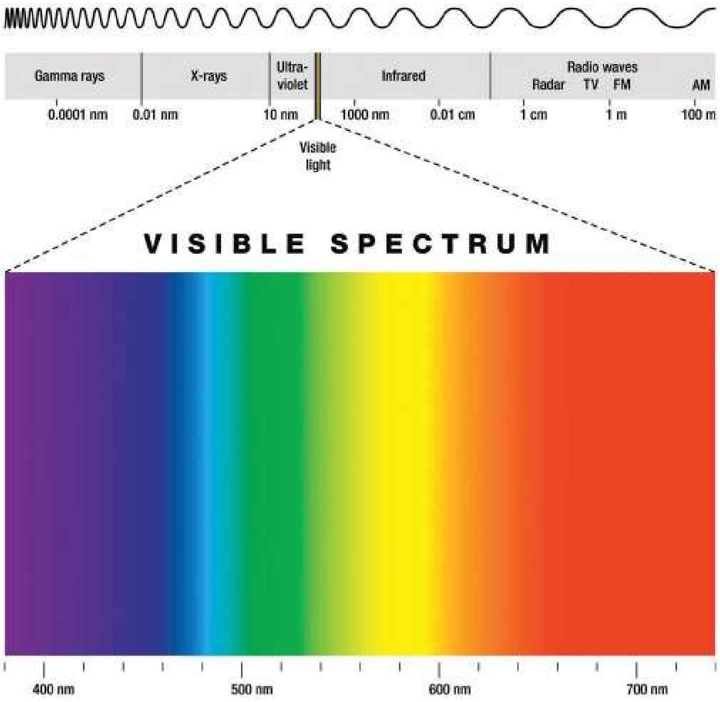

Figure 28.13: Spectra of white light.

It is more interesting to look at the spectrum from a hot gas. If you look at a lamp that contains a gas such as neon or sodium, you will see that only certain colours are present. Each colour has a unique wavelength. If the source is narrow and it is viewed through a diffraction grating, a **line spectrum** is seen.

Figure 28.14a–c show the line spectra of hot gases of the elements mercury, helium and cadmium. Each element has a spectrum with a unique collection of wavelengths. Line spectra can therefore be used to identify elements. This is exactly what the British astronomer William Huggins did when he deduced which elements are the most common in the stars.

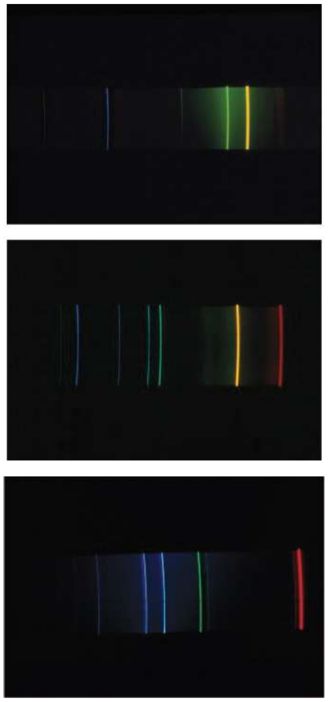

Figure 28.14: Spectra of light from **a** mercury, **b** helium and **c** cadmium vapour.

These line spectra, which show the composition of light emitted by hot gases, are called **emission line spectra**.

There is another kind of spectra, called **absorption line spectra**, which are observed when white light is passed through cool gases. After the light has passed through a diffraction grating, the continuous white light spectrum is found to have black lines across it (Figure 28.15). Certain wavelengths have been absorbed as the white light passed through the cool gas.

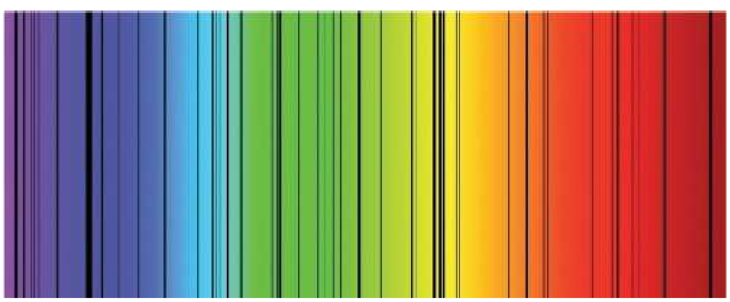

Figure 28.15: An absorption line spectrum formed when white light is passed through cool mercury vapour.

Absorption line spectra are found when the light from stars is analysed. The interior of the star is very hot and emits white light of all wavelengths in the visible range. However, this light has to pass through the **cooler** outer layers of the star. As a result, certain wavelengths are absorbed. Figure 28.16 shows the spectrum for the Sun.

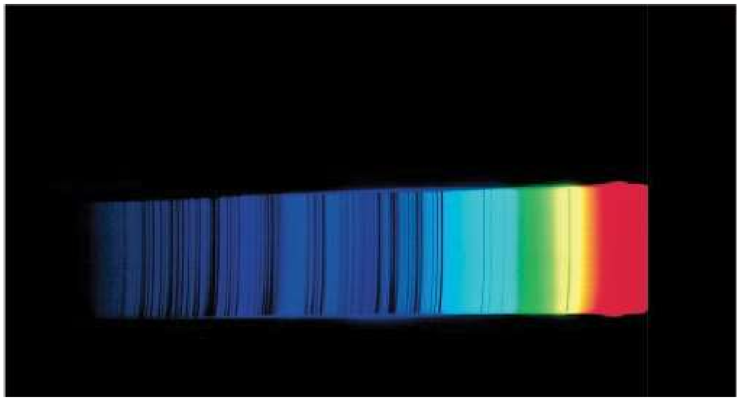

Figure 28.16: The Sun's spectrum shows dark lines. These dark lines arise when light of specific wavelengths coming from the Sun's hot interior is absorbed by its cooler atmosphere.

28.7 Explaining the origin of line spectra

From the description in the previous topic, we can see that the atoms of a given element (e.g., helium) can only emit or absorb light of certain wavelengths.

Different elements emit and absorb different wavelengths. How can this be? To understand this, we need to establish two points:

- First, as with the photoelectric effect, we are dealing with light (an electromagnetic wave) interacting with matter. Hence, we need to consider light as consisting of photons. For light of a single wavelength λ and frequency f, the energy E of each photon is given by the equation:

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

- Second, when light interacts with matter, it is the electrons that absorb the energy from the incoming photons. When the electrons lose energy, light is emitted by matter in the form of photons.

What does the appearance of the line spectra tell us about electrons in atoms? They can only absorb, or emit, photons of certain energies. From this we deduce that electrons in atoms can themselves only have certain fixed values of energy. This idea seemed very odd to scientists a hundred years ago. Figure 28.17 shows a diagram of the permitted **energy levels** (or **energy states**) of the electron of a hydrogen atom. An electron in a hydrogen atom can have only one of these values of energy. It cannot have an energy that is between these energy levels.

The energy levels of the electron are similar to the rungs of a ladder. The energy levels have **negative** values because external energy has to be supplied to remove an electron from the atom. The negative energy shows that the electron is trapped within the atom by the attractive forces of the atomic nucleus. An electron with zero energy is free from the atom.

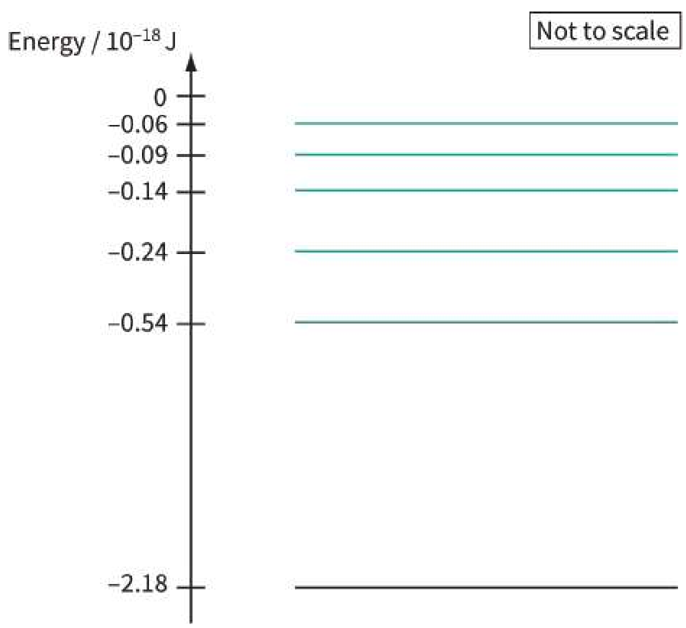

Figure 28.17: Some of the energy levels of the hydrogen atom.

The energy of the electron in the atom is said to be **quantised**. This is one of the most important statements of quantum physics.

Now we can explain what happens when an atom emits light. One of its electrons falls from a high energy level to a lower one (Figure 28.18a). The electron makes a **transition** to a lower energy level. It is important to note that, even on this microscopic scale, energy must be conserved. The loss of energy of the electron leads to the emission of a single photon of light. The one-to-one interaction rule of quantum physics is paramount – a single electron is responsible for producing a single photon. The energy of this photon is exactly equal to the energy difference between the two energy levels. If the electron makes a transition from a higher energy level, the energy loss of the electron is larger and this leads to the emission of a more energetic photon. The distinctive energy levels of an atom mean that the energy of the photons emitted, and hence the wavelengths emitted, will be unique to that atom. This explains why only certain wavelengths are present in the emission line spectrum of a hot gas.

Atoms of different elements have different line spectra because they have different spacings between their energy levels. It is not within the scope of this book to discuss why this is.

Similarly, we can explain the origin of absorption line spectra. White light consists of photons of many different energies. For a photon to be absorbed, it must have exactly the right energy to lift an electron from one energy level to another higher energy level (Figure 28.18b). This ‘excited’ electron, at the higher energy level, will eventually make a transition to a lower energy level – but this time, the photon will be re-emitted in any direction, and not necessarily in the original direction of the white light. This leads to lower intensity for photons of a specific wavelength. White light photons with energy not matching the difference between the energy levels will carry on moving in the original direction. The net result of all this is a dark absorption line seen against the background of a continuous spectrum.

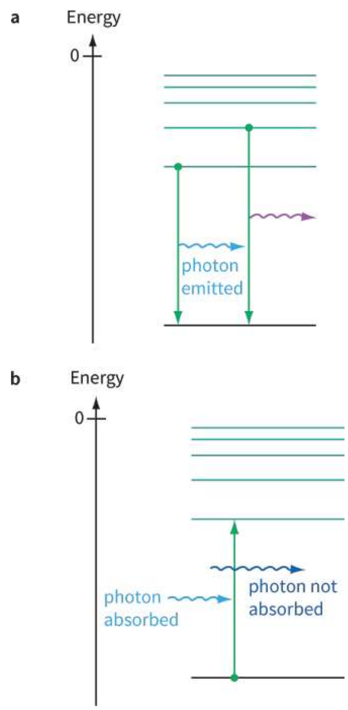

Figure 28.18: a When an electron drops to a lower energy level, it emits a single photon. **b** A photon must have just the right energy if it is to be absorbed by an electron.

28.8 Photon energies

When an electron changes its energy from one level E_1 to another E_2, it either emits or absorbs a **single** photon. The energy of the photon hf is simply equal to the **difference** in energies between the two levels:

$$\begin{aligned} \text{photon energy} &= \Delta E \\ hf &= E_1 - E_2 \end{aligned}$$

or

$$\frac{hc}{\lambda} = E_1 - E_2$$

Referring back to the energy level diagram for hydrogen (Figure 28.17), you can see that, if an electron falls from the second level to the lowest energy level (known as the **ground state**), it will emit a photon of energy:

$$\begin{aligned} \text{photon energy} &= \Delta E \\ hf &= ((-0.54) - (-2.18)) \times 10^{-18}\,\text{J} \\ &= 1.64 \times 10^{-18}\,\text{J} \end{aligned}$$

We can calculate the frequency f and wavelength λ of the emitted electromagnetic radiation.

The frequency is:

$$\begin{aligned} f &= \frac{E}{h} \\ &= \frac{1.64\times10^{-18}}{6.63\times10^{-34}} \\ &= 2.47 \times 10^{15}\,\text{Hz} \end{aligned}$$

The wavelength is:

$$\begin{aligned} \lambda &= \frac{c}{f} \\ &= \frac{3.00\times10^{8}}{2.47\times10^{15}} \\ &= 1.21 \times 10^{-7}\,\text{m} \approx 121\ \text{nm} \end{aligned}$$

This is a wavelength in the ultraviolet region of the electromagnetic spectrum.

KEY EQUATIONS

The energy of a photon, absorbed or emitted, as a result of an electron making a transition between two energy levels E_1 and E_2:

$$hf = E_1 - E_2$$

$$\frac{hc}{\lambda} = E_1 - E_2$$

Questions

14 Figure 28.19 shows part of the energy level diagram for the electrons in an imaginary atom. The arrows represent three transitions between the energy levels. For each of these transitions:

- **a** calculate the energy of the photon
- **b** calculate the frequency and wavelength of the electromagnetic radiation (emitted or absorbed)
- **c** state whether the transition contributes to an emission line in the spectrum or an absorption line in the spectrum.

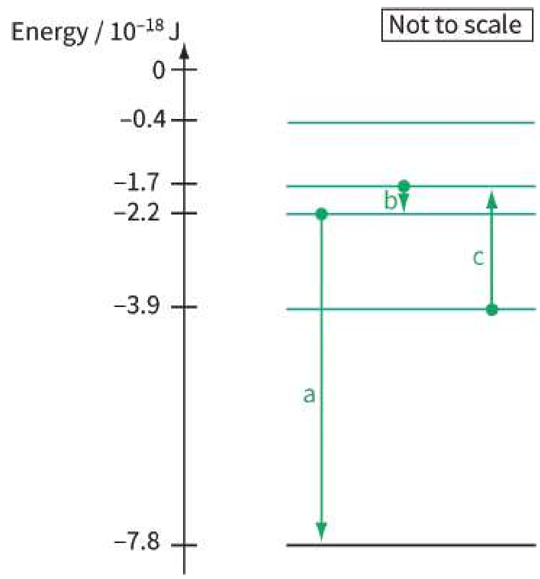

Figure 28.19: Electron energy level diagram, showing three electron transitions a, b and c. For Question 14.

15 Figure 28.20 shows another energy level diagram. In this case, energy is given in electronvolts (eV). The list shows the energies of some photons:

6.0 eV 9.0 eV 11 eV 20 eV 25 eV 34 eV 45 eV

State and explain which of these photons will be absorbed by the electrons.

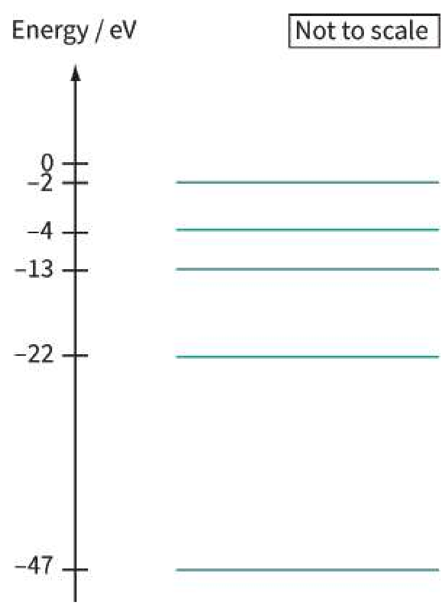

Figure 28.20: An energy level diagram. For Question 15.

16 The line spectrum for a particular type of atom is found to include the following wavelengths:

83 nm   50 nm   25 nm

a Calculate the corresponding photon energies in eV.

b Sketch the energy levels that could give rise to these photons. On the diagram, indicate the corresponding electron transitions responsible for these three spectral lines.

28.9 The nature of light: waves or particles?

It is clear that, in order to explain the photoelectric effect, we must use the idea of light (and all electromagnetic radiation) as particles. Similarly, photons explain the appearance of line spectra. However, to explain diffraction, interference and polarisation of light, we must use the wave model. How can we sort out this dilemma?

We have to conclude that sometimes light shows wave-like behaviour; at other times it behaves as particles (photons). In particular, when light is absorbed by a metal surface, it behaves as particles. Individual photons are absorbed by individual electrons in the metal. In a similar way, when a Geiger counter detects γ-radiation, we hear individual γ-photons being absorbed in the tube.

So what is light? Is it a wave or a particle? Physicists have come to terms with the dual nature of light. This duality is referred to as the **wave–particle duality** of light. In simple terms:

- Light interacts with matter (e.g., electrons) as a particle – the photon. The evidence for this is provided by the photoelectric effect.
- Light propagates through space as a wave. The evidence for this comes from the diffraction and interference of light using slits.

28.10 Electron waves

Light has a dual nature. (In fact, it is not only light, but all electromagnetic waves that have this dual nature.) Is it possible that particles such as electrons also have a dual nature? This interesting question was first considered by Louis de Broglie (pronounced 'de Broy') in 1924 (Figure 28.21).

Figure 28.21: Louis de Broglie provided an alternative view of how particles behave.

De Broglie imagined that electrons would travel through space as a wave. He proposed that the wave-like property of a particle like the electron can be represented by its wavelength λ, which is related to its momentum *p* of the particle by the equation:

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

where *h* is the Planck constant. The wavelength λ is often referred to as the **de Broglie wavelength**. The waves associated with the electron are referred to as matter waves.

The momentum *p* of a particle is the product of its mass *m* and its velocity *v*. Therefore, the de Broglie equation may also be written as:

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

The Planck constant *h* is the same constant that appears in the equation $E = hf$ for the energy of a photon. It is fascinating how the Planck constant *h* is tangled with the behaviour of both matter as waves (e.g. electrons) and electromagnetic waves as 'particles' (photons).

The wave property of the electron was eventually confirmed in 1927 by researchers in America and in England. The Americans, Clinton Davisson and Edmund Germer, showed experimentally that electrons were diffracted by crystals of nickel. The diffraction of electrons confirmed their wave-like property. In England, George Thomson fired electrons into thin sheets of metal in a vacuum tube. He, too, provided evidence that electrons were diffracted by the metal atoms.

Louis de Broglie received the 1929 Nobel Prize in Physics. Clinton Davisson and George Thomson shared the Nobel Prize in Physics in 1937.

Electron diffraction

We can reproduce the same diffraction results in the laboratory using an electron diffraction tube (Figure 28.22).

In an electron diffraction tube, the electrons from the heated filament are accelerated to high speeds by the large potential difference between the negative heater (cathode) and the positive electrode (anode). A beam of electrons passes through a thin sample of polycrystalline graphite. It is made up of many tiny crystals, each of which consists of large numbers of carbon atoms arranged in uniform atomic layers. The electrons emerge from the graphite film and produce diffraction rings on the phosphor screen. The diffraction rings are similar to those produced by light (a wave) passing through a small circular hole. The rings cannot be explained if electrons behaved as particles. Diffraction is a property of waves. Hence, the rings can only be explained if the electrons travel through the graphite film as a wave. The electrons are diffracted by the individual carbon atoms and the spacing between the layers of carbon atoms. The atomic layers of carbon behave like a diffraction grating with many slits. The electrons show diffraction effects because their de Broglie wavelength λ is similar to the spacing between the atomic layers.

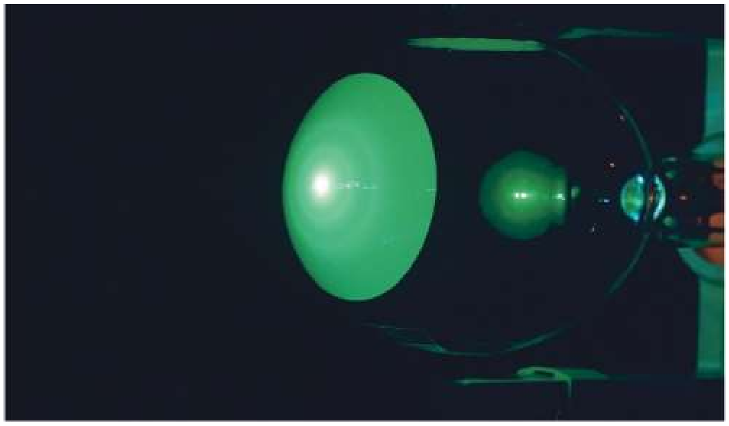

Figure 28.22: When a beam of electrons passes through a graphite film, as in this vacuum tube, a diffraction pattern is produced on the phosphor screen.

This experiment shows that electrons appear to travel as waves. If we look a little more closely at the results of the experiment, we find something even more surprising. The phosphor screen gives a flash of light for each electron that hits it. These flashes build up to give the diffraction pattern (Figure 28.23). But if we see flashes at particular points on the screen, are we not seeing individual electrons – in other words, are we not observing particles?

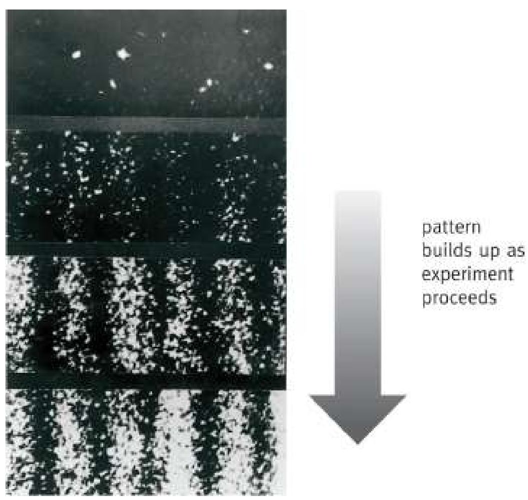

Figure 28.23: The speckled diffraction pattern shows that it arises from many individual electrons striking the screen.

PRACTICAL ACTIVITY 28.3

Investigating electron diffraction

If you have access to an electron diffraction tube (Figure 28.24), you can see for yourself how a beam of electrons is diffracted. The electron gun at one end of the tube produces a beam of electrons. By changing the voltage between the anode and the cathode, you can change the energy of the electrons, and hence their speed. The beam strikes a graphite target, and a diffraction pattern appears on the screen at the other end of the tube.

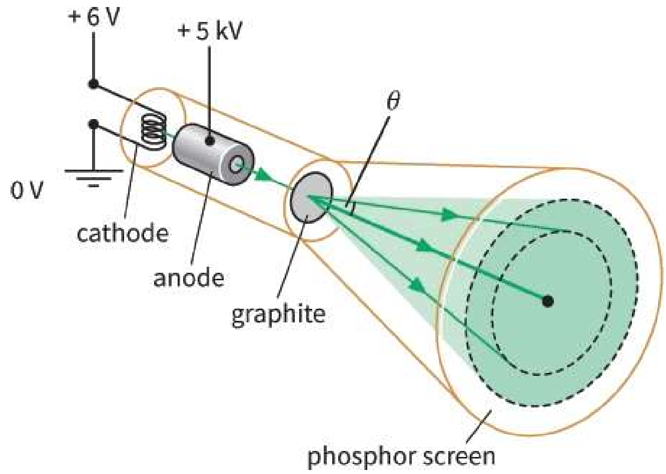

Figure 28.24: Electrons are accelerated from the cathode to the anode; they form a beam that is diffracted as it passes through the graphite film.

You can use an electron diffraction tube to investigate how the wavelength of the electrons depends on their speed. Qualitatively, you should find that increasing the anode–cathode voltage makes the pattern of diffraction rings shrink. The electrons have more kinetic energy (they are faster); the shrinking pattern shows that their wavelength has decreased. You can find the wavelength λ of the electrons by measuring the angle θ at which they are diffracted:

$$\lambda = 2d \sin\theta$$

where d is the spacing of the atomic layers of graphite.

You can find the speed of the electrons from the anode–cathode voltage V:

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

WORKED EXAMPLE

3 Calculate the de Broglie wavelength of an electron travelling through space at a speed of 1.0×10^7 m s^{-1}. State whether or not these electrons can be diffracted by solid materials. (Atomic spacing in solid materials ~ 10^{-10} m.)

Step 1 According to the de Broglie equation, we have:

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

Step 2 The mass of an electron is 9.11×10^{-31} kg. Hence:

$$\lambda = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times1.0\times10^{7}}$$

$$= 7.3 \times 10^{-11}\,\text{m}$$

Electrons travelling at 10^7 m s^{-1} have a de Broglie wavelength of order of magnitude 10^{-10} m – this is comparable the atomic spacing. Hence, the electrons can be diffracted by matter.

Question

17 X-rays are used to find out about the spacings of atomic planes in crystalline materials.

a Describe how beams of electrons could be used for the same purpose.

b How might electron diffraction be used to identify a sample of a metal?

People waves

The de Broglie equation applies to all matter; anything that has mass. It can also be applied to objects like golf balls and people!

Imagine a 65 kg person running at a speed of 3.0 m s^{-1} through an opening of width 0.80 m. According to the de Broglie equation, the wavelength of this person is:

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{65 \times 3.0} = 3.4 \times 10^{-36} \text{m}$$

This wavelength is very small indeed compared with the size of the gap, hence no diffraction effects would be observed. People cannot be diffracted through everyday gaps. The de Broglie wavelength of this person is much smaller than any gap the person is likely to try to squeeze through! For this reason, we do not use the wave model to describe the behaviour of people; we get much better results by regarding people as large particles.

Question

18 A beam of electrons is accelerated from rest through a p.d. of 1.0 kV.

- **a** What is the energy (in eV) of each electron in the beam?
- **b** Calculate the speed, and hence the momentum (mv), of each electron.
- **c** Calculate the de Broglie wavelength of each electron.
- **d** Would you expect the beam to be significantly diffracted by a metal film in which the atoms are separated by a spacing of 0.25×10^{-9} m?

Probing matter

All moving particles have a de Broglie wavelength. The structure of matter can be investigated using the diffraction of particles. Diffraction of slow-moving neutrons (known as thermal neutrons) from nuclear reactors is used to study the arrangements of atoms in metals and other materials. The wavelength of these neutrons is about 10^{-10} m, which is roughly the separation between the atoms.

Diffraction of slow-moving electrons is used to explore the arrangements of atoms in metals (Figure 28.25) and the structures of complex molecules such as DNA (Figure 28.26). It is possible to accelerate electrons to the right speed so that their wavelength is similar to the spacing between atoms, around 10^{-10} m.

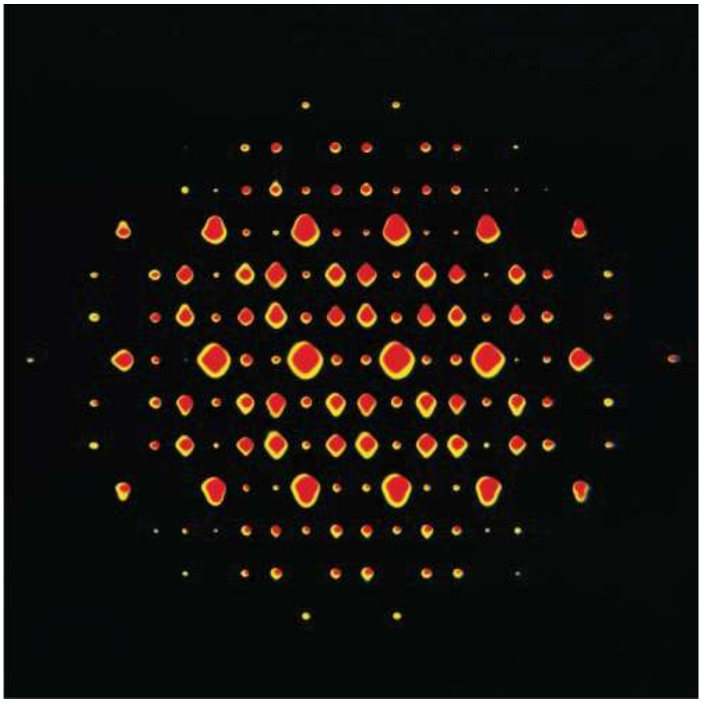

Figure 28.25: Electron diffraction pattern for an alloy of titanium and nickel. From this pattern, we can deduce the arrangement of the atoms and their separations.

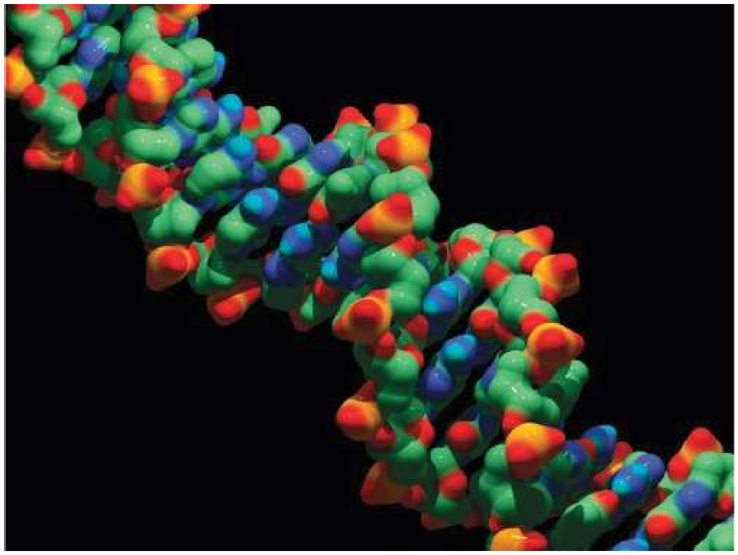

Figure 28.26: The structure of the giant molecule DNA, deduced from electron diffraction.

High-speed electrons from particle accelerators have been used to determine the diameter of atomic nuclei. This is possible because high-speed electrons have wavelengths of order of magnitude 10^{-15} m. This wavelength is similar to the size of atomic nuclei. Electrons travelling close to the speed of light are being used to investigate the internal structure of the nucleus. These electrons have to be accelerated by voltages up to 10^{9} V.

The nature of the electron: wave or particle?

The electron has a dual nature, just like electromagnetic waves. This duality is referred to as the **wave–particle duality** of the electron. In simple terms:

- An electron interacts with matter as a particle. The evidence for this is provided by Newtonian mechanics.
- An electron travels through space as a wave. The evidence for this comes from the diffraction of electrons.

28.11 Revisiting photons

It is worth finishing this topic on quantum physics by further examining the photon. A photon has momentum p and energy E. The two key equations for a photon are:

$$p = \frac{E}{c} \text{ and } E = \frac{hc}{\lambda}$$

Therefore,

$$\begin{aligned} p &= \frac{E}{c} \\ &= \frac{hc}{\lambda c} \\ &= \frac{h}{\lambda} \end{aligned}$$

This equation is identical to the de Broglie equation for momentum of particle and its wavelength. So, it appears that the equation can be used for the particle-like (photon) behaviour of electromagnetic radiation and the wave-like behaviour of particles. The de Broglie equation is an intriguing equation of quantum physics.

REFLECTION

Without looking at your textbook, summarise all the key equations containing the Planck constant h, and the key points of the photelectric effect.

Compare your summary with a fellow learner. Did you miss out any key ideas?

If you were the teacher, what comments would you make about your summary?

SUMMARY

For electromagnetic waves of frequency *f* and wavelength λ, each photon has energy *E* given by:

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

where *h* is the Planck constant.

One electronvolt is the energy transferred when an electron travels through a potential difference of 1 V:

1 eV = 1.60 × 10^{-19} J

A particle of charge e accelerated through a voltage V has kinetic energy given by:

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

The photoelectric effect is an example of a phenomenon explained in terms of the particle-like (photon) behaviour of electromagnetic radiation.

Einstein's photoelectric equation is:

$hf = \Phi + \frac{1}{2}m{v_{max}}^2$ or $\frac{hc}{\lambda} = \Phi + \frac{1}{2}m{v_{max}}^2$

where Φ = work function of the metal.

The threshold frequency is the **minimum** frequency of the incident electromagnetic radiation that will release an electron from the metal surface.

The threshold wavelength is the **longest** wavelength of the incident electromagnetic radiation that will release an electron from the metal surface.

Electron diffraction is an example of a phenomenon explained in terms of the wave-like behaviour of matter.

The de Broglie wavelength λ of a particle is related to its momentum *p* by the de Broglie equation:

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

where *p* = momentum of the particle = *mv*.

Both electromagnetic radiation (such as light) and matter (such as electrons) exhibit wave–particle duality; that is, they show both wave-like and particle-like behaviours, depending on the circumstances. In wave–particle duality:

- **interaction** is explained in terms of **particles**
- **propagation** through space is explained in terms of **waves**.

Photons have no mass, but they have momentum. The momentum *p* of a photon of energy *E* is given by the equation:

$p = \frac{E}{c}$

Line spectra arise for isolated atoms (the electrical forces between such atoms is negligible).

The energy of an electron in an isolated atom is quantised. The electron is allowed to exist in specific energy states known as energy levels.

An electron loses energy when it makes a transition from a higher energy level to a lower energy level. A photon of electromagnetic radiation is emitted because of this energy loss. The result is an emission line spectrum.

Absorption line spectra arise when a photon of electromagnetic radiation is absorbed by electrons in isolated atoms. An electron absorbs a photon of the correct energy to allow it to make a transition to a higher energy level.

The frequency *f* and the wavelength λ of the emitted or absorbed radiation are related to the energy levels E_1 and E_2 by the equations:

$hf = E_1 - E_2$ and $\frac{hc}{\lambda} = E_1 - E_2$

EXAM-STYLE QUESTIONS

1 In which of the following can you use the term work function in your explanation? **[1]**

a Diffraction of electrons by graphite

b Interference of light from a diffraction grating

c Photoelectric effect

d Reflection of light

2 A researcher is carrying out an experiment on the photoelectric effect. Electromagnetic radiation of different frequencies is incident on a metal and the maximum kinetic energy of the emitted electrons is determined.

The researcher plots a straight-line graph of maximum kinetic energy of the electrons $k.e_{max}$ against the frequency f of the radiation.

Which row is correct? **[1]**

	Gradient of graph	y-intercept of graph
A	the Planck constant	work function of metal
B	threshold frequency	the Planck constant
C	threshold wavelength	threshold frequency
D	work function of metal	threshold wavelength

Table 28.6

3 Calculate the energy of a photon of frequency 4.0×10^{18} Hz. **[2]**

4 The microwave region of the electromagnetic spectrum is considered to have wavelengths ranging from 5 mm to 50 cm. Calculate the range of energy of microwave photons. **[3]**

5 In a microwave oven, the photons are used to warm food. Each photon has energy 1.02×10^{-5} eV.

a Calculate the energy of each photon in joule (J). **[1]**

b Calculate the frequency of the photons. **[1]**

c Calculate the wavelength of the photons. **[1]**

[Total: 3]

6 **a** Alpha-particles of energy 5.0 MeV are emitted in the radioactive decay of radium. Express this energy in joules. **[1]**

b Electrons in an cathode-ray tube are accelerated through a potential difference of 10 kV. Calculate their energy:

i in electronvolts **[1]**

ii in joules. **[1]**

c In a nuclear reactor, neutrons are slowed to energies of 6×10^{-21} J. Calculates this in eV. **[1]**

[Total: 4]

7 A helium nucleus (charge = $+3.2 \times 10^{-19}$ C; mass = 6.8×10^{-27} kg) is accelerated through a potential difference of 7500 V.

Calculate:

a its kinetic energy in electronvolts **[2]**

b its kinetic energy in joules **[1]**

c its speed. **[2]**

[Total: 5]

8 Ultraviolet light with photons of energy 2.5×10^{-18} J is shone onto a zinc plate. The work function of zinc is 4.3 eV.

Calculate the maximum energy with which an electron can be emitted from the zinc plate. Give your answer in:

a eV **[3]**

b J. **[1]**

[Total: 4]

9 Calculate the minimum frequency of electromagnetic radiation that will cause the emission of photoelectrons from the surface of gold. **[2]**

(Work function for gold = 4.9 eV.)

10 The diagram shows five of the energy levels in a helium ion. The lowest energy level is known as the ground state.

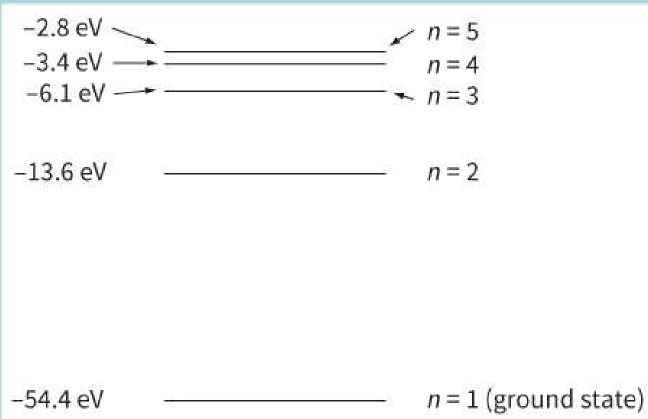

Figure 28.27

a Determine the energy, in joules, that is required to completely remove the remaining electron, originally in its ground state, from the helium ion. **[2]**

b Determine the frequency of the radiation that is emitted when the electron drops from the level n = 3 to n = 2. State the region of the electromagnetic spectrum in which this radiation lies. **[3]**

c Without further calculation, describe qualitatively how the frequency of the radiation emitted when the electron drops from the level n = 2 to n = 1 compares with the energy of the radiation emitted when it drops from n = 3 to n = 2. **[2]**

[Total: 7]

11 The spectrum of sunlight has dark lines. These dark lines are due to the absorption of certain wavelengths by the cooler gases in the atmosphere of the Sun.

a One particular dark spectral line has a wavelength of 590 nm. Calculate the energy of a photon with this wavelength. **[2]**

b The diagram shows some of the energy levels of an isolated atom of helium.

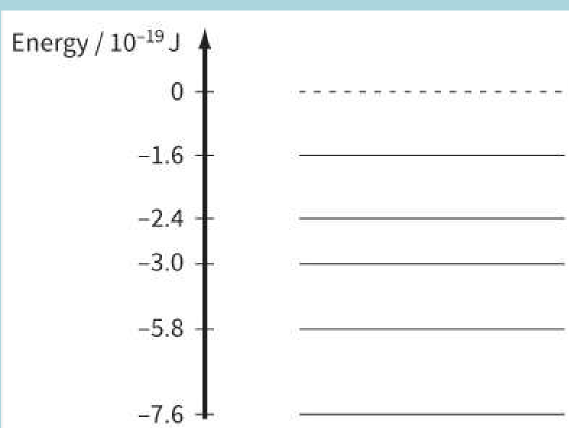

Figure 28.28

i Explain the significance of the energy levels having negative values. **[1]**

ii Explain, with reference to the energy level diagram, how a dark line in the spectrum may be due to the presence of helium in the atmosphere of the Sun. **[2]**

iii All the light absorbed by the atoms in the Sun's atmosphere is re-emitted. Suggest why a dark spectral line of wavelength of 590 nm is still observed from the Earth. **[1]**

[Total: 6]

12 The diagram shows three of the energy levels in an isolated hydrogen atom. The lowest energy level is known as the ground state.

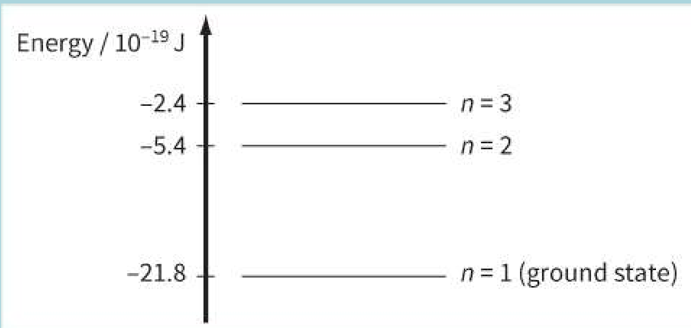

Figure 28.29

a Explain what happens to an electron in the ground state when it absorbs the energy from a photon energy 21.8×10^{-19} J. **[1]**

b **i** Explain why a photon is emitted when an electron makes a transition between energy levels n = 3 and n = 2. **[2]**

ii Calculate the wavelength of electromagnetic radiation emitted when an electron makes a jump between energy levels n = 3 and n = 2. **[3]**

iii In the diagram, each energy level is labelled with its 'principal quantum number' n. Use the energy level diagram to show that the energy E of an energy level is inversely proportional to n^2. **[4]**

[Total: 10]

13 **a** **i** Explain what is meant by the wave–particle duality of electromagnetic radiation. **[2]**

ii Explain how the photoelectric effect gives evidence for this phenomenon. **[2]**

The diagram shows the maximum kinetic energy E of the emitted photoelectrons as the frequency f of the incident radiation on a sodium plate is varied.

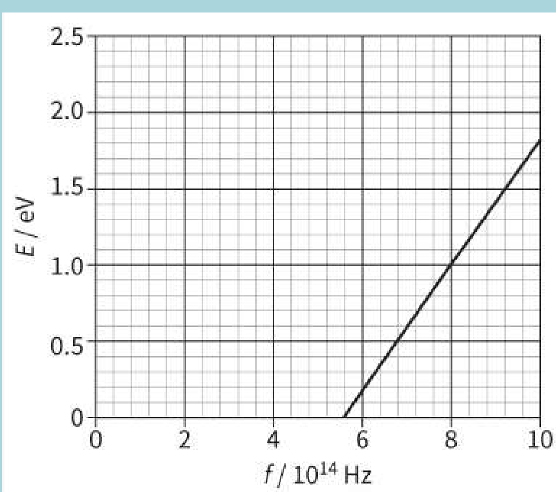

Figure 28.30

b Explain why there are no photoelectrons emitted when the frequency of the incident light is less than 5.6×10^{14} Hz. **[2]**

c Determine the work function for sodium. Explain your answer. **[3]**

d Use the graph to determine the value of the Planck constant. Explain your answer. **[3]**

[Total: 12]

14 a State what is meant by the **de Broglie wavelength** of an electron. **[2]**

b The diagram shows the principles of an electron tube used to demonstrate electron diffraction.

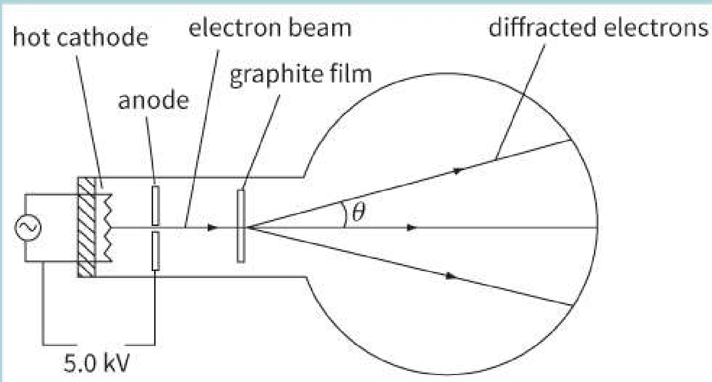

Figure 28.31

i Calculate the kinetic energy E (in joules) of the electrons incident on the graphite film. **[1]**

ii Show that the momentum of an electron is equal to $\sqrt{2Em_e}$ where m_e is the mass of an electron, and hence calculate the momentum of an electron. ($m_e = 9.11 \times 10^{-31}$ kg) **[3]**

iii Calculate the de Broglie wavelength of the electrons. **[2]**

c Explain how the wavelengths of neutrons and electrons moving with the same energy would compare. **[3]**

[Total: 11]

15 a Describe the importance of the Planck constant h in describing the behaviour of electromagnetic radiation and of electrons. **[2]**

b Light of wavelength 550 nm is incident normally on a metal plate. The intensity of the light is 800 W m^{-2}. All the incident light is absorbed by the metal plate. The plate has dimensions 5.0 cm × 5.0 cm.

i Explain how the light hitting the plate exerts force on the plate. **[3]**

ii Calculate the momentum of each photon of light. **[2]**

iii Calculate the force exerted on the plate due to the light. **[5]**

[Total: 12]