Cambridge

A2 Level

Physics

CODE: (9702)

Chapter 30

Chapter 30: Quantum physics

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

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 30.2)

Figure 30.2 Pool balls provide a good model for the behaviour of particles on a much smaller scale.

Area	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 30.1 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.

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 30.2 shows some phenomena that we explain in terms of waves.

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

Table 30.2 Wave models in science.

Waves or particles?

For over a century, physicists struggled to decide which model to use when explaining light. Newton's particle model, which suggested light travels faster in water than air, was widely accepted. However, French physicist Léon Foucault's 1853 experiments contradicted this, showing that light travels more slowly in water than air. This led to the belief that light travels through space as a wave.

Particulate nature of light

Light can behave as particles, as evidenced by the irregular clicks heard when a Geiger counter detects gamma-rays. These waves, part of the electromagnetic spectrum, are indistinguishable from α-particles and β-particles. This effect is most evident with γ-rays, as they are at the most energetic end of the spectrum.

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 which he thought made up light. Nowadays, we call them **photons** and we believe that all electromagnetic radiation consists of photons.

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**

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 16 that we use another energy unit, the **electronvolt**, when considering amounts of energy much smaller than a joule.

We can use this the electronvolt:

> One electronvolt (1 eV) is the energy transferred when an electron travels through a potential difference of one volt.

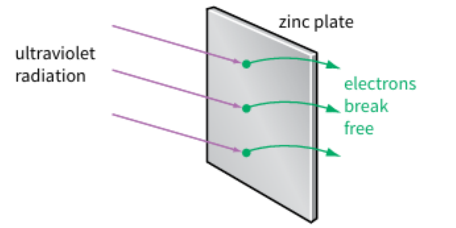


Figure 30.8 The photoelectric effect. When a photon of ultraviolet radiation strikes the metal plate, its energy may be sufficient to release an electron.

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**.

Low frequency, high frequency

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**.

A single electron requires a minimum energy Φ (Greek letter phi) to escape the surface of the metal. The w**ork function energy**, or simply **work function**, of a metal is the minimum amount of energy required by an electron to escape its surface.

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.

■ ■ 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 proportional to the rate at which photons arrive at the plate. Each photon still has energy which is less than the work function

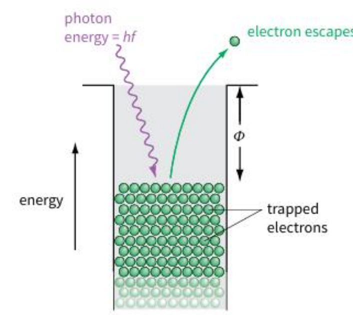


Figure 30.9 A single photon may interact with a single electron to release it.

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

$$hf_0 = \Phi$$

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

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

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

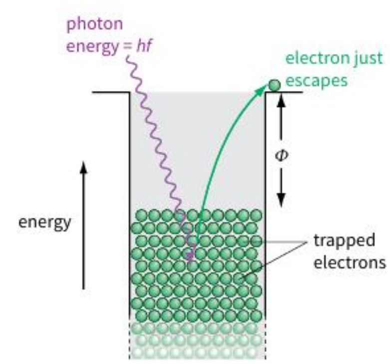


Figure 30.10 A more tightly bound electron needs more energy to release it from the metal.

Observation	Wave model	Photon model
Emission of electrons happens as soon as light shines on metal	Very intense light should be needed to have immediate effect	A single photon is enough to release one electron
Even weak (low-intensity) light is effective	Weak light waves should have no effect	Low-intensity light means fewer photons, not lower-energy photons
Increasing intensity of light increases rate at which electrons leave metal	Greater intensity means more energy, so more electrons are released	Greater intensity means more photons per second, so more electrons released per second
Increasing intensity has no effect on energies of electrons	Greater intensity should mean electrons have more energy	Greater intensity does not mean more energetic photons, so electrons cannot have more energy
A minimum threshold frequency of light is needed	Low-frequency light should work; electrons would be released more slowly	A photon in a low-frequency light beam has energy that is too small to release an electron
Increasing frequency of light increases maximum kinetic energy of electrons	It should be increasing intensity, not frequency, that increases energy of electrons	Higher frequency means more energetic photons; so electrons gain more energy and can move faster

Table 30.4 The success of the photon model in explaining the photoelectric effect.

Line spectra

We will now look at another phenomenon which we can explain in terms of light as photons. The technical term for the splitting of light into its components is **dispersion**.) 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.

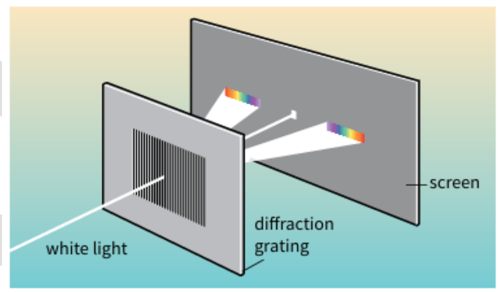


Figure 30.11 White light is split up into a continuous spectrum when it passes through a diffraction grating.

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

Figure 30.13 An absorption line spectrum formed when white light is passed through cool mercury vapour.

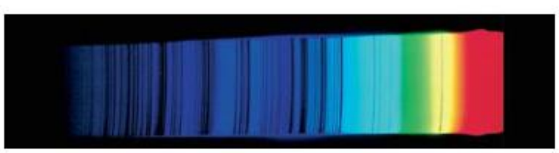


Figure 30.14 The Sun's spectrum shows dark lines. These dark lines arise when light of specific wavelengths coming from the Sun's hot interior is absorbed by its cooler atmosphere.

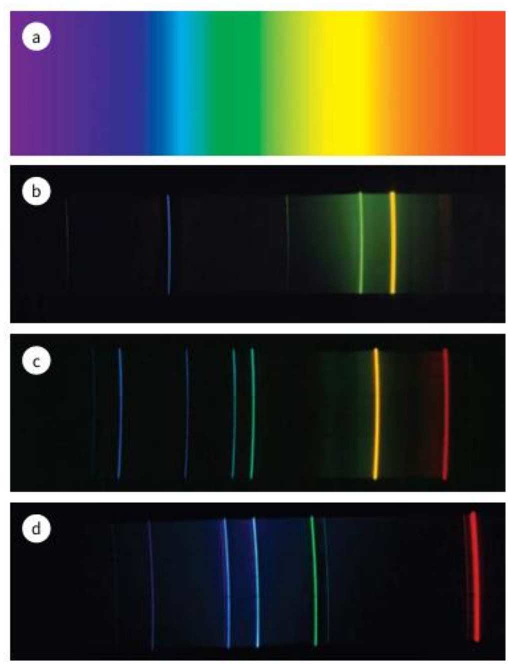
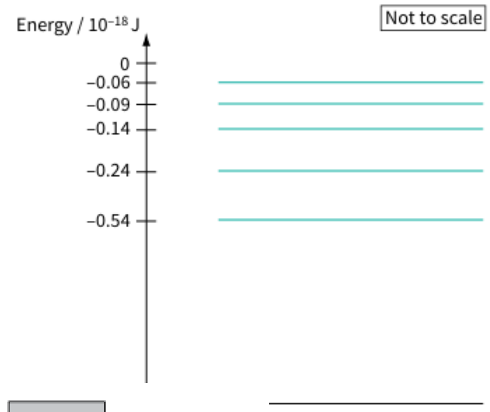


Figure 30.12 Spectra of **a** white light, and of light from **b** mercury, **c** helium and **d** cadmium vapour.

Explaining the origin of line spectra

From the description above, 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:



levels of the hydrogen atom.

form of

■ 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

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

■ Secondly, 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 photons.

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

The electron makes a **transition** to a lower energy level. The loss of energy of the electron leads to the emission of a single photon of light.

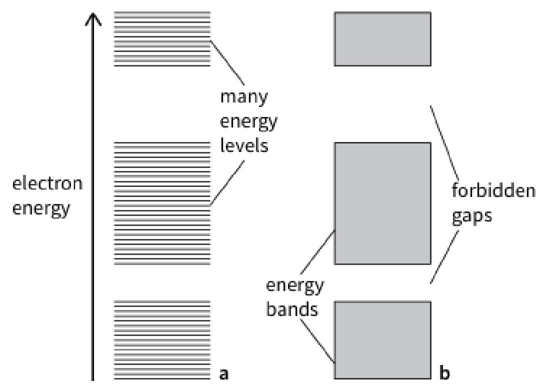


Figure 30.19 **a** In a solid, the electron energy levels are very close together. **b** The energy levels form bands with forbidden gaps between them.

Photon energies

When an electron changes its energy from one level E1 to another E2, 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:

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

$$hf = E_1 - E_2$$

or

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

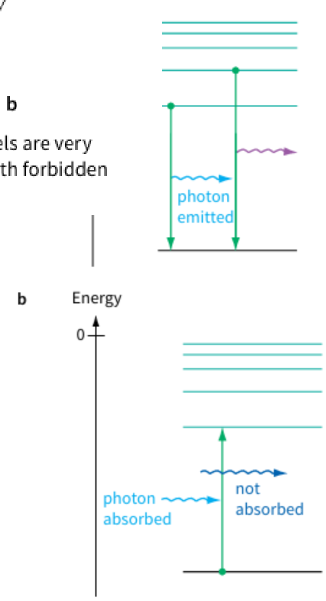


Figure 30.16 **a** When an electron drops to a lower energy level, it emits a single photon. **b** A photon must have just the right energy if it is to be absorbed by an electron.

Electron energies in solids

So far, we have only discussed the spectra of light from hot gases. In a gas, the atoms are relatively far apart, so they do not interact with one another very much. Gas atoms that exert negligible electrical forces on each other are known as **isolated atoms.**

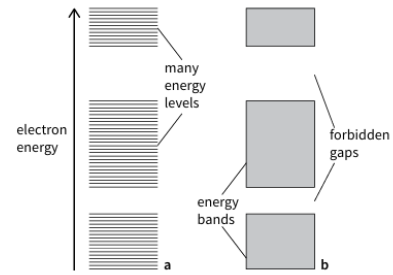


Figure 30.19 **a** In a solid, the electron energy levels are very close together. **b** The energy levels form bands with forbidden

Figure 30.19b shows a more conventional representation of these **energy bands** in a solid. An electron can have an energy at any level in one of the bands. However, it cannot have an energy value which lies in the **forbidden gap** between bands

Band theory and electrical conduction

We can use this **band theory** of solids to explain why some materials are better conductors than others. In Figure 30.20, the energy bands are shown with green shading where they are occupied and with grey shading where they are unoccupied.

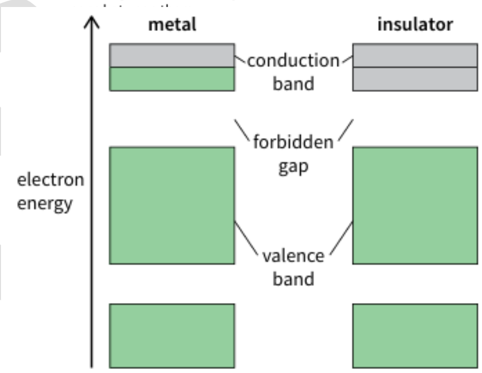


Figure 30.20 How the energy bands are filled in a metal and in an insulator.

■ ■ In a metal, one band, known as the conduction band, is only partially filled. The electrons in the conduction band are the conduction or free electrons which give the metal its conductivity, as discussed in Chapter 11.

■ ■ In an insulator, the conduction band is unoccupied. The band below this, known as the **valence band**, is fully occupied. An electron whose energy lies in the valence band is bound to an individual atom.

Semiconductors have a small gap between their valence and conduction bands, allowing a few electrons to jump across to form a current. They have one free electron per million atoms at room temperature, making their electrical conductivity one-millionth of that of a metal. When heated, the number of electrons in the conduction band increases, reducing resistance.

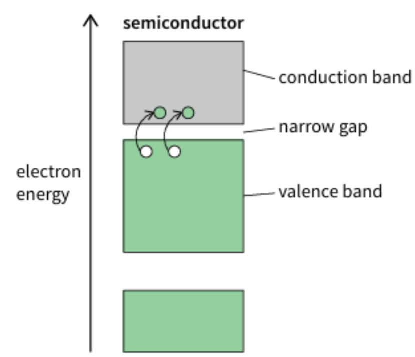


Figure 30.21 Electron energy bands in a semiconductor.

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.

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 travels through space as a wave. The evidence for this comes from the diffraction and interference of light using slits

Electron waves

Light has a dual nature. Is it possible that particles such as electrons also have a dual nature? This interesting question was first contemplated by Louis de Broglie (pronounced 'de Broy') in 1924 (Figure 30.22)

wavelength λ, which is related to its momentum p 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 be written as:

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

Electron diffraction

We can reproduce the same diffraction results in the laboratory using an electron diffraction tube; see Figure 30.23.

In an electron diffraction tube, electrons are accelerated by a large potential difference between the negative heater and positive electrode. A beam of electrons passes through a thin sample of polycrystalline graphite, consisting of carbon atoms arranged in uniform atomic layers. The electrons emerge from the graphite film and produce diffraction rings on a phosphor screen, similar to light waves passing through a small circular hole. The phosphor screen produces flashes of light for each electron that hits it, indicating that electrons appear to travel as waves.

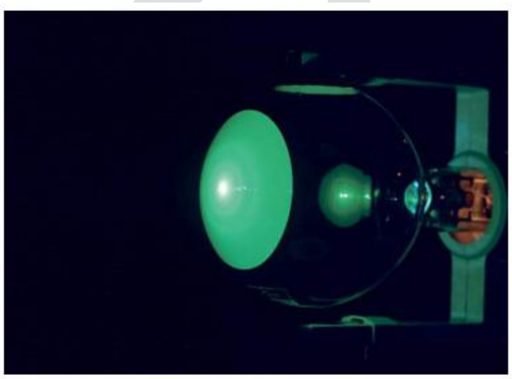


Figure 30.23 When a beam of electrons passes through a graphite film, as in this vacuum tube, a diffraction pattern is produced on the phosphor screen.

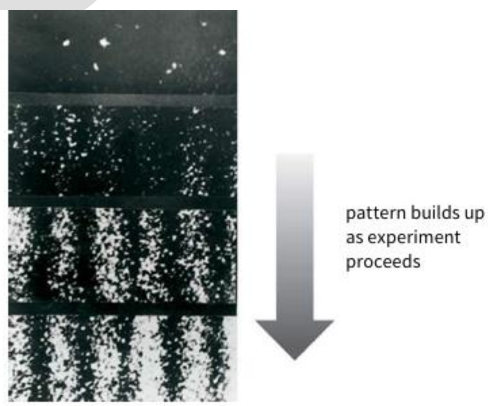


Figure 30.24 The speckled diffraction pattern shows that it arises from many individual electrons striking the screen.

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:

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

$$\lambda = \frac{6.63 \times 10^{-34}}{65} \times 3.0$$

$$\lambda = 3.4 \times 10^{-36}\,\mathrm{m}$$

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.

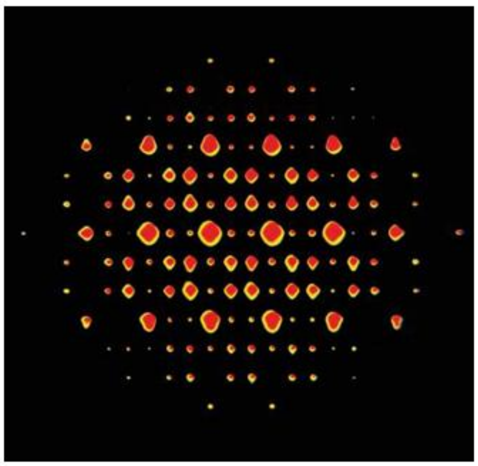


Figure 30.26 Electron diffraction pattern for an alloy of titanium and nickel. From this pattern, we can deduce the arrangement of the atoms and their separations.

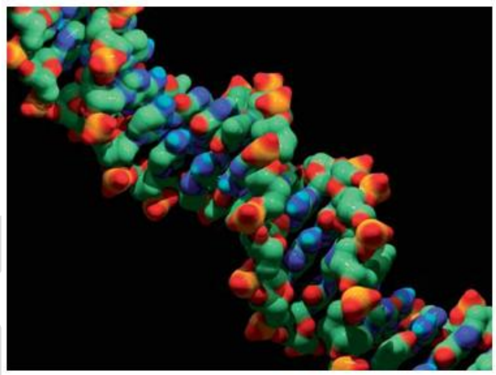


Figure 30.27 The structure of the giant molecule DNA, deduced from electron diffraction.

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.