Atomic physics

Unit 8

Contents

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8.2 Atoms and nuclei (page 322)	• Describe Rutherford's model of the atom. • Describe Bohr's model of the atom. • Show understanding that electrons can only exist at specific energy states, and will not be found with energies between those levels. • Compute the change in energy of an atom using the relation $\Delta E = E_f - E_i$. • Represent diagrammatically the structure of simple atoms. • Use the relationship $A = Z + N$ to explain what is meant by the term isotope. • Compare the charge and mass of the electron with the charge and mass of the proton. • Identify nuclear force is a very strong force that holds particles in a nucleus together. • State some important properties of the strong force. • Show radius and mass number are related mathematically $R = (1.2 \times 10^{-15}\ \mathrm{m})A^{1/3}$. • State the approximate size of an atom. • State nuclear properties. • Explain how nuclear stability is determined by binding energy per nucleon. • Define the term binding energy. • Compare graphs of stable and unstable nuclei. • Interpret graphs of binding energy per nucleon versus mass number. • Associate radioactivity with nuclear instability. • Define the term nuclear fission. • Define the term nuclear fusion. • Distinguish between fission and fusion. • Show understanding that radioactivity emission occurs randomly over space. • Identify that the decay process is independent of conditions outside the nucleus.

Contents

Section	Learning competencies
	• Identify the nature of the three types of emissions from radioactive substances. • Distinguish between the three kinds of emissions in terms of their nature, relative ionising effect, relative penetrating power. • Describe the need for safety measures in handling and using radioisotopes. • Describe experiments to compare the range of alpha, beta and gamma radiation in various media. • Predict the effect of magnetic and electric fields on the motion of alpha, beta and gamma rays. • Name the common detectors for α–particles, β–particles and γ–rays. • Associate the release of energy in a nuclear reaction with a change in mass. • Apply quantitatively the laws of conservation of mass and energy, using Einstein's mass–energy equation. • Represent and interpret nuclear reactions of the form ${}^{14}_{6}C \rightarrow {}^{14}_{6}N + {}^{0}_{-1}e$ (beta). • Represent nuclear reactions in the form of equations. • Define the term half-life. • Work through simple problems on half-life. • Use graphs of random decay to show that such processes have a constant half-life. • State the uses of radioactive isotopes. • Discuss problems posed by nuclear waste.

8.1 Dual nature of matter and radiation

By the end of this section you should be able to:

- Identify that black bodies absorb all electromagnetic radiation.
- Describe the photoelectric effect and its characteristics.
- Show understanding that matter has wave nature.
- Use the de Broglie equation $\lambda = \frac{h}{p}$ to find the wavelength of a matter particle.
- State Heisenberg's uncertainty principle.
- Use the uncertainly principle to relate the uncertainties in position and momentum.
- Find the uncertainty in position from the uncertainty in momentum.

Black bodies

Electromagnetic radiation is given off across a wide range of wavelengths (the electromagnetic spectrum) and is emitted by all objects. Our eyes can only see electromagnetic radiation in the visible part of the spectrum, and radiation from hot objects such as glowing coals on a fire.

A black body is an object that is a perfect radiator of electromagnetic energy – it will radiate energy over the entire electromagnetic spectrum, as shown in Figure 8.1.

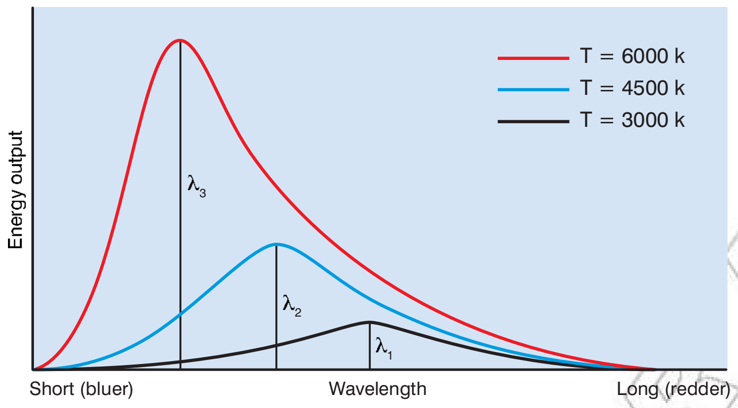


Figure 8.1

A **black body** will also absorb energy over the entire electromagnetic spectrum.

Worked example 8.1

In a cold country on a sunny day, a lady decides to try and melt snow by sprinkling a thin layer of soot over it. Explain her thinking.

The thin layer of soot will cover the snow and make it appear to be a black body. This black body will then absorb all the radiation emitted by the Sun and this energy will melt the snow.

The photoelectric effect and its characteristics

When light, particularly ultraviolet light, is shone on a clean metal surface, the surface will emit electrons. These electrons are known as photoelectrons, and the emission of photoelectrons is called the **photoelectric effect**.

The energy of the photoelectrons is proportional to the frequency of the radiation from the ultraviolet lamp. We can use the equation

$E = hf$

where E is the energy of the photoelectron, f is the frequency of the radiation and h is a constant known as the Planck constant, which has been shown to be 6.63×10^{-34} J s to 3 significant figures, to find the energy of the photoelectrons.

KEY WORDS

black body *an object that is a perfect radiator and absorber of electromagnetic energy*

photoelectric effect *emission of photoelectrons from metal surface when light is shone on the surface*

DID YOU KNOW?

The German physicist who first noticed the photoelectric effect, Heinrich Hertz, showed an aptitude for languages while studying in Hamburg, learning Arabic and Sanskrit. He supplied the first experimental evidence for the existence of radio waves, generating them by means of an electric spark.

For radiation in the electromagnetic spectrum, we know that the speed of radiation, $c = 3 \times 10^8$ m/s and that $c = f\lambda$ where f is the frequency and λ is the wavelength of the radiation. So our equation for the energy of the photoelectrons can also be written

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

Activity 8.1: Demonstrating the photoelectric effect

You can demonstrate the photoelectric effect using the apparatus shown in Figure 8.2.

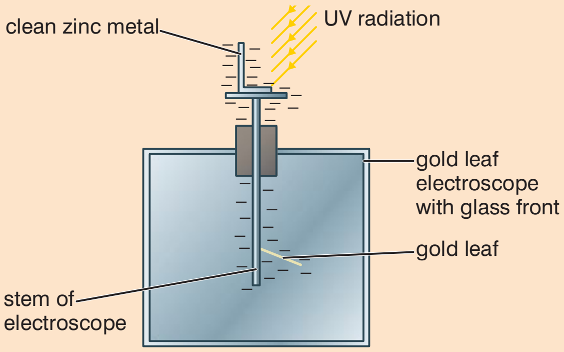


Figure 8.2

Place a piece of clean zinc metal on the electroscope. The metal will become negatively charged. The stem of the electroscope will also become negatively charged and the negatively charged gold leaf will be repelled from the stem.

Now bring an ultraviolet lamp near to the zinc. The gold leaf will start to fall back towards the stem. Remove the lamp. The leaf will stop falling. This means that the ultraviolet light from the lamp is causing electrons to be emitted from the zinc – the photoelectric effect.

Worked example 8.2

Ultraviolet radiation of wavelength 4×10^{-8} m falls on a sample of zinc. Photoelectrons are emitted. Calculate the energy of these electrons. Take the Planck constant to be 6.63×10^{-34} J s and the speed of light to be 3×10^8 m/s.

E (J)	h (J s)	c (m/s)	λ (m)
?	6.63×10^{-34}	3×108	4×10^{-8}

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

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{4 \times 10^{-8}}$$

$$= 4.97 \times 10^{-18} \text{ J}$$

Electronvolts

The energy of photoelectrons is very low, as shown by worked example 8.2. We use a unit called the **electronvolt** (eV) to describe photoelectron energy.

One electronvolt is the energy change of an electron when it moves through a potential difference of one volt.

Since we know that one volt is one joule per coulomb and the charge on an electron is 1.6×10^{-19} C, we get

$1 \text{ eV} = 1 \text{ J/C} \times 1.6 \times 10^{-19} \text{ C} = 1.6 \times 10^{-19} \text{ J}$

So we can express the answer to worked example 8.2 as

$4.97 \times 10^{-18} \text{ J or } \dfrac{4.97 \times 10^{-18}}{1.6 \times 10^{-19}} = 31.1 \text{ eV}$

KEY WORDS

electronvolt *the energy change of an electron when it moves through a potential difference of one volt*
$1 \text{ eV} = 1.6 \times 10^{-19}$ J

Think about this...

If the light shining on the metal were more intense, would more or fewer photoelectrons be emitted?

If the light shining on the metal were more intense, what would happen to the maximum kinetic energy of the photoelectrons?

Activity 8.2: Investigating the energy of the photoelectrons

You could use the circuit shown in Figure 8.3 to measure the energy of the photoelectrons.

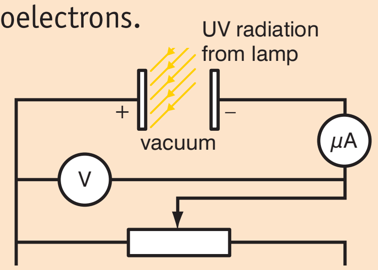


Figure 8.3

Apply a p.d. between the source of the electrons and the metal plate. The photoelectrons have a negative charge, so they are repelled by the negative plate and attracted to the positive one. If, however, the electrons have sufficient kinetic energy they are able to overcome the repulsion of the negative plate and reach it and you can record a current (a photocurrent).

Vary the potential between the plates from negative values to positive values and observe how the photocurrent varies. Record your results and draw a graph of photocurrent against p.d. between the plates.

From Activity 8.2, you should obtain a graph like the one shown in Figure 8.4.

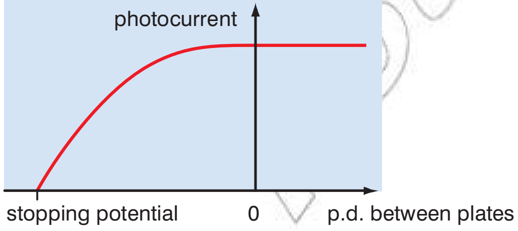


Figure 8.4

The value of the stopping potential marked on the graph can be equated to the maximum energy of the photoelectrons. The

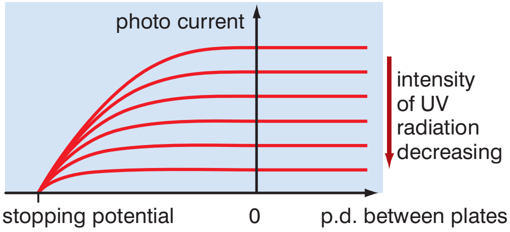


Figure 8.5

electronvolt is useful here, since if the stopping potential is, for example, 1.85 V, then we can say that the maximum energy for the photoelectrons is 1.85 eV.

You might think that if the light shining on a metal to produce photoelectrons were more intense, more electrons would be emitted, and vice versa. This is indeed the case. You might also think that the maximum kinetic energy of the photoelectrons would also be related to the intensity of the radiation that caused them to be emitted. However, experimentally we find that the maximum kinetic energy of the photoelectrons remains constant, as shown in Figure 8.5.

This result was unexpected and it led Einstein to suggest that some of the ultraviolet radiation hitting the surface of the metal was used to release an electron from the surface atom of the metal, and any remaining energy became the kinetic energy of the electron. Using the law of conservation of energy gives the equation

photon energy = energy to release electron + kinetic energy of the electron

$$hf = \varphi + \left(\frac{1}{2}mv^2\right)_{max}$$

The minimum energy required to release the electron, φ, is called the **work function** for the metal.

This equation is called the Einstein photoelectric equation.

It can be rearranged to give

$$KE_{max} = hf - \varphi$$

KEY WORDS

work function *minimum energy required to release the electron from surface of metal*

Worked example 8.3

An ultraviolet lamp is used to illuminate a clean zinc surface and photoelectrons are emitted. The stopping potential of the photoelectrons is –1.92 V. The work function energy of zinc is 4.24 eV. Calculate the wavelength of the UV radiation. Take the value of the Planck constant to be 6.63×10^{-34} J s.

photon energy (eV)	φ (eV)	KE_{max} (eV)
?	4.24	1.92

Use

$$hf = \varphi + \left(\frac{1}{2}mv^2\right)_{max}$$

$$= 4.24 + 1.92$$

$$= 6.16 \text{ eV}$$

$$6.16 \text{ eV} = 6.16 \times 1.6 \times 10^{-19} \text{ J}$$

$$= 9.856 \times 10^{-19} \text{ J}$$

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

$$\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{9.856 \times 10^{-19}}$$

$$= 2.02 \times 10^{-7} \text{ m}$$

$$= 202 \text{ nm}$$

The wave nature of matter

The photoelectric effect provided evidence that electromagnetic waves could be considered as a stream of particles called photons. This evidence was reinforced when, in 1922, Arthur Compton discovered that X-rays were colliding with electrons and behaving as particles.

In 1924, Louis de Broglie suggested that an atom's electrons, protons and neutrons possess both particle and wave properties. This is known as the **wave–particle duality of matter**.

To prove that particles can also act as waves, you need to show particles exhibiting a behaviour that is also demonstrated by waves, such as interference or diffraction. It is possible to diffract electrons using the apparatus shown in Figure 8.6.

Electrons from an electron gun are accelerated through a vacuum towards a layer of graphite. (The atomic spacing in graphite is the right order of magnitude for electrons to be diffracted.) A circular diffraction pattern such as the one shown in Figure 8.7 is obtained.

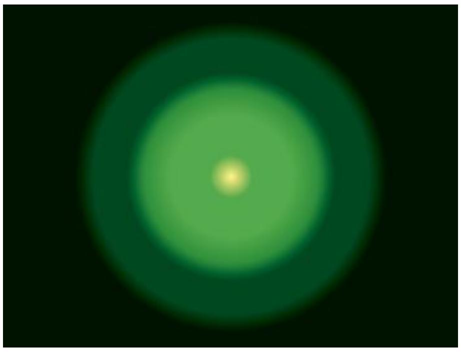


Figure 8.7 An electron diffraction pattern

You can calculate the wavelength of the electrons by measuring the ring diameters in the diffraction pattern. It can be shown that the wavelength, λ, is inversely proportional to the speed, v, of the electron. Further evidence gives the equation

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

where m is the mass of the electron, h is the Planck constant and p is the momentum (mv) of the electron. This equation is known as the de Broglie equation.

KEY WORDS

wave–particle duality of matter *theory that matter possesses both wave and particle properties, depending on circumstances*

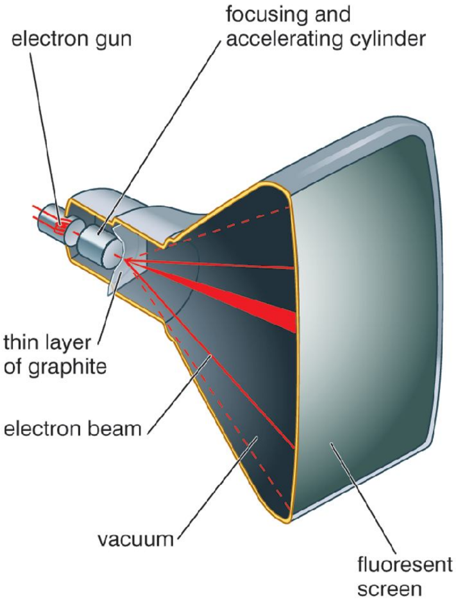


Figure 8.6

DID YOU KNOW?

Electron diffraction can be used to determine atomic spacing. High-speed electrons can be used to measure the diameter of a nucleus.

Worked example 8.4

Electrons are accelerated through a potential difference of 4000 V before striking a layer of graphite and being diffracted. The mass of an electron is 9.11×10^{-31} kg. Planck's constant is 6.63×10^{-34} J s.

Calculate

a) the speed of the electrons when they hit the layer of graphite

b) the momentum of the electrons

c) the wavelength of the electrons.

a) 4000 V is 4000 J/C

An electron has a charge of 1.6×10^{-19} C so its kinetic energy will be $4000 \times 1.6 \times 10^{-19}$ J = 6.4×10^{-16} J

KE (J)	m (kg)	v (m/s)
6.4×10^{-16}	9.11×10^{-31}	?

Use $KE = \frac{1}{2}mv^2$

$$v = \sqrt{\frac{2 \times KE}{m}}$$

$$= \sqrt{\frac{2 \times 6.4 \times 10^{-16}}{9.11 \times 10^{-31}}}$$

$$= \sqrt{\frac{1.28 \times 10^{-15}}{9.11 \times 10^{-31}}}$$

$$= 3.7 \times 10^{7} \text{ m/s}$$

b)

p (kg m/s)	m (kg)	v (m/s)
?	9.11×10^{-31}	3.7×10^{7}

Use $p = mv$

$$= 9.11 \times 10^{-31} \times 3.7 \times 10^{7}$$

$$= 3.37 \times 10^{-23} \text{ kg m/s}$$

c)

λ (m)	h (J s)	p (kg m/s)
?	6.63×10^{-34}	3.37×10^{-23}

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

$$= \frac{6.63 \times 10^{-34}}{3.37 \times 10^{-23}}$$

$$= 1.97 \times 10^{-11} \text{ m}$$

Activity 8.4: The wave and particle nature of photons and electrons

In a small group, discuss the wave and particle nature of photons and electrons. Discuss an experiment where a photon behaves like a particle and an experiment where it behaves like a wave.

Heisenberg's uncertainty principle

We know that the wavelength and momentum of a particle such as an electron are related by the de Broglie equation, $\lambda = \frac{h}{p}$.

However, Heisenberg's uncertainty principle states that it is impossible to know both the exact position and the exact velocity (and therefore momentum) of a particle at the same time.

In order to observe any particle, smaller particles must be reflected off it. For example, to find the position and momentum of an electron, at least one photon of light must be used. The photon must hit the electron and then be reflected back to the measuring device. If objects are large, such as sand grains or buses, the percentage uncertainty in the measurements of position and momentum are insignificant. However, for subatomic particles, which are much smaller, the percentage uncertainty in the position and momentum measurements is far larger, and finding momentum and position becomes more difficult.

An electron has momentum p = mass × velocity

When photons are moving, they have an apparent mass due to their kinetic energy. When one of the photons bounces off the electron, the momentum of the electron will be changed (in the same way as the momentum of a billiard ball is changed when it collides with another ball or the sides of the table). This change in momentum ($\Delta mv = \Delta p$) is uncertain and will be of the same order of magnitude as the photon's momentum, so we can say that $\Delta p \approx \frac{h}{\lambda}$.

The photon of light cannot measure the electron's position (x) with perfect accuracy. To increase the accuracy of the position measurement, a photon with a smaller wavelength must be used. To see why this is the case, consider Figure 8.8, which shows two photons with different wavelengths, with the position of the electron marked.

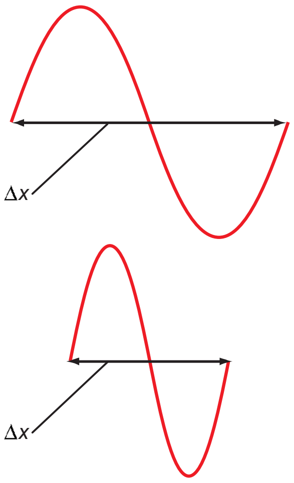


Figure 8.8

You can see that the position of the electron, which must be somewhere in the distance Δx in each case, can be more accurately determined with photon b) than with photon a).

However, decreasing the wavelength increases the frequency and thus the energy of the photon. Therefore, when the photon collides with the electron, it will change the momentum of the electron by a larger amount, so if the position is more accurately determined the momentum is less accurately determined. The opposite is also true – if the momentum is more accurately determined then the position must be less accurately determined.

An estimate of the position of the particle is at least one photon wavelength from the original position.

The uncertainty in position, $\Delta x \geq \lambda$.

We know that $\Delta p \approx \frac{h}{\lambda}$

We can combine the equations to give

$\Delta p \Delta x \geq \frac{h}{\lambda} \times \lambda \geq h$

Worked example 8.5

Light of wavelength 3×10^{-6} m is used to measure the position of an electron of wavelength 1.97×10^{-11} m. Find the uncertainty in the position of the electron. Planck's constant is 6.63×10^{-34} J s.

Δp (kg m/s)	h (J s)	λ (m)
?	6.63×10^{-34}	1.97×10^{-11}

Use $\Delta p \approx \frac{h}{\lambda}$

$$\Delta p \approx \frac{6.63 \times 10^{-34}}{1.97 \times 10^{-11}} \approx 3.37 \times 10^{-23} \text{ kg m/s}$$

Δx (m)	h (J s)	Δp (kg m/s)
?	6.63×10^{-34}	3.37×10^{-23}

Use $\Delta p \Delta x \geq h$

$$\Delta x \geq \frac{h}{\Delta p}$$

$$\geq \frac{6.63 \times 10^{-34}}{3.37 \times 10^{-23}}$$

$$\geq 1.97 \times 10^{-11} \text{ m}$$

Summary

In this section you have learnt that:

- Black bodies absorb all electromagnetic radiation.
- The **photoelectric effect** is the emission of photoelectrons from metal surface when light is shone on the surface.
- The minimum energy required to release the electron, φ, is called the **work function** for the metal.
- $KE_{max} = hf - \varphi$
- Matter has a wave nature as well as a particle nature.
- The de Broglie equation $\lambda = \frac{h}{p}$ is used to find the wavelength of a matter particle.
- Heisenberg's uncertainty principle is that it is impossible to know both the exact position and the exact velocity (and therefore momentum) of a particle at the same time.
- The uncertainties in position and momentum are related by the equation $\Delta p \Delta x \geq h$

Review questions

1. What is a black body?
2. Ultraviolet radiation of wavelength 200 nm falls on a sample of magnesium. Photoelectrons are emitted. Calculate the energy of these electrons. Take the Planck constant to be 6.63×10^{-34} J s and the speed of light to be 3×10^8 m/s.
3. An ultraviolet lamp is used to illuminate a clean lithium surface and photoelectrons are emitted. The stopping potential of the photoelectrons is –1.92 V. The work function energy of lithium is 2.93 eV. Calculate the wavelength of the UV radiation. Take the value of the Planck constant to be 6.63×10^{-34} J s.
4. Electrons are accelerated through a potential difference of 5000 V before striking a layer of graphite and being diffracted. The mass of an electron is 9.11×10^{-31} kg. Planck's constant is 6.63×10^{-34} J s.

   Calculate

   a) the speed of the electrons when they hit the layer of graphite

   b) the momentum of the electrons

   c) the wavelength of the electrons.
5. State Heisenberg's uncertainty principle.
6. Light of wavelength 3×10^{-6} m is used to measure the position of an electron of wavelength 1.73×10^{-11} m. Find the uncertainty in the position of the electron. Planck's constant is 6.63×10^{-34} J s.

8.2 Atoms and nuclei

By the end of this section you should be able to:

- Describe Rutherford's model of the atom.
- Describe Bohr's model of the atom.
- Show understanding that electrons can only exist at specific energy states, and will not be found with energies between those levels.
- Compute the change in energy of an atom using the relation $\Delta E = E_f - E_i$.
- Represent diagrammatically the structure of simple atoms.
- Use the relationship $A = Z + N$ to explain what is meant by the term isotope.
- Compare the charge and mass of the electron with the charge and mass of the proton.
- Identify nuclear force is a very strong force that holds particles in a nucleus together.
- State some important properties of the strong force.
- Show that radius and mass number are related mathematically $R = (1.2 \times 10^{-15}\ \text{m})A^{1/3}$.
- State the approximate size of an atom.
- State nuclear properties.
- Explain how nuclear stability is determined by binding energy per nucleon.
- Define the term binding energy.
- Compare graphs of stable and unstable nuclei.
- Interpret graphs of binding energy per nucleon versus mass number.
- Associate radioactivity with nuclear instability.
- Define the term nuclear fission.
- Define the term nuclear fusion.
- Distinguish between fission and fusion.
- Show understanding that radioactivity emission occurs randomly over space.
- Identify that the decay process is independent of conditions outside the nucleus.
- Identify the nature of the three types of emissions from radioactive substances.

- Distinguish between the three kinds of emissions in terms of their nature, relative ionising effect, relative penetrating power.
- Describe the need for safety measures in handling and using radioisotopes.
- Describe experiments to compare the range of alpha, beta and gamma radiation in various media.
- Predict the effect of magnetic and electric fields on the motion of alpha, beta and gamma rays.
- Name the common detectors for α–particles, β–particles and γ–rays.
- Associate the release of energy in a nuclear reaction with a change in mass.
- Apply quantitatively the laws of conservation of mass and energy, using Einstein's mass–energy equation.
- Represent and interpret nuclear reactions of the form $^{14}_{6}C \rightarrow {}^{14}_{6}N + {}^{0}_{-1}e$ (beta).
- Represent nuclear reactions in the form of equations.
- Define the term half-life.
- Work through simple problems on half-life.
- Use graphs of random decay to show that such processes have a constant half-life.
- State the uses of radioactive isotopes.
- Discuss problems posed by nuclear waste.

Rutherford's model of the atom

Before the 20th century, there had been various models of the atom. In 1906, Thomson discovered that electrons could be removed from the atom and proposed that the main part of the atom was positively charged and had negatively charged electrons scattered through it.

Between 1909 and 1911, two of Lord Rutherford's students, Geiger and Marsden, aimed charged particles at an extremely thin piece of gold foil. They used apparatus similar to that shown in Figure 8.9.

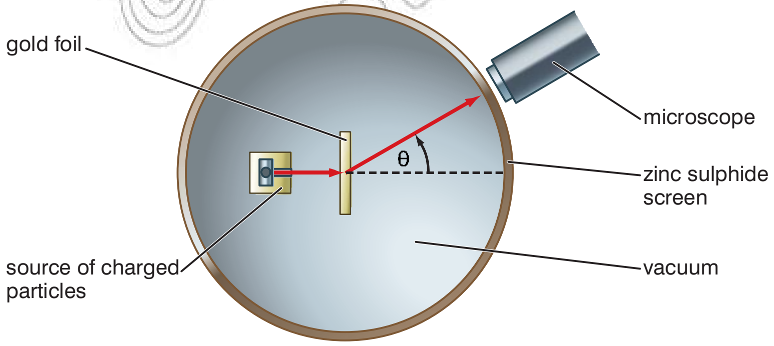
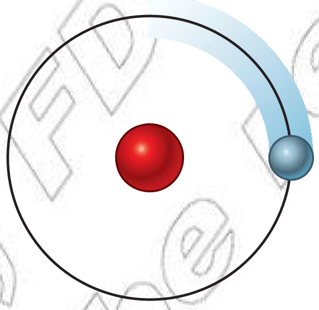


Figure 8.9

They expected that all the charged particles would pass through the foil, perhaps with a little deviation. This was the case with most of the particles. However, some of them were deflected at quite large angles – some were even sent back the way they had come. This result was very surprising if Thomson's model of the atom was correct. Rutherford repeated the experiment many times, with the same result. He was forced to conclude that, in order to explain the results, which are shown in the table, the model of the atom needed to be changed.

Angle of deflection (°)	Evidence	Conclusion
0–10	Most charged particles pass through with little deviation	Most of the atom is empty space
10–90	Some charged particles deflected through large angle concentrated in one place	All the atom's positive charge
90–180	A few charged particles sent back to source	Most of the mass, and all positive charge, is in tiny, central nucleus

Rutherford's model of the atom is as shown in Figure 8.10.



Rutherford's nuclear model of the atom: All the positive charge and most of the mass is concentrated in a tiny central nucleus. Most of the atom is empty space, and electrons orbit at the edge.

Figure 8.10

DID YOU KNOW?

Lord Rutherford supervised many Nobel Prize winners: Chadwick for discovering the neutron (in 1932), Cockcroft and Walton for an experiment which was to be known as splitting the atom using a particle accelerator, and Appleton for demonstrating the existence of the ionosphere.

Bohr model of the atom

Niels Bohr proposed that specific energy levels existed within an atom's structure and that electrons move in circular orbits around the nucleus. In his model, electrons that are closer to the nucleus have a lower energy state than those that are further away. It is possible for electrons to exist in different states, but as they move from a higher energy level, E_1, to a lower energy level, E_2, they emit radiation. The energy of a quantum of this radiation is given by the equation

$$hf = E_1 - E_2$$

Electrons can only exist in specific energy states and will not be found with energies between these states.

Bohr's model of the atom allows line spectra to be explained. Only certain frequencies are present in line spectra and each element has a unique pattern as shown in Figure 8.11. Such spectra are produced by hot gases, where atoms are far apart.

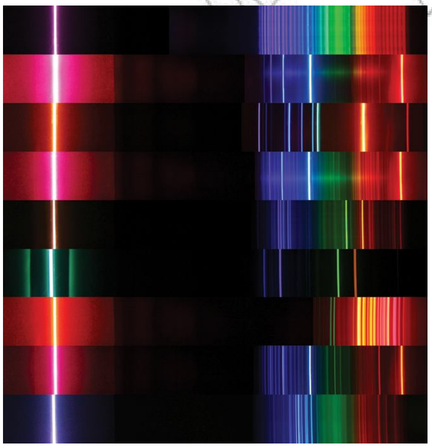


Figure 8.11

Worked example 8.6

Two lines in the spectrum of a sodium lamp have wavelengths of 589 nm and 589.6 nm.

a) What are the frequencies of these wavelengths?

b) What energy changes do these transitions correspond to in electronvolts?

Take $c = 3 \times 10^{8}$ m/s, $h = 6.63 \times 10^{-34}$ J s and 1 eV = 1.6×10^{-19} J.

a)

c (m/s)	f (Hz)	λ (m)
3×10^{8}	?	589×10^{-9}
3×10^{8}	?	589.6×10^{-9}

Use $f =$

For $\lambda = 589 \times 10^{-9}$ m

$$f = \frac{3 \times 10^{8}}{589 \times 10^{-9}}$$

$$= 5.09 \times 10^{14} \text{ Hz}$$

For $\lambda = 589.6 \times 10^{-9}$

$$f = \frac{3 \times 10^{8}}{589.6 \times 10^{-9}}$$

$$= 5.088 \times 10^{14} \text{ Hz}$$

b) For $\lambda = 589 \times 10^{-9}$ m

$E_1 - E_2$ (eV)	h (J s)	f (Hz)
?	6.63×10^{-34}	5.09×10^{14} Hz

Use $E_1 - E_2 = hf$

$$= 6.63 \times 10^{-34} \times 5.09 \times 10^{14}$$

$$= 3.375 \times 10^{-19} \text{ J}$$

$$= \frac{3.375 \times 10^{-19}}{1.6 \times 10^{-9}} \text{ eV}$$

$$= 2.109 \text{ eV}$$

For $\lambda = 589.6 \times 10^{-9}$ m

$E_1 - E_2$ (eV)	h (J s)	f (Hz)
?	6.63×10^{-34}	5.088×10^{14} Hz

Use $E_1 - E_2 = hf$

$$= 6.63 \times 10^{-34} \times 5.088 \times 10^{14}$$

$$= 3.373 \times 10^{-19} \text{ J}$$

$$= \frac{3.373 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV}$$

$$= 2.108 \text{ eV}$$

Activity 8.4: To demonstrate a simple absorption spectrum

Crush some leaves in an alcohol solution. Use a diffraction grating spectrometer or a prism to show that the solution will absorb at both ends of the spectrum.

The model of the atom used now

The model of the atom that we use now was proposed by Heisenberg in the 1920s. We know that Heisenberg's uncertainty principle means that we cannot know the precise position and velocity of a particle such as an electron at any given moment. In Heisenberg's model, there is a central nucleus around which there are regions in which there is a high probability of finding an electron, and the shape of these 'probability clouds' represent what we refer to as the electron 'orbitals' (see Figure 8.12).

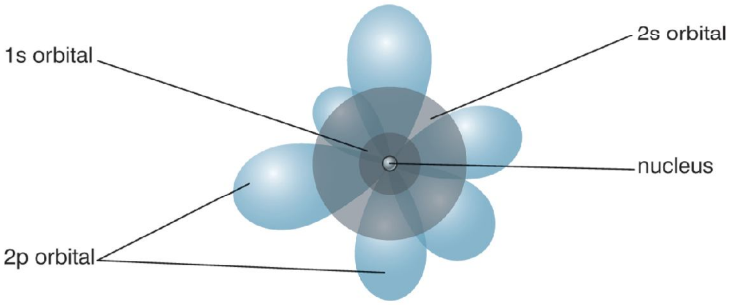


Figure 8.12

You may have met a simplified model in chemistry, such as the one shown in Figure 8.13. This is called a dot and cross diagram – the crosses represent electrons and circles show the shells. The nucleus is shown as a circle in the middle.

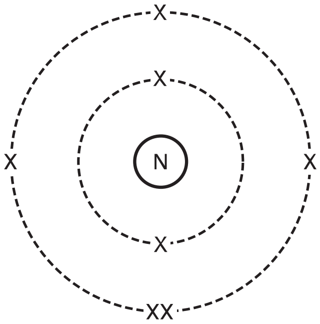


Figure 8.13

Activity 8.5: Representing the structure of a simple atom diagrammatically

The element carbon has six electrons, two in an inner shell and four in an outer shell. Use this information to represent the structure of carbon using a dot and cross diagram like the one in Figure 8.13.

Dot and cross diagrams represent the distribution of electrons in an atom but they do not give any detail about what is in the nucleus. We now know that there are two types of particles in most atomic nuclei: protons (which are positively charged) and neutrons which do not have any charge. The collective name for these particles is nucleons. The number of protons in the nucleus determines what element the atom is: carbon atoms have a different number of protons from nitrogen atoms, for example. The number of protons in an uncharged atom is the same as the number of electrons. Check that you understand why we can say that a nitrogen nucleus has 7 protons and a carbon nucleus has 6 protons! The elements in the periodic table are listed in order of proton number, which is also called the atomic number and is often given the symbol Z. The number of neutrons must be at least as great as the number of protons, but some elements have more neutrons than protons. There are some elements that have different forms of atom, which have the same number of protons (so they are the same element) but different numbers of neutrons. For example, carbon can have atoms with 6 neutrons, atoms with 7 neutrons and atoms with 8 neutrons (but all these have 6 protons). These different atoms are called **isotopes** of carbon.

We can use a chemical shorthand to describe atoms of elements. We combine the chemical symbol for the element with the atomic number, Z, as a subscript, and the mass number, A (which is the total number of protons, Z, plus the total number of neutrons, N, so $A = Z + N$) as a superscript. For example, we can write the isotopes of carbon mentioned above as shown in Figure 8.14.

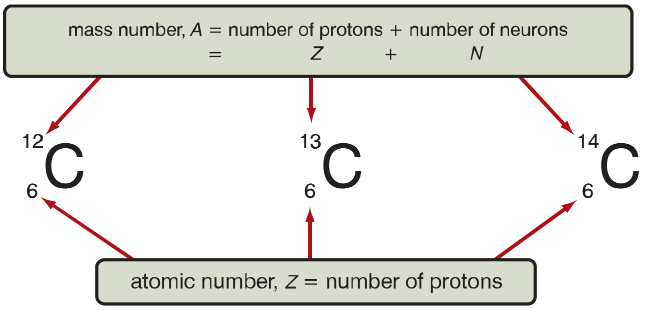


Figure 8.14

Activity 8.6: Isotopes of chlorine

Chlorine has two isotopes, chlorine-35 and chlorine-37.

a) Write down the shorthand for each of these isotopes. The chemical symbol for chlorine is Cl and it has 17 protons.

b) How many neutrons are there in the nucleus of the atom of each of these isotopes?

The strong nuclear force

The protons and neutrons in the nucleus of an atom are held together by one of the four basic forces in nature, the strong nuclear force (the others are gravity, the electromagnetic force and the weak nuclear force). It is the strongest of the four forces but it has the shortest range, so particles have to be extremely close together before its effects are felt. It is strong enough to overcome the repulsion between the positive charges on protons. It is created between nucleons by the exchange of particles called mesons, as shown in Figure 8.15. An analogy for this exchange is a tennis ball being constantly hit backwards and forwards between two players. As long as this exchange can happen, the strong force can hold the nucleons together.

The nucleons must be extremely close for this exchange to happen – the distance must be about the diameter of a proton or a neutron. If the nucleons are unable to get this close, the strong force is too weak to make them stick together and other competing forces (usually the electromagnetic force) will influence the particles

KEY WORDS

isotope *atoms of the same element that have different numbers of neutrons*

Atomic mass unit

A precise definition for the atomic mass unit is that it is one twelfth of the mass of an isolated atom of carbon-12 (^{12}C) at rest and in its ground state. A simpler definition is that it is the mass of a proton or a neutron. It is equivalent to 1.6×10^{-27} kg.

The charge and mass of electrons and protons

We know that the charge on a proton is positive and the charge on an electron is negative. The mass of a proton is 1 atomic mass unit (1.6×10^{-27} kg). The mass of an electron is taken to be $\frac{1}{1836}$ that of a proton.

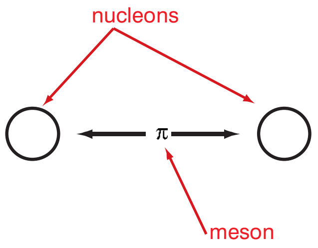


Figure 8.15

to move apart. In Figure 8.16, the dotted line represents any electrostatic repulsion that might be present because of the charges of the nucleons that are involved. A particle must be able to cross this barrier in order for the strong force to 'glue' the particles together.

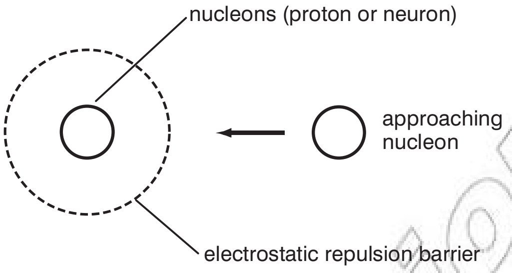


Figure 8.16

If the approaching nucleon in Figure 8.16 is a proton or another nucleus, the closer they get, the more they feel the repulsion from the other proton or nucleus. In order to get two protons or nuclei close enough to begin exchanging mesons, they must either be moving extremely fast (which means the temperature must be extremely high) or they must be under immense pressure so that they are forced to be close enough together to allow the exchange of mesons needed for the strong force. The temperature and pressure could both be extremely high, which would also allow the strong force to operate.

Neutrons in the nucleus help to reduce the repulsion between protons in the nucleus. They have no charge and so do not add to the repulsion already present, but they help separate the protons so that they do not feel so much repulsion from other protons and the neutrons also add to the strong nuclear force since they participate in meson exchange. These factors, together with the fact that protons are tightly packed in the nucleus so that they can exchange mesons, create enough strong force for the protons to overcome the repulsion between them and allow the nucleons to stay bound together.

There is evidence that the strong force is the same between any pair of nucleons. Electron scattering experiments suggest that nuclei are roughly spherical and appear to have a constant density. The data are summarised in the Fermi model as

$$r = 1.2 \times 10^{-15} \times A^{\frac{1}{3}}\ \text{m}$$

where r is the radius of the nucleus and A is the mass number for the atom. Experimental results show that the radii of atoms vary from 35×10^{-12} m for hydrogen atoms where A is 1, to 175×10^{-12} m for americium atoms where A is 95.

Worked example 8.7

The mass number of oxygen is 16. Calculate the radius of an oxygen nucleus.

r (m)	A
?	16

Use $r = 1.2 \times 10^{-15} \times 16^{\frac{1}{3}}$ m

$= 1.2 \times 10^{-15} \times 16^{\frac{1}{3}}$

$= 1.2 \times 10^{-15} \times 2.52$

$= 3.024 \times 10^{-15}$ m

Nuclear properties

Nuclei of atoms can be ordered according to atomic number and number of nucleons. When this is done, the following properties are observed.

- For the lighter nuclei, if we look at the most common isotope, N is approximately equal to Z.
- As we get to heavier nuclei, past $Z = 20$, we begin to see N considerably greater than Z. As nuclei get heavier this becomes more apparent.
- Bismuth is the heaviest stable nucleus. Heavier nuclei exist but they are all unstable – they undergo certain spontaneous changes which we observe as radioactivity (see page 330). Nuclei from $Z = 84$ (polonium) to 92 (uranium) are found in nature (on Earth) and all their isotopes are radioactive.
- Nuclei heavier than uranium exist but they are all artificial – they have been created by scientists in laboratories. The heaviest known nucleus has $Z = 118$. It was produced in 2006.

Nuclear stability

We know, from page 327, that an element may have several isotopes (nuclei with the same number of protons but different numbers of neutrons). Isotopes are known collectively as nuclides. About 256 (76%) of the nuclides that occur naturally on Earth have not been observed to decay and are therefore referred to as 'stable isotopes'. For 80 of the chemical elements, there is at least one stable isotope. The average number of stable isotopes per element among those that have stable isotopes is 3.1. Twenty-seven elements have only a single stable isotope, while the largest number of stable isotopes observed for any element is ten, for the element tin. Elements 43, 61, and all elements numbered 83 or higher have no stable isotopes.

The stability of isotopes is affected by the ratio of protons to neutrons in the nucleus. Figure 8.17 overleaf shows how, as the atomic number, Z, increases, the number of stable isotopes diverges from the line $Z = N$.

DID YOU KNOW?

The discovery of element 118 is an example of how important it is for scientific experiments to be repeatable by others. The discovery of element 118 was first reported by a team of scientists at Berkeley Lab in 2000, but in 2002 they retracted their paper after several confirmation experiments failed to reproduce the results.

The discovery announced in 2006 was a result of collaboration between scientists at the Lawrence Livermore National Laboratory in the USA and from Dubna, the Joint Institute for Nuclear Research in Russia. The discovery would only be confirmed after other groups had reproduced it.

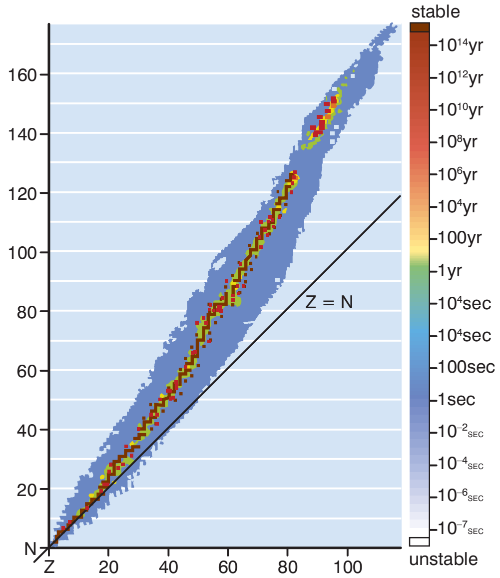


Figure 8.17

Nuclear stability is also determined by the **binding energy** per nucleon. Binding energy is defined as the energy required to disassemble a nucleus into the same number of free unbound protons and neutrons as it is composed of, in such as way that the particles are distant enough from each other so that the strong nuclear force can no longer cause the particles to interact. The net binding energy of a nucleus is that of nuclear attraction, minus the disruptive energy of the electrostatic force. Any system will always try and move to a state of lower energy (or more stable state).

As nuclei get heavier than helium, their net binding energy per nucleon (which can be found by calculating the difference in mass between the nucleus and the sum of the masses of the nucleons of which it is composed) grows more and more slowly and reaches its peak at iron, as shown in Figure 8.18.

KEY WORDS

binding energy *the energy required to disassemble a nucleus into the same number of free unbound protons and neutrons as it is composed of, in such as way that the particles are distant enough from each other so that the strong nuclear force can no longer cause the particles to interact*

radioactivity *the process by which a nucleus will reach a lower energy state and thus become more stable by emitting particles*

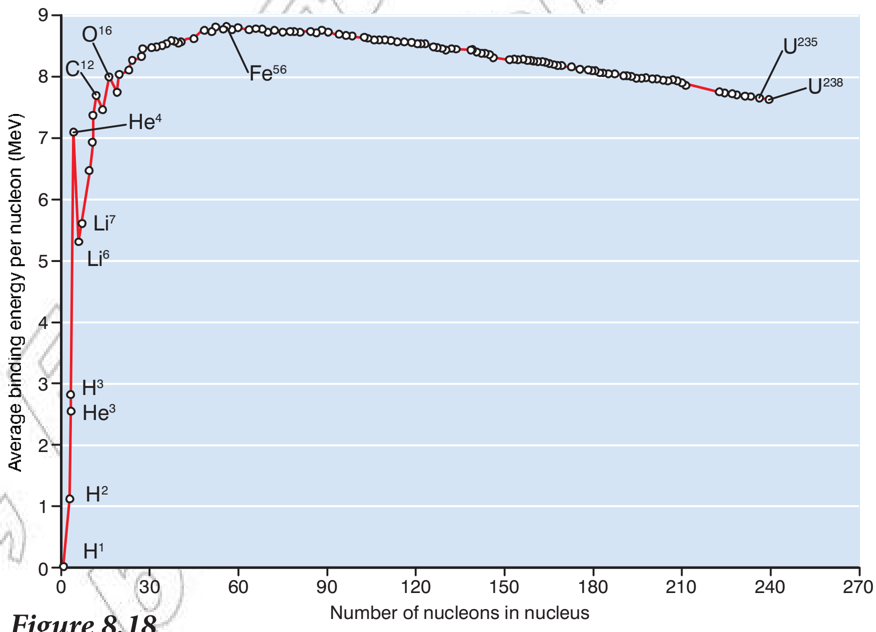


Figure 8.18

As nucleons are added, the total binding energy increases but so does the total disruptive energy of the electrostatic forces and, once nuclei are heavier than that of iron, the increase in disruptive energy has more effect than the increase in binding energy. To reduce the disruptive energy, the weak interaction allows more neutrons to be added so that the number of neutrons exceeds the number of protons. However, at some stage the only way for the nucleus to reach a lower energy state (one that is more stable) will be to emit particles. This is the process we call **radioactivity**.

Radioactivity

If a nucleus emits particles and therefore loses energy in order to become more stable, then the nucleus has been split into two or more parts in the process known as **nuclear fission**. In other words, an atom of one type, the parent nuclide, transforms into an atom of another type, called the daughter nuclide, together with some form of radiation. According to quantum mechanics, it is impossible to predict precisely when a given atom will decay so radioactive emissions occur randomly over space. However, as we shall see on page 337, when a large number of similar atoms decay, the average decay rate can be predicted. The decay of nuclei is independent of conditions outside the nucleus – it is solely governed by the energy state of the nucleus.

Nuclear fusion is the process by which two nuclides are fused together to form a new nuclide. This process requires high temperature and pressure. It occurs naturally in stars but research into artificial nuclear fusion is ongoing.

KEY WORDS

nuclear fission *the process in which the nucleus becomes more stable by splitting into two or more parts and emitting particles*

nuclear fusion *the process by which two nuclides are fused together to form a new nuclide*

Types of nuclear radiation

There are three types of nuclear radiation: alpha (α), beta (β) and gamma (γ) radiation. Each of these comes about through a different process in the decaying nucleus, each one is composed of different particles and each one has different properties.

When a nuclear decay occurs, the particle emitted will leave the nucleus with a certain amount of kinetic energy. As the particle travels, it will ionize particles in its path, losing a small amount of kinetic energy at each ionization. When it has transferred all its kinetic energy, it will stop and will be absorbed by the substance it is in at that moment.

An alpha particle has two protons and two neutrons, the same as a helium nucleus. It can be written as $^{4}_{2}\alpha$. It is a relatively large particle with a significant positive charge of +2, so it ionises a lot. As it does so it loses its kinetic energy quickly and is easily absorbed. When it has travelled a few centimetres in air it is absorbed and it is completely blocked by paper or skin.

Beta particles are emitted from the nucleus when a neutron decays into a proton. It is a high speed particle, with a negative charge and little mass. It can be written as $^{0}_{-1}\beta$. Because it is much smaller than an alpha particle and has a single negative charge, it is much less ionizing than alpha particles and so it can penetrate much further. Several metres of air, or a thin sheet of aluminium, are needed to absorb beta particles.

Gamma rays are high energy, high frequency, electromagnetic radiation. They have no charge and no mass so they rarely interact with particles in their path, so they are the least ionizing of the three radiations. They are never completely absorbed, although their energy can be significantly reduced by several centimetres of lead, or several metres of concrete. If the energy is reduced to a safe level, gamma rays are often said to have been absorbed.

Radioactive sources need to be handled with extreme care. Safety precautions must be taken when using them (see box). Ionising radiations can interact with human cells. There may be so much ionization that cells die as a result. Where there is less ionisation, the molecules of DNA in the cell may change slightly, which could cause the cells to have an increased tendency to become cancerous. Because the radiations ionize to different extents, the hazard level is different for each one. The hazards are summarised in the table.

Type of radiation	Inside body	Outside body
alpha	Highly ionising – very dangerous radiation poisoning and cancer possible	Absorbed by surface layer of dead skin cells – no danger
beta	Moderate ionisation and danger should be minimised	Moderate so exposure ionisation and danger, close exposure should be minimised
gamma	minimal ionisation, cancer danger from long-term exposure	minimal ionisation – cancer danger from long–term exposure

Think about this...

Which of the three radiations do you think is most suitable for medical uses?

Safety precautions when using radioactive sources

Radioactive sources which are used in school are usually very weak.

They can only be used in the presence of an authorised teacher.

They are kept in a sealed container except when they are being used in an experiment or demonstration.

They are immediately returned to the container when the experiment or demonstration is finished.

When using the radioactive source it should be

1. Handled with tongs or forceps, never with bare hands.
2. Kept at arm's length, pointing away from the body.
3. Always kept as far as possible from the eyes.

Hands must be washed after the experiment and definitely before eating.

Activity 8.7: Predict the effect of magnetic and electric fields on the motion of alpha, beta and gamma rays

Work in a small group. Based on what you know about alpha, beta and gamma radiations, discuss what effect magnetic and electric fields will have on the motion of alpha, beta and gamma rays. Justify your reasoning.

Activity 8.8: Simulating nuclear reactions

Use marbles accelerated down a sloping aluminium channel into a saucer to simulate nuclear reactions produced by high-speed particles. The marbles in the saucer are analogous to target nuclei. Try using several marbles of different sizes. Show the effect of speed by launching the marbles from different heights and angles and the effect of mass and increased momentum of projectiles by using marbles of different sizes. Marbles coming down the slope with sufficient momentum can eject one of more marbles from the saucer. Discuss how this is analogous to bombarding nuclei with ever increasing mass: a proton, deuteron (two protons) and an alpha particle.

Activity 8.9: Penetrating power of alpha, beta and gamma radiation

Work in a small group. **Before you begin, make sure that you know the safety precautions that you must follow when using radioactive materials.**

Set up the equipment as shown in Figure 8.19.

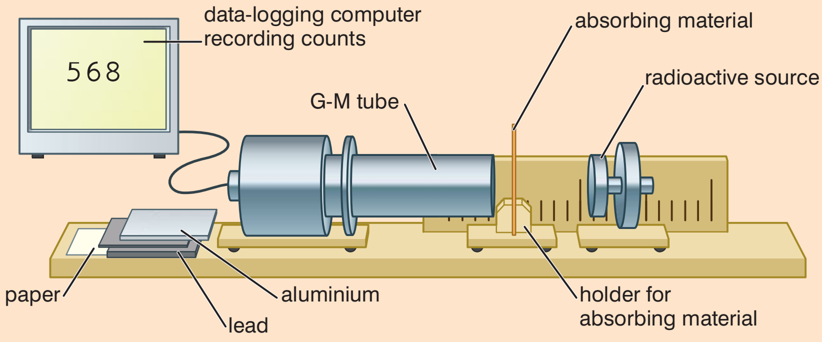


Figure 8.19

The source of radiation can emit alpha, beta or gamma rays. The Geiger–Muller tube will detect all three types of radiation. Place absorber sheets which progressively increase in density between the source and the detector, and record the average count rate in each case.

Note that, in order to remove all risk of exposure to radiation hazards, this experiment is often carried out using computer software.

Activity 8.10: Research the common detectors for α–particle, β–particle and γ–rays

In a small group, research the various forms of detectors for nuclear radiation. Prepare a summary of your research to present to the rest of your class. Choose an appropriate format for your presentation.

The relationship between mass and energy

One of Einstein's most important theories suggests that energy and mass are related by the equation

$$E = mc^2$$

where E is energy, m is mass and c is the speed of light (3×10^8 m/s).

On page 330, we learnt about the binding energy, that is, the energy required to hold the nucleus together. Any nuclear reaction which increases the binding energy per nucleon will give out energy. Using Einstein's equation, we can see that a change in energy will be associated with a change in mass. In fact, we find that there is a difference between the mass of a nucleus that we calculate by adding up the masses of its constituent protons and neutrons, and the measured mass of the nucleus. This difference is called the mass deficit, Δm.

When calculating the binding energy, we often use atomic mass units for the masses of subatomic particles.

Particle	Mass (atomic mass units, u)	Mass (kg)
proton	1.007 276	$1.672\ 623 \times 10^{-27}$
neutron	1.008 665	$1.674\ 929 \times 10^{-27}$
electron	0.000 548 58	$9.109\ 390 \times 10^{-31}$

If you use atomic mass units in nuclear energy calculations, then you multiply Δm (in atomic mass units) by 931.5 to give your result in MeV.

Worked example 8.8

a) Find the mass deficit for a carbon-12 nucleus.

b) Use this mass deficit to calculate the binding energy for a carbon-12 nucleus in joules.

c) Use this mass deficit to calculate the binding energy for a carbon-12 nucleus in electronvolts.

a) Use Figure 8.20 for this part of the question.

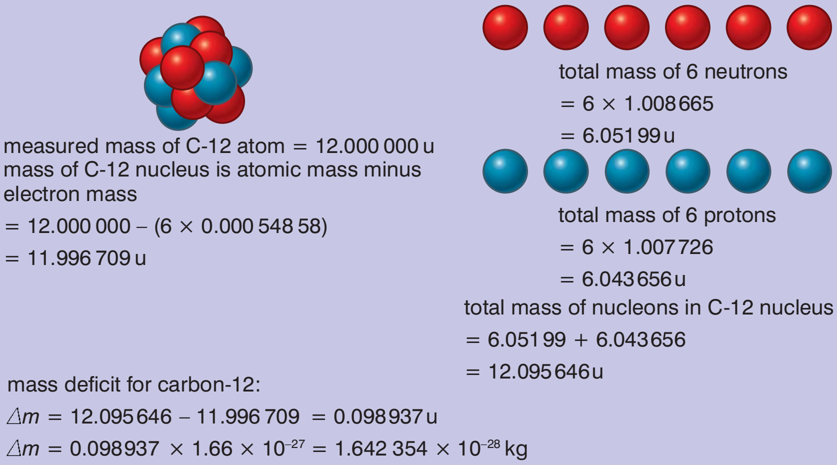


Figure 8.20

b)

ΔE (J)	Δm (kg)	c (m/s)
?	$1.642\ 354 \times 10^{-28}$	3×10^{8}

Use $\Delta E = \Delta mc^2$

$$= 1.642\ 354 \times 10^{-28} \times (3 \times 108)^2$$

$$= 1.478 \times 10^{-11}\ \text{J}$$

c)

ΔE (MeV)	Δm (u)	c (m/s)
?	$1.642\ 354 \times 10^{-28}$	3×10^{8}

Use $\Delta E = \Delta m \times 931.5$

$$= 0.098\ 937 \times 931.5$$

$$= 92.2\ \text{MeV}$$

Representing and interpreting nuclear reactions

We can represent nuclear reactions in the form of equations such as

$${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta$$

This equation represents the decay of a carbon-14 nucleus leaving a daughter nitrogen nucleus and emitting a beta particle in the process. Notice that the equation is 'balanced' in the sense that the total mass number and atomic number is the same on both sides of the arrow. This must always be the case. We know that energy is conserved in the reaction, so the energy released when a carbon-14 nucleus decays to a nitrogen nucleus is emitted in the form of a beta particle.

Worked example 8.9

Complete the following equation which represents a nuclear fission reaction and find the value of X.

$${}^{235}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{X}\mathrm{Rb} + {}^{139}\mathrm{Cs} + 2\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

The equation is balanced on both sides so the total mass number on the left side must be the same as the total mass number on the right side

$$\begin{aligned} 235 + 1 &= X + 139 + 2 \\ 236 &= X + 141 \\ 236 - 141 &= X \\ &= 95 \end{aligned}$$

We can combine nuclear reaction equations and data about the mass of the elements on both sides of the equation to find out how much energy is released per fission.

Worked example 8.10

Calculate the energy released in the following fission reaction. Give your answer in MeV.

$${}^{235}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

The data you need are:

mass of U-235 is 235.0439 u

mass of Ba-141 is 140.9144 u

mass of Kr-92 is 91.9262 u

mass of ${}^{1}_{0}\mathrm{n}$ is 1.008 665 u.

Consider mass on each side of the equation

$$235.0439\ \mathrm{u} + 1.008\,66\ \mathrm{u} \rightarrow 140.9144\ \mathrm{u} + 91.9262\ \mathrm{u} + (3 \times 1.008\,665\ \mathrm{u})$$

$$236.05256\ \mathrm{u} \rightarrow 235.866595\ \mathrm{u}$$

$$\begin{aligned} \Delta m &= (236.05256 - 235.866595)\ \mathrm{u} \\ &= 0.185\,965\ \mathrm{u} \end{aligned}$$

$$\begin{aligned} \text{Energy released} &= 0.185\,96 \times 931.5\ \mathrm{MeV} \\ &= 173\ \mathrm{MeV} \end{aligned}$$

Radioactive half-life

We know that radioactive decay is a random process. For every second, there is a probability that a nucleus will decay which is called the decay constant and given the symbol λ. If we have a sample of the nuclei, the probability of decay will determine the fraction of the sample that will decay. Of course, if the sample is larger, then more nuclei will decay in each second. This means that the activity (A) (the number decaying per second) is proportional to the number of nuclei in the sample, N. Mathematically we write this as

$$A = -\lambda N$$

$$\frac{dN}{dt} = -\lambda N$$

There is a minus sign in the formula because the number of nuclei in the sample decreases with time but in practice we ignore the minus sign when we use the formula. The units for activity are bequerel (Bq).

Worked example 8.11

What is the activity of a sample of 100 million atoms of carbon-14? The decay constant, λ, is 3.84×10^{-12} s^{-1}.

$\frac{dN}{dt}$ (Bq)	λ (s^{-1})	N
?	3.84×10^{-12}	100×10^{6}

Use $\frac{dN}{dt} = -\lambda N$

$= (3.84 \times 10^{-12}) \times (100 \times 10^{6})$

$= 3.84 \times 10^{-4}$ Bq

The formula for the rate of decay of nuclei in a sample is a differential equation that can be solved to give a formula for the number of nuclei remaining in a sample, N, after a fixed time, t

$$N = N_0 e^{-\lambda t}$$

where N_0 is the initial number of nuclei within a sample and λ is the decay constant.

Worked example 8.12

If the sample of 100 million carbon-14 atoms in worked example 8.11 were left for 250 years, how many carbon-14 atoms would remain?

N	N_0	λ (s^{-1})	t (s)
?	100×10^6	3.84×10^{-12}	$250 \times 365 \times 24 \times 60 \times 60$ $= 7.884 \times 10^9$

Use $N = N_0 e^{-\lambda t}$

$$= 100 \times 10^6 \times e^{-7.884 \times 10^9 \times 3.84 \times 10^{-12}}$$

$$= 100 \times 10^6 \times e^{-0.03027456}$$

$$= 9.701 \times 10^7 \text{ atoms}$$

KEY WORDS

half-life *the time taken for half the atoms of a given nuclide within a sample to decay*

We know that the activity of a sample of radioactive nuclei decreases over time and that the activity depends on the number of nuclei present. The rate at which the activity decreases depends on the particular isotope that is decaying. A measure of this rate of decrease of activity is called the **half-life**, $t_{1/2}$. The half life can be defined as the time taken for half the atoms of a given nuclide within a sample to decay.

We can find a mathematical expression for the half-life by putting $N = \frac{1}{2}N_0$ into the decay equation

$$N = N_0 e^{-\lambda t}$$

$$\frac{1}{2}N_0 = N_0 e^{-\lambda t_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$\ln\frac{1}{2} = -\lambda t_{1/2}$$

$$-\ln 2 = -\lambda t_{1/2}$$

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

Worked example 8.13

What is the half-life of carbon-14?

λ (s^{-1})	ln 2	$t_{1/2}$ (s)
3.84×10^{-12}	0.6931	?

Use $t_{1/2} = \dfrac{0.6931}{3.84 \times 10^{-12}}$

$= 1.81 \times 10^{11}$ s

$= 5.027777778 \times 10^{7}$ hours

$= 2.094907407 \times 10^{6}$ days

$= 5739$ years

If you were to carry out an experiment to measure the half-life of a radioactive substance, you would measure its activity over time. Activity is proportional to the number of nuclei present and so, when the activity is plotted against time, the shape of the curve is exponential decay as shown in Figure 8.21.

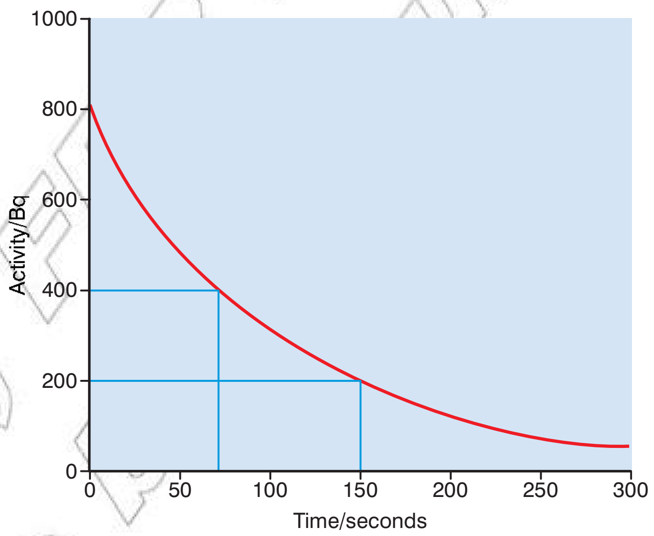


Figure 8.21

The activity, A, follows the equation

$A = A_0 e^{-\lambda t}$

The graph can be used to find the half-life of the substance by finding the time it takes for the activity to halve. On Figure 8.21, you can see that the time taken for the activity to drop from 800 Bq to 400 Bq was 70 s and the time taken to drop from 400 Bq to 200 Bq was 80 s. This gives an average for the half-life of 75 s. The time interval is not identical each time because of the random nature of radioactive decay and experimental and graphing errors. For this reason, several values need to be taken for the half-life and then these should be averaged, as above.

Worked example 8.14

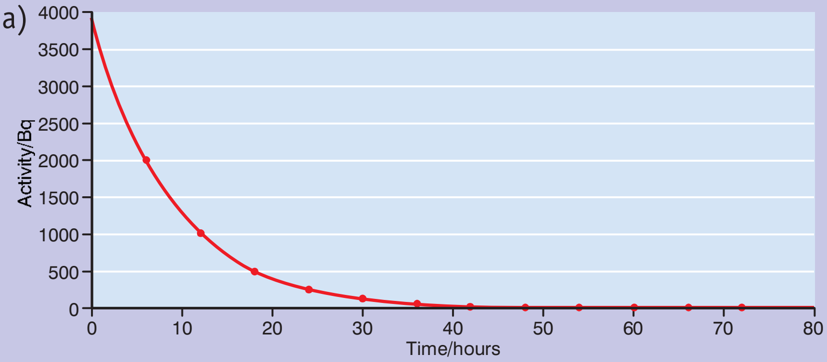
Here is a table showing the activity of a sample of technetium-99, a gamma emitter which is often used in medical investigations.

Activity (Bq)	Time (hours)
4000	0
2000	6
1000	12
500	18
250	24
125	30
75	36

a) Plot a graph to show this data.

b) Work out the half life for technetium-99.

a)



b) The graph shows that the activity falls from 4000 Bq to 2000 Bq in 6 hours, from 2000 Bq to 1000 Bq in 6 hours and from 1000 Bq to 500 Bq in 6 hours. The half-life for this substance is therefore 6 hours.

Uses of radioactive isotopes

Radioactive substances have many applications. Radiation is used to treat cancer – the radiation destroys the cancerous cells, while treatment is designed to protect non-cancerous cells. An example is the use of iodine-131, in the form of iodine chloride, which is used to treat thyroid cancer. The patient takes the radioactive substance orally and then the chemical travels to the thyroid and the radiation treats the disease.

The most commonly used radioactive isotope for medical applications is technetium-99. This is the daughter nuclide from the decay of molybdenum-99, which is itself produced from the fission on uranium-235 in nuclear reactors. Technetium-99 emits 140 keV gamma radiation so it is relatively low energy for gamma radiation and is therefore less likely to produce damaging ionisation in the body but is energetic enough to be detected outside the body. Technetium-99 is used for gamma ray scanning to produce images

Activity 8.11: Uses of radioisotopes in dating archaeological samples

In a small group, research the uses of radioisotopes in dating archaeological samples.

of the body, and also as a tracer to check the function of different organs of the body, including the bone marrow, brain and heart.

The radioactive isotope plutonium-238, which emits alpha radiation, is commonly used in atomic power supplies, such as those required for space travel.

Radioactive isotopes are also used in nuclear power stations to generate electricity. An objection raised against nuclear power is the problem of disposing of the waste material, which we shall discuss next.

Activity 8.12: Research nuclear power

Work in a small group to research one of the following topics.

- The fraction of energy generated from nuclear power in Africa and the rest of the world
- Peaceful uses of nuclear radiation in Ethiopia and Africa
- Nuclear facilities in Africa

Present your findings to the rest of your class in a form of your choice.

The problems posed by nuclear waste

In your research for Activity 8.12, you may have come across some of the problems posed by nuclear waste. One of the main difficulties is that the isotopes used in nuclear power stations typically have very long half lives. Plutonium-239 has a half-life of 24 100 years; in contrast plutonium-238 has a half-life of 88 years.

Spent nuclear fuel is the most important source of waste from nuclear power stations and is mainly unconverted uranium. About 3% of it is fission products from nuclear reactions. The actinides (uranium, plutonium, and curium) are responsible for the bulk of the long-term radioactivity, whereas the fission products are responsible for the bulk of the short-term radioactivity.

After about 5 percent of a nuclear fuel rod has reacted inside a nuclear reactor, that rod is no longer able to be used as fuel (due to the build-up of fission products). Scientists are experimenting on methods for reusing these rods in order to reduce waste and use the remaining actinides as fuel (large-scale reprocessing is being used in a number of countries).

A typical 1000- MW nuclear reactor produces approximately 20 m^3 (about 27 tonnes) of spent nuclear fuel each year (but this reduces to 3 m^3 if the waste is reprocessed). The remaining waste will be substantially radioactive for at least 300 years.

Spent nuclear fuel is initially very highly radioactive and so must be handled with great care. It becomes significantly less radioactive over the course of thousands of years of time. Some scientists believe that, after 10 000 years of radioactive decay, the spent nuclear fuel will no longer pose a threat to public health and safety.

When they are first extracted from the reactor, spent fuel rods are stored in shielded basins of water (spent fuel pools), usually located on-site. The water provides both cooling for the still-decaying fission products, and shielding from the continuing radioactivity. After about five years, the now cooler, less radioactive fuel is typically moved to a dry-storage facility or dry cask storage, where the fuel is stored in steel and concrete containers.

An article published in 2007 states 'Today we stock containers of waste because currently scientists don't know how to reduce or eliminate the toxicity, but maybe in 100 years perhaps scientists will... Nuclear waste is an enormously difficult political problem which to date no country has solved. It is, in a sense, the Achilles heel of the nuclear industry.'

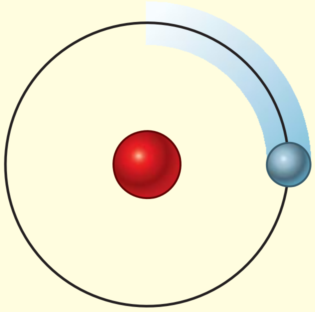
Despite all this, you should be aware that in countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes, much of which remains hazardous indefinitely. Overall, nuclear power produces far less waste material by volume than fossil-fuel based power plants. Coal-burning plants are particularly noted for producing large amounts of toxic and mildly radioactive ash due to concentrating naturally occurring metals and mildly radioactive material from the coal. It has been stated in a recent report from Oak Ridge National Laboratory that coal power actually results in more radioactivity being released into the environment than nuclear power operation, and that the population effective dose equivalent from radiation from coal plants is 100 times as much as from ideal operation of nuclear plants. Another factor is that although coal ash is much less radioactive than nuclear waste, ash is released directly into the environment, whereas nuclear plants use shielding to protect the environment from the irradiated reactor vessel, fuel rods, and any radioactive waste on site.

There is no easy answer to the issues and the debate will certainly continue for many years.

Summary

In this section you have learnt that:

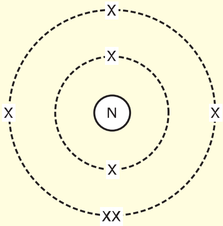
- Rutherford's model of atom is as shown here.



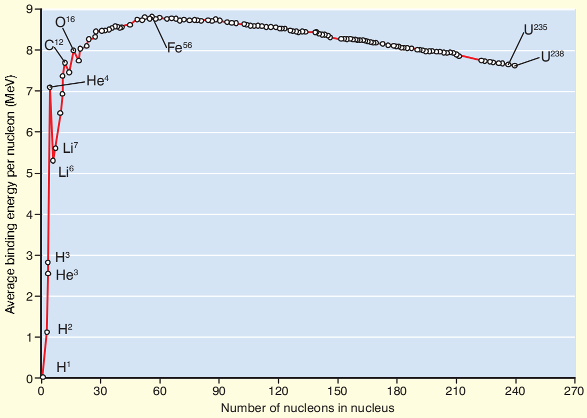
Rutherford's nuclear model of the atom: All the positive charge and most of the mass is concentrated in a tiny central nucleus. Most of the atom is empty space, and electrons orbit at the edge.

- Niels Bohr proposed that specific energy levels existed within an atom's structure and that electrons move in circular orbits around the nucleus. In his model, electrons that are closer to the nucleus have a lower energy state than those that are further away.

- Bohr's model means that electrons can only exist at specific energy states, and will not be found with energies between those levels.
- The change in energy of an atom can be calculated using the relation $\Delta E = E_f - E_i$
- The structure of simple atoms can be represented using simple diagrams like this.



- Isotopes of an element have the same atomic number (Z) but a different mass number (A). The relationship $A = Z + N$ means that isotopes of an element must therefore have different numbers of neutrons in their nuclei, but the same number of protons.
- The charge and mass of the electron is approximately $\frac{1}{1836}$ the charge and mass of the proton.
- The nuclear force is a very strong force that holds the particles in a nucleus together.
- The strong force is the same between any two nucleons and acts over a very short range.
- The radius of a nucleus and its mass number are related mathematically by the relationship $R = (1.2 \times 10^{-15}\text{ m})A^{1/3}$.
- Experimental results show that the radii of atoms vary from 35×10^{-12} m for hydrogen atoms where A is 1, to 175×10^{-12} m for americium atoms where A is 95.
- When nuclei of atoms are ordered according to atomic number and number of nucleons, the following properties are observed.
    - For the lighter nuclei, if we look at the most common isotope, N is approximately equal to Z.
    - As we get to heavier nuclei, past Z = 20, we begin to see N considerably greater than Z. As nuclei get heavier this becomes more apparent.
    - Bismuth is the heaviest stable nucleus. Heavier nuclei exist but they are all unstable – they undergo certain spontaneous changes which we observe as radioactivity. Nuclei from Z = 84 (polonium) to 92 (uranium) are found in nature (on Earth) and all their isotopes are radioactive.
    - Nuclei heavier than uranium exist but they are all artificial – they have been created by scientists in laboratories. The heaviest known nucleus has Z = 118. It was produced in 2006.
- **Binding energy** is the energy required to disassemble a nucleus into the same number of free unbound protons and neutrons as it is composed of, in such as way that the particles are distant enough from each other so that the strong nuclear force can no longer cause the particles to interact
- As nuclei get heavier than helium, their net binding energy per nucleon (which can be found by calculating the difference in mass between the nucleus and the sum of the masses of the nucleons of which it is composed) grows more and more slowly and reaches its peak at iron, as shown in the diagram.

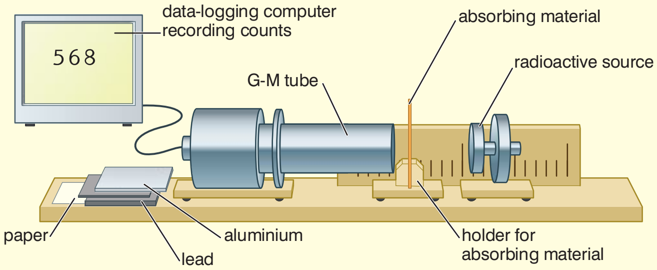


- As nucleons are added, the total binding energy increases but so does the total disruptive energy of the electrostatic forces and, once nuclei are heavier than iron, the increase in disruptive energy has more effect than the increase in binding energy. To reduce the disruptive energy, the weak interaction allows more neutrons to be added so that the number of neutrons exceeds the number of protons. However, at some stage the only way for the nucleus to reach a lower energy state (one that is more stable) will be to emit particles by **radioactivity**.

- **Nuclear fission** is the nucleus becoming more stable by splitting into two or more parts and emitting particles. An atom of one type, the parent nuclide, transforms into an atom of another type, called the daughter nuclide, together with some form of radiation. According to quantum mechanics, it is impossible to predict precisely when a given atom will decay so radioactive emissions occur randomly over space. The nuclear decay process is independent of conditions outside the nucleus.
- **Nuclear fusion** the process by which two nuclides are fused together to form a new nuclide. This process requires high temperature and pressure. It occurs naturally in stars but research into artificial nuclear fusion is ongoing.
- The three types of emissions from radioactive substances are alpha, beta and gamma rays.
- Because of the ionizing effects of the radiation, safety measures are needed when handling and using radio-isotopes.
- Radioactive sources which are used in school are usually very weak.
- They can only be used in the presence of an authorised teacher.
- They are kept in a sealed container except when they are being used in an experiment or demonstration.
- They are immediately returned to the container when the experiment or demonstration is finished.
- When using the radioactive source it should be
  1. Handled with tongs or forceps, never with bare hands.
  2. Kept at arm's length, pointing away from the body.
  3. Always kept as far as possible from the eyes.
- Hands must be washed after the experiment and definitely before eating.

Radiation	Nature	Relative ionizing effect	Relative penetrating power	Effect of electric field on radiation	Effect of magnetic field on radiation	Common detector
alpha	$^{4}_{2}$He nucleus	Highly ionising	A few centimetres in air, completely blocked by paper and skin	Deflects	Deflects	Geiger–Muller tube
Beta	Negative charge, mass of electron	Less ionising than alpha	Several metres of air, thin sheet of aluminium will absorb	Deflects in opposite direction to alpha	Deflects in opposite direction to alpha	Geiger–Muller tube
Gamma	No mass, electromagnetic radiation	Least ionising radiation	Never completely absorbed but energy can be significantly reduced by several centimetres of lead or several metres of concrete	No charge so no deflection	No charge so no deflection	Geiger–Muller tube

- The range of alpha, beta and gamma radiation in various media can be compared using the equipment shown here.



- The release of energy in a nuclear reaction is associated with a change in mass according to Einstein's equation $E = mc^2$ where E is the energy released, m is the change in mass and c is the speed of light. This equation may also be used with atomic mass units where it reduces to $E = (931.5 \times \Delta m)$ MeV
- Nuclear reactions can be represented in the form $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$
- This equation represents the decay of a carbon–14 nucleus leaving a daughter nitrogen nucleus and emitting a beta particle in the process. The equation is 'balanced' in the sense that the total mass number and atomic number is the same on both sides of the arrow.
- **Half-life** is the time taken for half the atoms of a given nuclide within a sample to decay

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

- Graphs of random decay show that such processes have a constant half-life.
- Uses of radioactive isotopes include: medical treatment and diagnosis, to date archaeological samples and to generate electricity.
- The problems posed by nuclear waste are a result of the very long half lives of the isotopes used to generate electricity, and the safe storage of the waste.

Review questions

1. Describe a) Rutherford's model of the atom, b) Bohr's model of the atom.
2. Suppose that an atom has two energy levels of value E_1 and E_2 above the ground-state level, taken as zero energy. Photons are emitted from the atom at wavelengths 620 nm (red), 540 nm (green) and 290 nm (uv).
   a) Sketch the energy level diagram.
   b) Add and label the three transitions causing the emitted light.
   c) Calculate the energy levels which will give these three spectral lines in joules.
3. Represent diagrammatically the structure of a carbon-6 atom.
4. What is meant by the term isotope?
5. How does the charge and mass of the electron compare with the charge and mass of the proton?

6. a) What is the strong nuclear force?
   b) What are some important properties of the strong force?
7. a) How are the radius and the mass number related mathematically?
   b) What is the range for sizes of atomic nuclei?
8. State nuclear properties.
9. How is nuclear stability determined by binding energy per nucleon?
10. a) How is radioactivity associated with nuclear instability?
    b) What is the difference between nuclear fission and nuclear fusion?
11. a) Identify the nature of the three types of emissions from radioactive substances.
    b) Draw a table to distinguish between the three kinds of emissions in terms of their nature, relative ionizing effect, relative penetrating power, the effect of magnetic and electric fields on the radiation, and the common detectors.
    c) Describe the need for safety measures in handling and using radioisotopes.
    d) Describe experiments to compare the range of alpha, beta and gamma radiation in various media.
12. How is the release of energy in a nuclear reaction associated with a change in mass?
13. Caesium-137 is a by-product of nuclear fission within a nuclear reactor.
    a) Copy and complete this equation which describes the production of $^{137}_{55}\mathrm{Cs}$.

       $$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{137}_{55}\mathrm{Cs} + ^{95}\mathrm{Rb} + ^{1}_{0}\mathrm{n}$$

    b) The half-life of is 30 years. When the fuel rods are removed from a nuclear reactor core, the total activity of caesium-137 is 5.8×10^{15} Bq. After how many years will this have fallen to 1.6×10^{6} Bq?
    c) Comment on the problems of storage of the fuel rods over this time period.
14. State some uses of radioactive isotopes.

End of unit questions

1. Explain the meaning of the term ‘black body’.
2. Radiation of wavelength 290 nm falls on a sample of magnesium. Photoelectrons are emitted. Calculate the energy of these electrons. Take the Planck constant to be 6.63×10^{-34} J s and the speed of light to be 3×10^{8} m/s.
3. An ultraviolet lamp is used to illuminate a clean sodium surface and photoelectrons are emitted. The stopping potential of the photoelectrons is −1.92 V. The work function energy of sodium is 2.36 eV. Calculate the wavelength of the UV radiation. Take the value of the Planck constant to be 6.63×10^{-34} J s.
4. Electrons are accelerated through a potential difference of 7500 V before striking a layer of graphite and being diffracted. The mass of an electron is 9.11×10^{-31} kg. Planck’s constant is 6.63×10^{-34} J s.

   Calculate

   a) the speed of the electrons when they hit the layer of graphite

   b) the momentum of the electrons

   c) the wavelength of the electrons.
5. State Heisenberg’s uncertainty principle.
6. Light of wavelength 2.5×10^{-11} m is used to measure the position of an electron of wavelength 1.54×10^{-11} m. Find the uncertainty in the position of the electron. Planck’s constant is 6.63×10^{-34} J s.
7. How does Bohr’s model of the atom refine Rutherford’s model?
8. a) There is a dark line in the Sun’s spectrum at 588 nm. Calculate the energy of a photon with this wavelength in joules. Planck’s constant is 6.63×10^{-34} J s.

   b) A helium atom as energy levels at -1.59×10^{-19} J, -2.42×10^{-19} J, -3.00×10^{-19} J, -5.80×10^{-19} J, -7.64×10^{-19} J. Explain, with reference to these energy levels, how the dark line in the Sun’s spectrum at 588 nm may be due to the presence of helium in the gases which surround the Sun.
9. a) Represent diagrammatically the structure of a chlorine-35 atom. The atomic number of chlorine is 17.

   b) Use the example of chlorine to explain the term isotope.
10. List some important properties of the nuclear strong force.
11. State nuclear properties.
12. Explain how nuclear instability and binding energy can lead to the release of energy.

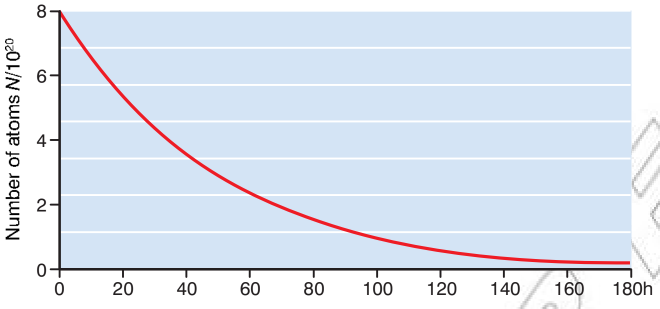
13. Compare alpha and beta emissions in terms of their nature, relative ionising effect, relative penetrating power, the effect of magnetic and electric fields on the radiation, and the common detectors.

14. Radon-220 is a radioactive gas which decays by alpha emission to polonium-216. The atomic number for polonium is 84.

    a) Write a nuclear reaction equation to describe this decay.

    b) The half-life of this decay is about 1 minute. Describe an experiment that you could perform to check this half-life value.

    c) The graph shows the decay of a radioactive nuclide.

    Determine the half-life of this nuclide.

    d) Use your value of half-life to calculate the decay constant λ of this radionuclide.

15. Explain carbon dating.