

10

The evidence for the nucleus

PRIOR KNOWLEDGE

Before you start, make sure that you are confident in your knowledge and understanding of the following points:

- An atom has a small, massive, positively charged nucleus.
- Rutherford scattering gives evidence for the nuclear model of the atom.
- The atom is neutral; the positively charged nucleus is balanced by negatively charged electrons, which orbit the nucleus.
- Unstable nuclei emit radioactive particles.
- Different isotopes of an element have the same number of protons but different numbers of neutrons.
- Alpha particles are helium nuclei.
- Beta particles are fast-moving electrons.
- Gamma rays are electromagnetic photons, which carry energy away from an unstable nucleus.
- Alpha, beta and gamma radiations may be identified by their differing powers of penetration.

TEST YOURSELF ON PRIOR KNOWLEDGE

- 1 Describe the nuclear model of the atom.
- 2 Outline briefly the penetrating powers of alpha, beta and gamma radiations.
- 3 Nobelium-254, $^{254}_{102}\text{No}$, emits an alpha particle to become an isotope of the element fermium, Fm.
 - a) Explain the meaning of the word 'isotope'.
 - b) Write a balanced equation to describe the alpha decay of nobelium-254.
- 4 Krypton-85, $^{85}_{36}\text{Kr}$, decays by emitting a β -particle to become an isotope of rubidium, Rb. Write a balanced equation to describe this decay.

We use radioactive sources for many purposes in medicine, industry and agriculture. Imagine that a patient is about to receive a dose of gamma radiation to help cure a cancerous tumour. Such doses must be carefully calculated and directed accurately at the cancerous area of the body. The differing ionising and penetrating powers of alpha, beta and gamma rays allow them to be used in various ways to investigate the body and then treat the patient.

Rutherford scattering

Figure 10.1 shows a plan view of the sort of apparatus that Geiger and Marsden used in 1911 to investigate the scattering of alpha particles by a thin foil of gold. Gold was chosen because it can be hammered into very

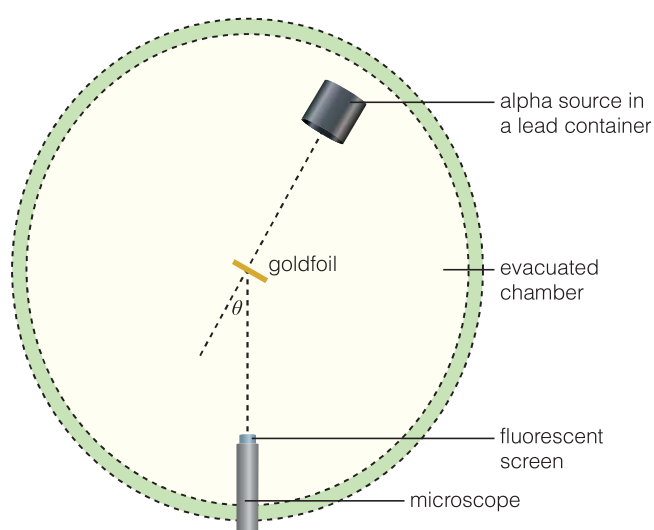


Figure 10.1 A plan view of Geiger and Marsden's apparatus.

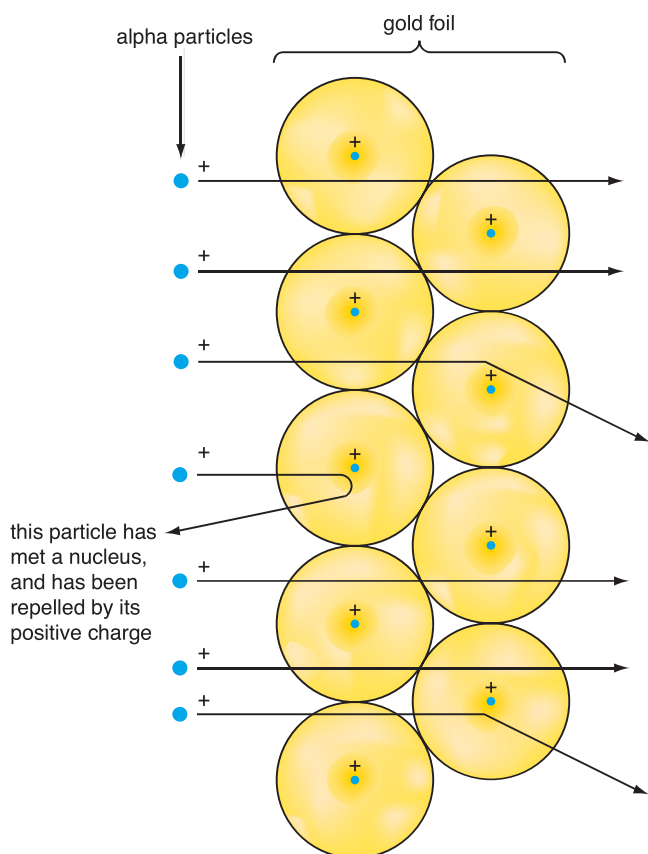


Figure 10.2 Only alpha particles that have a very close encounter with a gold nucleus are deflected through large angles.

thin sheets. An alpha source was placed in a long thin lead container to produce a well-directed beam of alpha particles. The whole apparatus was evacuated so that the alpha particles could travel without being stopped by the air.

Over a period of months, Geiger and Marsden counted the number of alpha particles deflected at different angles θ , shown in Figure 10.2. The alpha particles were detected by a fluorescent screen. Each time an alpha particle hit the screen, a small flash of light was emitted, which was seen through the microscope. Geiger and Marsden counted hundreds of thousands of such flashes of light. The vast majority of the alpha particles were deflected through very small angles. But a very small number of particles were deflected through large angles of about 150° or more. Figure 10.2 illustrates some typical paths of deflected alpha particles.

Rutherford drew the following conclusions from this experiment.

- The atom has a very small positively charged nucleus. Rutherford suggested that the positive charge on the nucleus is responsible for the repulsive force on the positively charged alpha particle, which causes it to change direction. The fact that only a very small number of particles undergo a large deflection tells us that the nucleus is much smaller in diameter than the atom.
- The second important conclusion about the nucleus is that it contains nearly all the mass of the atom. Considerations of the conservation of momentum tell us that the alpha particle would knock a small nucleus out of the way, but that the alpha particle will bounce back after an encounter with a nucleus heavier than itself.

Using our knowledge of electrostatic theory, it is possible to calculate the maximum size of the gold nucleus. If an alpha particle is turned round by 180° , it must have encountered a gold nucleus head-on, and there must have been a moment when the alpha particle stopped moving. Then all of the alpha particle's kinetic energy has been transferred to electrical potential energy.

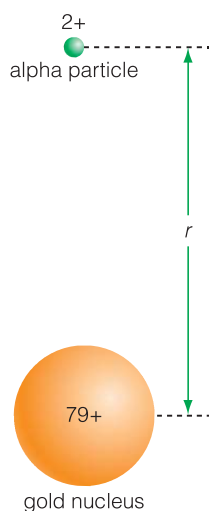


Figure 10.3 An alpha particle at its closest distance of approach to a gold nucleus.

Femtometre Nuclear radii and diameters are measured in femtometres, 10^{-15} m. The unit is abbreviated to fm.

In Figure 10.3 an alpha particle has been stopped by the gold nucleus and reached its closest distance of approach.

The kinetic energy of the alpha particles, used in the original Geiger and Marsden experiment, was about 5 MeV or $5 \times 10^6 \times 1.6 \times 10^{-19} \text{ J} = 8 \times 10^{-13} \text{ J}$. So we can write

$$8 \times 10^{-13} \text{ J} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r}$$

The expression on the right-hand side of the equation gives the electrical potential energy of two charges, Q_1 and Q_2 , separated by a distance r . The charge on the gold nucleus is $79e$ and that on the alpha particle is $2e$. The permittivity of free space is $8.85 \times 10^{-12} \text{ F m}^{-1}$.

$$8 \times 10^{-13} \text{ J} = \frac{(79 \times 1.6 \times 10^{-19} \text{ C}) \times (2 \times 1.6 \times 10^{-19} \text{ C})}{4\pi \times 8.85 \times 10^{-12} \text{ F m}^{-1} \times r}$$

Therefore

$$\begin{aligned} r &= \frac{(79 \times 1.6 \times 10^{-19} \text{ C}) \times (2 \times 1.6 \times 10^{-19} \text{ C})}{(4\pi \times 8.85 \times 10^{-12} \text{ F m}^{-1}) \times (8 \times 10^{-13} \text{ J})} \\ &= 4.5 \times 10^{-14} \text{ m or } 45 \text{ fm} \end{aligned}$$

By carrying out scattering experiments on lighter nuclei, Rutherford was able to deduce that the nucleus was even smaller than 45 fm (where fm is the abbreviation for **femtometre**). But he had established the nuclear model of the atom.

MATHS BOX

Another way to make an estimate of the nuclear size is to consider the number of alpha particles scattered through large angles. For example, in a scattering experiment, 1 in 8000 alpha particles is scattered by an angle larger than 150° – this counts as a ‘direct hit’. Measurement of the gold foil tells us that it is about 2000 atoms thick.

So, had the foil been only one atom thick, we can deduce that only 1 in 16 000 000 alpha particles would have had a ‘direct hit’. Therefore, we deduce that:

$$\frac{\text{cross-sectional area of the atom}}{\text{cross-sectional area of the nucleus}} = \frac{\pi r_a^2}{\pi r_n^2} = 16\,000\,000$$

and

$$\frac{\text{atomic radius}}{\text{nuclear radius}} = \frac{r_a}{r_n} = 4000$$

Because the radius of a gold atom is $1.35 \times 10^{-10} \text{ m}$, the nuclear radius is

$$r_n = \frac{1.35 \times 10^{-10} \text{ m}}{4000} = 3 \times 10^{-14} \text{ m or } 30 \text{ fm}$$

TEST YOURSELF

- 1 Give an account of the evidence that led to Rutherford proposing the nuclear model of the atom. (You should write your answer to secure six marks in an extended writing exercise.)
- 2 This question refers to the design of the Rutherford scattering experiment illustrated in Figure 10.1.
 - a) Explain why the apparatus must be evacuated.
 - b) Explain why the gold foil must be extremely thin, about 10^{-7} m thick.
 - c) Explain how the design of the holder for the alpha source produces a well-directed beam of radiation.
- 3 Figure 10.4 shows the path of an alpha particle being deflected by a heavy nucleus with charge $+Ze$.
 - a) Sketch diagrams to show possible paths of an alpha particle approaching the same nucleus if the alpha particle has
 - i) less kinetic energy
 - ii) more kinetic energy.
 - b) Sketch diagrams to show possible paths of the alpha particle with its original energy approaching nuclei that have
 - i) a charge greater than Z
 - ii) a charge less than Z .
- 4 An alpha particle with energy 7.7 MeV is scattered back through an angle of 180° by a thin sheet of aluminium foil.
 - a) Calculate the closest distance of approach of the alpha particle to the aluminium nucleus. The atomic number of aluminium is 13; $\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$.
 - b) i) Calculate the force that the alpha particle and nucleus exert on each other at their closest approach.
ii) Calculate the maximum acceleration of the alpha particle. The mass of the alpha particle is $6.8 \times 10^{-27} \text{ kg}$.

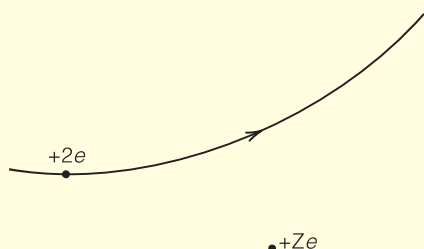


Figure 10.4

Nuclear radius and density

Figure 10.5 shows a diffraction pattern produced by shining green laser light through a thin film of lycopodium powder, which contains very small particles of about $30 \mu\text{m}$ in diameter. The photograph shows a series of circular diffraction rings, caused by the scattering and interference of the light off the particles.

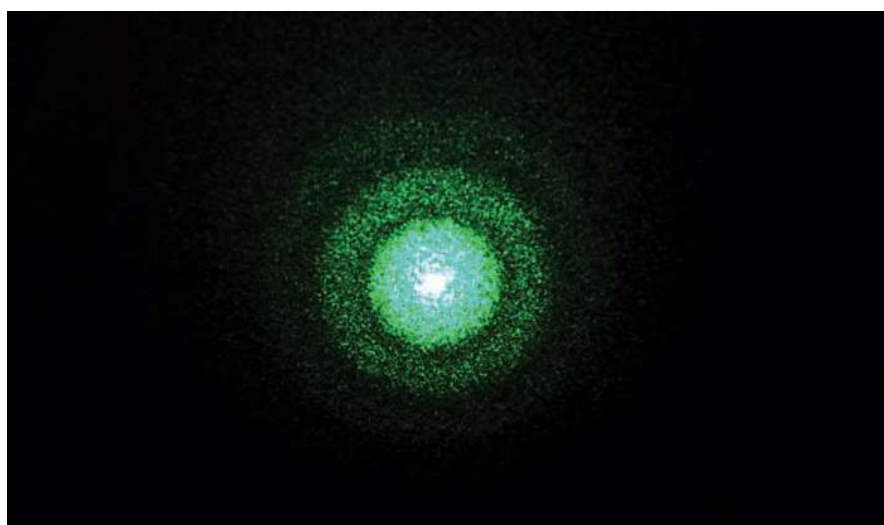


Figure 10.5 Diffraction pattern produced by the scattering of green light off lycopodium powder.

Diffraction theory predicts that the angle, θ , of the first diffraction minimum is given by

$$\sin \theta = 1.22 \frac{\lambda}{d}$$

where λ is the wavelength of the light and d is the diameter of the particles.

This diffraction theory enabled nuclear scientists to investigate accurately the diameter of the nucleus of atoms. The principle behind the experiment is illustrated in Figure 10.6.

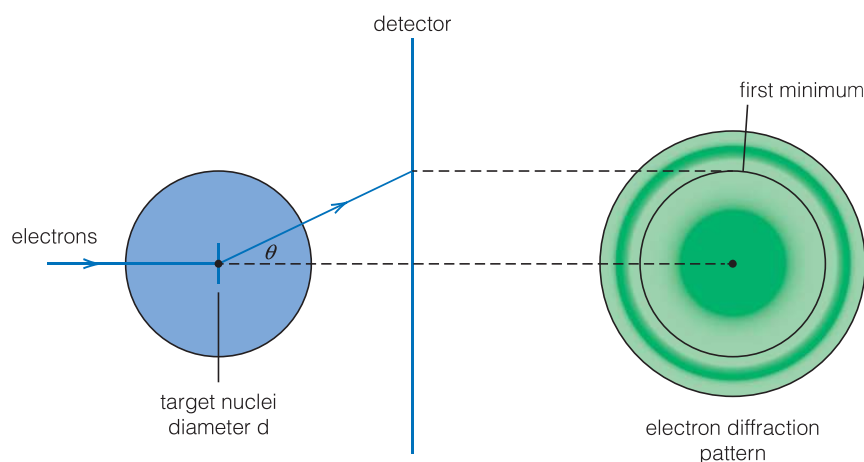


Figure 10.6

High-energy electrons are directed at thin targets of an element, and the nuclei act to scatter electrons in the same way that the lycopodium powder scatters light. You will recall that we can calculate the wavelength, λ , of the electrons using the formula

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

where h is the Planck constant, $6.6 \times 10^{-34} \text{ Js}$, and p is the electron's momentum. Such high-energy electrons are travelling close to the speed of light, and we must calculate their momentum using the equation

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

where E is the electron energy and c is the speed of light.

EXAMPLE

Electron scattering

A beam of electrons with energy 420 MeV is scattered off a target of carbon. The first diffraction minimum occurs at an angle of 52° .

1 Calculate the momentum of the electrons.

Answer

The momentum of the electrons is given by

$$\begin{aligned} p &= \frac{E}{c} \\ &= \frac{420 \times 10^6 \times 1.6 \times 10^{-19} \text{ J}}{3 \times 10^8 \text{ m s}^{-1}} \\ &= 2.24 \times 10^{-19} \text{ kg m s}^{-1} \end{aligned}$$

2 Calculate the wavelength of the electrons.

Answer

The wavelength of the electrons is

$$\begin{aligned} \lambda &= \frac{h}{p} = \frac{6.6 \times 10^{-34} \text{ J s}}{2.24 \times 10^{-19} \text{ kg m s}^{-1}} \\ &= 2.94 \times 10^{-15} \text{ m} \end{aligned}$$

3 Calculate the radius of a carbon nucleus.

Answer

The diameter of the nucleus is calculated from the equation

$$\begin{aligned} \sin \theta &= 1.22 \frac{\lambda}{d} \\ d &= \frac{1.22 \lambda}{\sin \theta} \\ &= \frac{1.22 \times 2.94 \times 10^{-15} \text{ m}}{\sin 52^\circ} \\ &= 4.6 \times 10^{-15} \text{ m} \end{aligned}$$

So the nuclear radius is $2.3 \times 10^{-15} \text{ m}$.

Empirical The equation $r = r_0 A^{\frac{1}{3}}$ is an empirical equation. The word 'empirical' means that the equation is based purely on experimental results. It is not exact, but it gives an approximate value for a nuclear radius.

Atomic mass unit One atomic mass unit (1 u) is equal to $1.67 \times 10^{-27} \text{ kg}$.

Experiments to determine the radius of nuclei allowed scientists to produce an approximate **empirical** formula for the radius of a nucleus, which is

$$r = r_0 A^{\frac{1}{3}}$$

where r is the radius of the nucleus, $r_0 = 1.2 \text{ fm}$ and A is the mass number or nucleon number of the nucleus. Figure 10.7 shows how the nuclear radius depends on the nucleon number of the nucleus.

We often use the expression u, which is an abbreviation for **atomic mass unit**. A proton and neutron each have a mass approximately equal to $1.67 \times 10^{-27} \text{ kg}$, and this is 1 u. So, in the example, the mass of a zinc nucleus is 66 u.

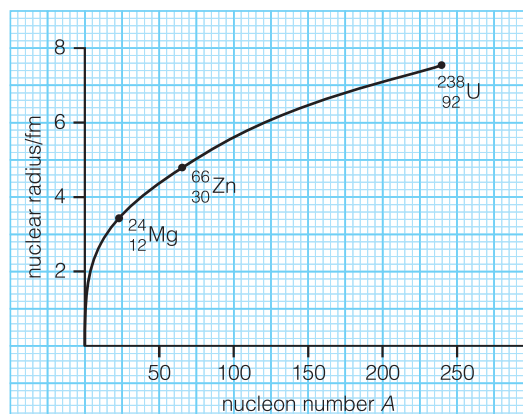


Figure 10.7 This graph shows the relationship between nuclear radius and nucleon number.

EXAMPLE**Empirical formula for nuclear radius**

- 1 Calculate the nuclear radius of the isotope ${}^{66}_{30}\text{Zn}$.

$$\begin{aligned} r &= r_0 A^{\frac{1}{3}} \\ &= 1.2 \text{ fm} \times 66^{\frac{1}{3}} \\ &= 4.8 \text{ fm} \end{aligned}$$

- 2 Calculate the density of a zinc nucleus, given that 1 u has a mass of $1.67 \times 10^{-27} \text{ kg}$.

Answer

Mass of nucleus = $\frac{4}{3}\pi\rho r^3$, where ρ is the nuclear density. So

$$\begin{aligned} \rho &= \frac{3}{4\pi r^3} \times m \\ &= \frac{3 \times (66 \times 1.67 \times 10^{-27} \text{ kg})}{4\pi \times (4.8 \times 10^{-15} \text{ m})^3} \\ &= 2.4 \times 10^{17} \text{ kg m}^{-3} \end{aligned}$$

This calculation shows us that the nuclear density is immense – over 100 million million times more dense than water.

TEST YOURSELF

- 5 a) Use Figure 10.7 to determine the nuclear radius of uranium-238.
 b) Calculate the density of a uranium nucleus; 1 u is $1.67 \times 10^{-27} \text{ kg}$.
- 6 a) Explain the principle behind using electron diffraction to determine the radius of a nucleus.
 b) Explain one advantage that electron diffraction has over Rutherford scattering as a means of determining nuclear radius.
- 7 The element livermorium is a short-lived transuranic element, which has been produced in nuclear reactors.
 a) i) Explain what 'transuranic' means.
 ii) Why are transuranic elements short-lived?
 b) One isotope of livermorium is ${}^{293}_{116}\text{Lv}$. Use the empirical formula to predict the radius of a livermorium nucleus.
- 8 An electron beam with energy 890 MeV is used to investigate the radii of some elements. Figure 10.8 shows how the intensity of scattered electrons varies for two isotopes, gadolinium-160 and calcium-40.
- a) Use the expression $p = \frac{E}{c}$ to show that the momentum of each electron in the beam is about $4.7 \times 10^{-19} \text{ kg m s}^{-1}$.

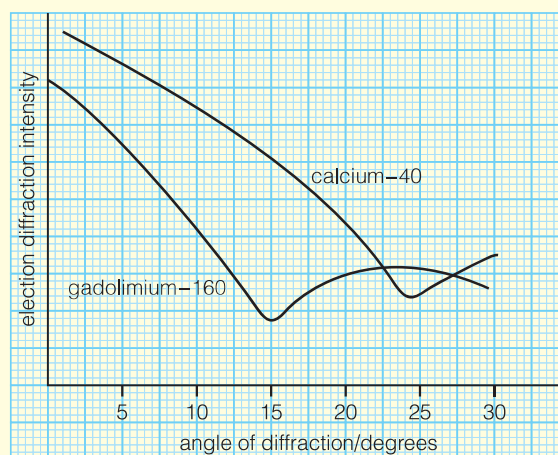


Figure 10.8

- b) Calculate the wavelength of the electrons in the beam. Planck's constant = $6.6 \times 10^{-34} \text{ J s}$.
 c) Use the information in Figure 10.8, and the information in the text about electron diffraction, to calculate the nuclear radius for
 i) gadolinium
 ii) calcium.
 d) Check your answers for part (c) with the predictions for nuclear radius shown in Figure 10.7.

Becquerel The activity of a radioactive source is equal to the number of particles emitted per second. The unit of activity is the becquerel (Bq): 1 becquerel (1 Bq) = an emission of one particle per second.

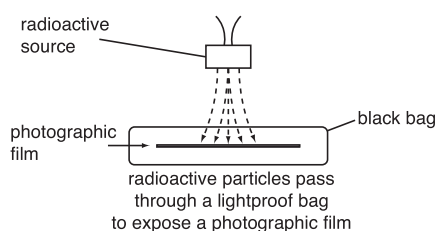


Figure 10.9

Radioactive emissions

Henry Becquerel discovered radioactivity in 1896. He placed some uranium salts next to a photographic plate, which had been sealed in a thick black bag to prevent light exposing the plate (Figure 10.9). When the plate was later developed, it had been affected as if it had been exposed to light (Figure 10.10). Becquerel realised that a new form of energy was being emitted from the uranium salts. In his honour, the **activity** of a radioactive source is measured in **becquerels**.

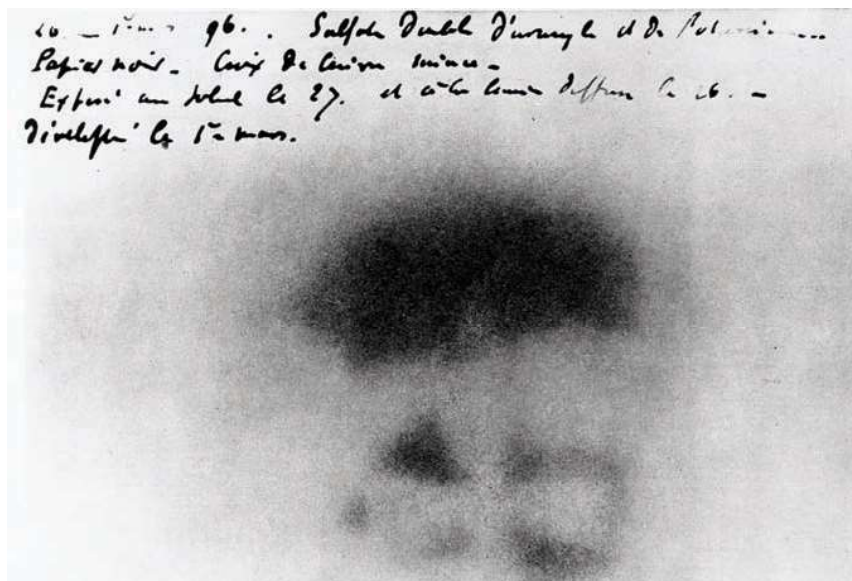


Figure 10.10

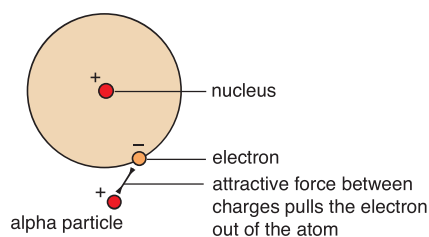


Figure 10.11 The strong electric field of the alpha particles pulls or knocks electrons out of atoms to create positive and negative ions.

The nature of alpha (α), beta (β) and gamma (γ) radiations

Unstable nuclei emit various types of radiation, the most common of which are alpha, beta and gamma radiation. Their nature and properties are summarised below.

Alpha particles

Alpha particles are the nuclei of helium atoms. So they are made up of two protons and two neutrons. They have a mass of 4 u and a charge of +2e.

Alpha particles are strongly ionising. The strong charge on the alpha particle pulls electrons out of atoms, creating pairs of positive and negative ions along the particle's path (Figure 10.11). An alpha particle produces about 10 000 ion-pairs per millimetre of path in air.

Alpha particles travel a few centimetres in air, and can be stopped by a thick piece of paper (Figure 10.12).

Alpha particles are deflected slightly in strong electric and magnetic fields. Typically, alpha particles have kinetic energies of a few MeV as they leave

the parent nucleus. An alpha particle with an energy of 5 MeV travels at about 5% of the speed of light (Table 10.1).

Beta particles

Beta particles are fast-moving electrons, which travel at just less than the speed of light. Typically, beta particles have kinetic energies of a few MeV.

Beta particles are much less ionising than alpha particles, producing about 100 ion-pairs per millimetre of path travelled in air.

Beta particles may travel several metres in air, and they are absorbed by aluminium a few millimetres thick (Figure 10.12).

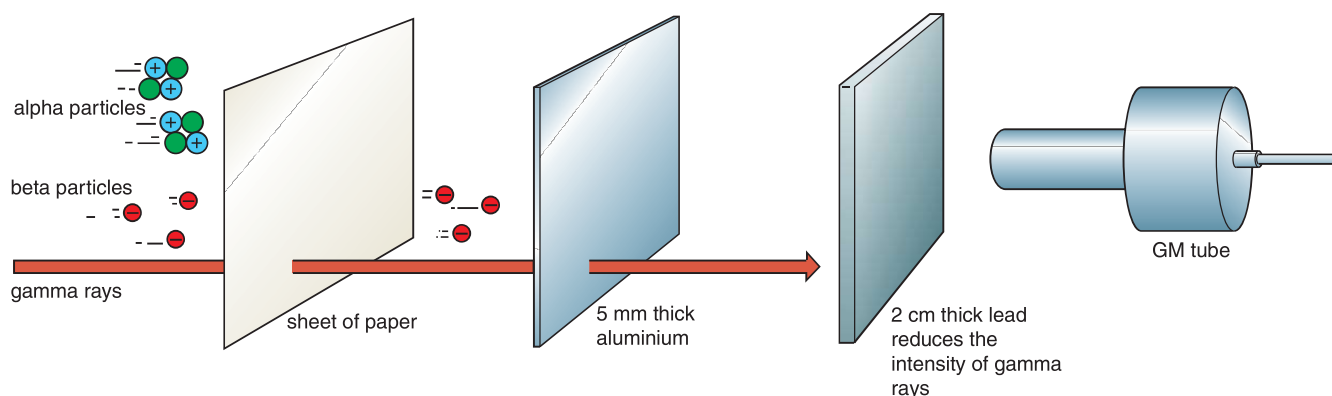


Figure 10.12 The penetrating powers of alpha, beta and gamma radiations.

Beta particles may be deflected through large angles by electric and magnetic fields (Table 10.1).

Gamma rays

Gamma rays are electrically neutral emissions, which are photons (just like any other type of electromagnetic radiation). Typically, a gamma-ray photon might have an energy of about 1 MeV, which corresponds to a wavelength of about 10^{-12} m.

Gamma rays are not deflected in magnetic and electric fields because they are not charged (Table 10.1).

Table 10.1 Properties of alpha, beta and gamma radiations.

Radiation	Alpha particle	Beta particle	Gamma ray
Nature	Helium nucleus	Fast electron	Electromagnetic photon
Charge	+2e	-e	0
Mass	6.6×10^{-27} kg (4amu)	9.1×10^{-31} kg	0
Speed	5% of c	98–99% of c	c (speed of light)
Ions per mm of air for a particle of 3MeV	10 000	100	1
Detection	Slight deflection in electric and magnetic fields Affects photographic film	Significant deflection in electric and magnetic fields Affects photographic film	No deflection in electric and magnetic fields Affects photographic film

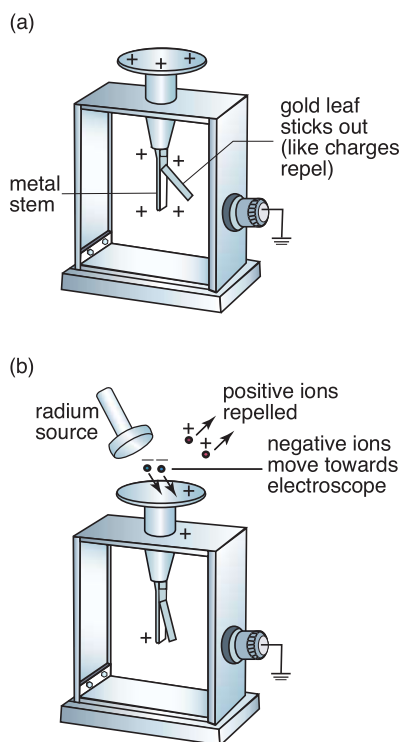


Figure 10.13

Gamma rays are very weakly ionising, producing about one ion-pair per millimetre of path travelled in air. Gamma rays are very penetrating, and their intensity is reduced by a few centimetres thickness of lead (Figure 10.12). Gamma rays can transfer their energy to electrons in metals (rather like a photoelectric effect); then the moving electrons create ion-pairs.

Ionisation

Figure 10.13 shows how a charged gold leaf electroscope can be used to illustrate the strong ionising power of alpha radiation. An alpha source is held above a positively charged electroscope. The alpha particles produce positive and negative ions. The positive ions are repelled from the positively charged electroscope, but the negative ions are attracted to the electroscope and it is discharged.

We make use of the ionising properties of alpha, beta and gamma radiation to detect them. This is done using a Geiger–Muller (GM) tube. Figure 10.14 shows how the tube works. Although GM tubes are still used in schools, solid-state detectors (working on a similar principle) are more widely used elsewhere.

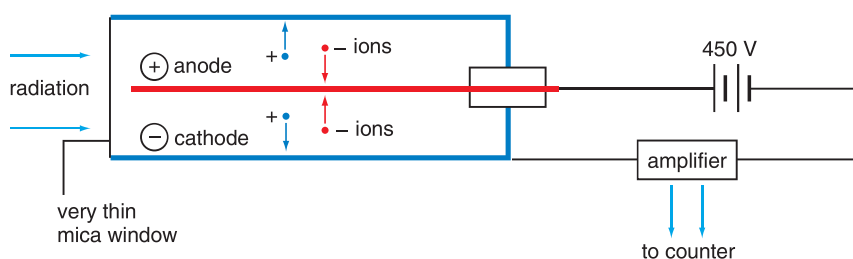


Figure 10.14

A metal tube is filled with argon gas at low pressure. A voltage of about 450 V is applied between a central anode and the outside of the tube. When radiation enters the tube through a narrow window at the front of the tube, atoms are ionised and a small current flows. Each current pulse is amplified and counted, so that we can record the rate at which particles enter the tube.

It is important that we can detect and then understand the effects of ionising radiation. When ionising particles enter the body, the ions that are produced can damage or destroy cells in our bodies, with serious consequences for our health. This is discussed at greater length later.

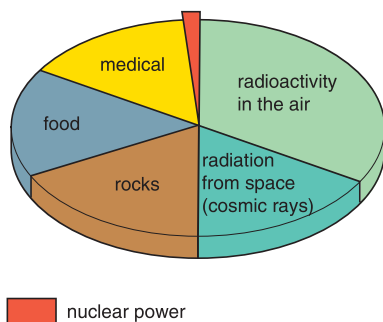


Figure 10.15 Sources of radiation in Britain.

Background radiation

There are a lot of rocks in the Earth that contain radioactive uranium, thorium, radon and potassium, and so we are always exposed to some ionising particles. Radon is a gas that emits alpha particles. Because we can inhale this gas, it is dangerous as radiation can get inside our lungs. In addition, the Sun emits lots of protons, which can also create ions in our atmosphere. These are two of the sources that make up background radiation. Figure 10.15 shows the contribution to the total background radiation from all places in Britain. Fortunately the level of background radiation is quite low, and in most places it does not cause a serious health risk.

In some jobs workers are at a higher risk. X-rays used in hospitals also cause ionisation. Radiographers make sure that their exposure to X-rays is as small as possible. In nuclear power stations, neutrons are produced in nuclear reactors. The damage caused by neutrons is a source of danger for workers in that industry.

TEST YOURSELF

- 9 Refer to Figure 10.13. The plate on the electroscope is charged negatively. Explain whether or not the gold leaf electroscope would still be discharged by an alpha radiation source.
- 10 a) Explain what is meant by the term 'background radiation'. What are the sources of background radiation?
b) Design an experiment to investigate what the background count is in your school.
- 11 To answer this question, you may need to revise the work covered in Chapter 7.

Figure 10.16(a) shows an experiment in which some beta particles are deflected by a magnetic field.

- a) Explain how the direction of the beta particle deflection confirms that they are negatively charged.

Figure 10.16(b) shows how the count rate of the deflected beta particles varies with angle.

- b) Explain which beta particles have the higher energy, those deflected through 20° or those deflected through 40° .

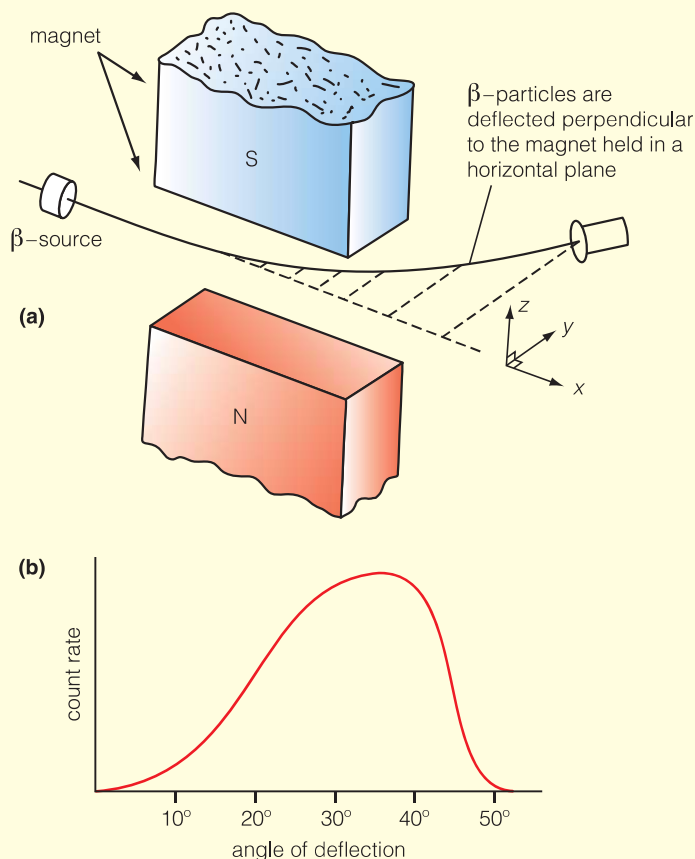


Figure 10.16

ACTIVITY**Identification of radiations**

Figure 10.17 shows an experimental arrangement to identify the radiations emitted by a radioactive source.

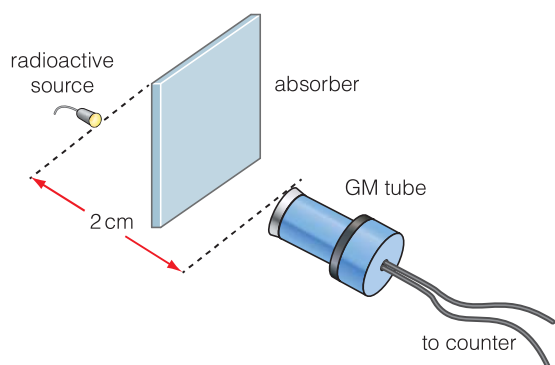


Figure 10.17

- 1 First, the GM tube is left without a source nearby to establish the background count. Over a period of 15 minutes, the GM tube recorded a background count of 330.

Determine the background count in counts per minute.

- 2 Then a source A is placed in front of the counter at a fixed distance of 2 cm. Various absorbers are placed between the source and the GM tube. Table 10.2 shows a summary of the results obtained.

Determine the radiation(s) emitted by source A.

Table 10.2

Absorber	Thickness/mm	Count rate/min ⁻¹
None		5054
Paper	0.3	3294
Aluminium	0.1	3084
Aluminium	0.5	1954
Aluminium	1.0	244
Lead	1.0	21
Lead	2.0	24

- 3 A second source B is placed in front of the GM tube at a fixed distance of 2 cm, and the absorbers are placed between the source and the GM tube as before. The results are shown in Table 10.3.

Determine the type(s) of radiation emitted from source B.

Table 10.3

Absorber	Thickness/mm	Count rate/min ⁻¹
None		2084
Paper	0.3	2079
Aluminium	0.1	1954
Aluminium	0.5	1251
Aluminium	1.0	1246
Lead	2.0	1068
Lead	5.0	641
Lead	10.0	355

TIP

If the above experiment is actually performed, remember that the appropriate source must be handled safely, in line with agreed standard operating procedures. These should be agreed with a suitable RPA (Radiation Protection Adviser).

Inverse square law for γ -radiation

Gamma radiation behaves like any other electromagnetic radiation, in that it spreads out symmetrically in all directions from its source. The intensity of a light source obeys an inverse square law.

This idea was discussed before in Chapter 3, and Figure 3.2 shows you the reasoning behind the law. So for gamma radiation we can write

$$I = \frac{k}{x^2}$$

where I is the intensity of the radiation (which can be measured in W m^{-2}), x is the distance from the source and k is a constant.

EXAMPLE**Radioactivity and inverse square law**

1 The count rate measured by a GM tube at a distance of 15 cm from a gamma source is 2800 Bq. The source is then moved further away from the GM tube.

a) What will the count rate be at 30 cm?

Answer

This problem is relatively easy to solve, using $I = \frac{k}{x^2}$, because x is doubled, x^2 is quadrupled and $\frac{1}{x^2}$ is a quarter of its previous value.

Thus the corrected count rate is $\frac{1}{4} \times 2800 \text{ Bq} = 700 \text{ Bq}$.

b) What will the corrected count rate be at 50 cm?

Because $I = \frac{k}{x^2}$, it follows that $k = Ix^2$ or $I_1 x_1^2 = I_2 x_2^2$. So

$$\begin{aligned} I_2 \times 50^2 &= 2800 \text{ Bq} \times 15^2 \\ I_2 &= 2800 \text{ Bq} \times \left(\frac{15}{50}\right)^2 \\ &= 250 \text{ Bq} \end{aligned}$$

2 A Geiger-Muller tube window has an area of 2.8 cm^2 . A gamma source is placed a distance of 0.1 m from the window and the counter detects a corrected count rate of 150 Bq.

Assuming that the γ -source emits radiation uniformly in all directions, calculate the total number of emissions per second from the source. State any assumptions in the calculation.

First, we assume that all γ -rays are detected at the GM tube window (as you will see later, this is not actually the case).

The γ -radiation is spread over an area of $4\pi R^2$, where R is the distance from the source ($4\pi R^2$ is the surface area of a sphere). So the count detected is:

$$C = C_T \frac{2.8 \text{ cm}^2}{4\pi R^2}$$

where C_T is the total count. So

$$\begin{aligned} C_T &= \frac{C \times 4\pi R^2}{2.8 \text{ cm}^2} \\ &= \frac{150 \text{ Bq} \times 4\pi \times (10 \text{ cm})^2}{2.8 \text{ cm}^2} \\ &= 67\,000 \text{ Bq} \end{aligned}$$

REQUIRED PRACTICAL 12**Inverse square law for γ -radiation**

Note: This is just one example of how you might tackle this required practical.

Figure 10.18 shows an experimental arrangement to investigate the relationship between the intensity of radiation from a gamma source and its distance from a Geiger-Muller tube.

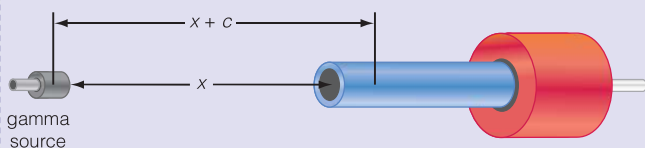


Figure 10.18

In Figure 10.18, x has been defined as the distance between the edge of the source container and the window of the GM tube. However, there is a difficulty with this definition. The source itself is inside the container, and the radiation is not all detected at the window of the tube. So the true distance between the source and the place where the radiation is detected

is $x + c$. This is called the corrected distance. So we write

$$\begin{aligned} I &= \frac{k}{(x+c)^2} \\ (x+c)^2 &= \frac{k}{I} \\ x+c &= \left(\frac{k}{I}\right)^{\frac{1}{2}} \end{aligned}$$

Therefore, if we plot a graph of x against $I^{-\frac{1}{2}}$, we would expect to see a straight line.

In an experiment, the results shown in Table 10.4 were obtained. The background count was determined to be an average of 18 counts per minute.

Table 10.4

x/cm	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
GM count over 10 s	431	260	195	138	110	81	73	61





- 1 Copy the table and add two further rows to it.
- 2 a) Make a suitable correction allowing for background count and add to your table.
b) Add a further row to show $(\text{count rate})^{-\frac{1}{2}}$.
- 3 a) Plot a suitable graph to investigate whether the intensity of the gamma radiation obeys an inverse square law.
b) Use your graph to estimate the value of c shown in Figure 10.18.

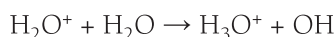
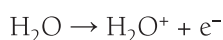
The biological effects of radiation

In the early 1900s, scientists working with radioactive materials did not understand the dangers of radiation, and consequently many people suffered injury and in some cases death.

Ionising radiation is dangerous because ions are produced in our bodies, which damage cells and the functions of enzymes are changed.

Our bodies are made up of many different types of complicated molecules. If an electron is removed or added to a molecule, it has been changed chemically and will therefore behave differently in any interaction with another molecule. Typically it requires a few eV of energy to remove an electron from a molecule. Such energy is carried by photons of ultraviolet light. Alpha and beta particles, and gamma-ray photons all carry energy measured in MeV. Such radiations cause ionisation, and **ionising radiation** is dangerous to us because it can change the chemistry of our bodies. The functions of enzymes can be altered, cells can be damaged and mutations can occur to our DNA, which can lead to cancer.

It is also known that the irradiation of water produces free radicals (see H_2O^+ and H_3O^+ and OH^- below), which are highly reactive. These free radicals change the structure of surrounding molecules with biological implications. Such reactions include



Radiation dose

An absorbed **dose** of radiation is defined as the energy absorbed per kilogram of a body:

$$D = \frac{E}{m}$$

The unit of dose is J kg^{-1} and this is given the name **gray** (Gy).

Clearly, if we receive a high dose of radiation, we are at a higher risk of becoming ill due to the damage caused to our bodies. However, the impact of the radiation on our bodies also depends on how the dose is administered, and this depends on the type of radiation we are exposed to.

From our earlier work on the penetration of radiations, you will recall that alpha particles are easily stopped by 5 cm of air, or by a sheet of paper. The lack of penetration of alpha particles is explained by their very high ionising power. Alpha particles lose energy over a shorter range than beta particles and gamma rays, because alpha particles are relatively slow-moving and they carry a high charge. By contrast, beta and gamma rays lose their energy over much longer distances. Consequently, alpha particles are much more damaging to our bodies because many ions are produced in a small volume.

Dose The energy absorbed per kilogram of a body.

Gray The unit of dose is J kg^{-1} , which is called one gray (Gy).

Dose equivalent The measure of the damage done by radiation.

Sievert The unit of dose equivalent is also J kg^{-1} , but for dose equivalent the unit is called the sievert (Sv).

We measure the damage done by radiation in **dose equivalents**, which is defined as

$$H = W_R D$$

where W_R is the radiation weighting factor, which is a dimensionless number that depends on the type of radiation – see Table 10.5. Dose equivalent has the same units as dose, namely J kg^{-1} , but to distinguish dose from dose equivalent, the latter is given the unit **sievert** (Sv).

Table 10.5

Type of radiation	W_R
X-rays, gamma rays, β -particles	1
Protons	2
Alpha particles, nuclear fission products	20

When we handle radioactive sources, we must take care to minimise the risk. First, a radioactive source should be enclosed in a container that is leak-proof to avoid the escape of any radioactive liquid or gases. In schools, radioactive sources are of low intensity, but we adopt these precautions:

- Sources are kept in lead-lined boxes and locked away in metal cupboards.
- When in use, sources are used for a short period of time.
- Sources are kept away from our bodies and are handled with long tongs.

There are strict regulations for the handling of radioactive materials in laboratories, hospitals and industry. A leak of a radioactive gas or liquid is particularly hazardous because we can inhale a gas or swallow a liquid, which could then allow radiation to be emitted inside our bodies.

TEST YOURSELF

- Describe an experiment that would enable you to detect the type of radiations being emitted from a radioactive source. (Remember to describe the apparatus you would use and what measurements you would take.)
- A source of gamma radiation is placed a distance of 0.2 m away from a small radiation detector. The detector records a corrected count rate of 200 Bq from the gamma source.
Calculate what count rate would be recorded when the detector is moved a distance of 0.5 m away from the source.
- Calculate the energy of an ultraviolet photon with a wavelength of 2×10^{-7} m. Express your answer in electronvolts (eV). (You may need to refer back to the work in Chapter 3 of book 1.)
 - Explain why sunbathing for too long can cause skin cancer.
- Explain what is meant by the term 'ionising radiation'.
 - Why are ionising radiations dangerous to us?
- A teacher leaves two radioactive sources on a laboratory bench. One source emits γ -rays, and it is kept in a lead-lined box. The second source is an alpha source, which is left out of its box.
 - Explain which source is potentially more dangerous to pupils 2 m away in the class.
 - Radon is a radioactive gas that emits alpha particles. The gas is emitted by granite rocks. Explain why radon might be a hazard to health to those who live in an area with granite rocks.
 - Explain why gamma rays emitted by rocks are less dangerous than radon's alpha particles.

Use the following information to answer questions 8, 9 and 10.

The table below contains information about four types of radiation A, B, C and D.

Characteristic	A	B	C	D
Penetrating power	Many cm of lead	A few mm of metal	Many cm of lead	A few cm in air
Mass/kg	1.67×10^{-27}	9.1×10^{-31}	0	6.64×10^{-27}
Deflection in a magnetic field	0	Large	0	Small
Ionisation	Very weak	Weak	Very weak	Strong

8 Which radiation is made up of alpha particles?

9 Which radiation is gamma rays?

10 Which radiation is made up of neutrons?

11 The radius of an atomic nucleus is given by

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

where A is the mass number of the nucleus.

a) Calculate the density of a nucleus of barium ($^{138}_{56}\text{Ba}$) in kg m^{-3} . (3)

b) Calculate the radius of a star that has the same density as barium, if the star has a mass of $4 \times 10^{30} \text{ kg}$. (3)

12 Describe an experiment you would carry out to investigate whether or not the intensity of gamma radiation emitted from a source obeys an inverse square law. (6)

13 A strong source of gamma radiation is used in a hospital to treat a patient suffering from cancer.

Describe precautions that should be taken to safeguard the health of

a) the patient (2)

b) the radiographer who is administering the dose of radiation. (2)

14 The graph in Figure 10.19 shows how many ion-pairs are produced per millimetre by an alpha particle at each point of its track.

a) Suggest why the alpha particle produces more ions per millimetre towards the end of its track, just before it stops moving. (2)

b) Estimate the total number of ion-pairs produced by the alpha particle along its 50 mm track. (2)

c) Each ion-pair requires about 30 eV of energy to form. Use this information to estimate the initial energy of the alpha particle. (1)

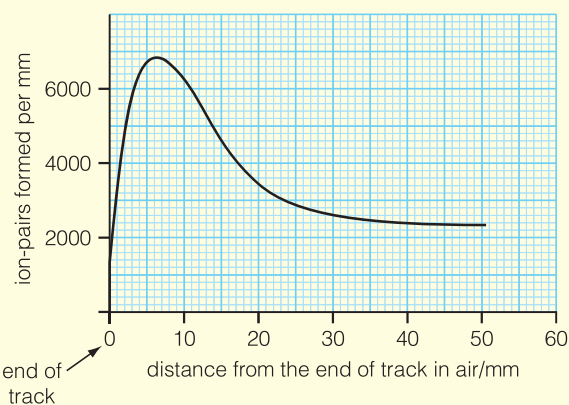


Figure 10.19

- 15 A source of gamma radiation is placed 0.15 m away from the window of a Geiger–Muller tube, which has an area of $3.2 \times 10^{-4} \text{ m}^2$. The GM tube records a corrected count rate of 38 Bq.
- Assuming that the gamma rays are emitted uniformly in all directions, estimate the total number of gamma rays emitted per second by the source, if the GM tube only detects 1 in 500 of the gamma rays that enter the tube. (4)
 - The gamma rays have an energy of 1.2 MeV. Calculate the energy emitted by the source each second. Express your answer in joules. (2)
 - Estimate the count rate measured by the GM tube if the source is moved to a distance 0.10 m away from the window. (2)

- 16 Figure 10.20 shows the paths of two alpha particles that are deflected by a nucleus N. At its closest point, alpha particle A is a distance r away from the nucleus and particle B is a distance $2r$ away from the nucleus.

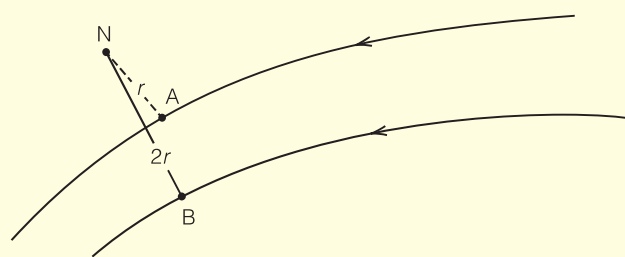


Figure 10.20

- The forces on the two particles are electrical. How do the size of the two forces compare at positions A and B. (2)
 - Explain, by looking at the shape of the tracks, which particle is moving faster. (2)
- 17 The nuclei of atoms may be produced artificially in particle accelerators by firing high-energy alpha particles at a target nucleus. The equation below gives an example of such a reaction:
- $${}_{13}^{27}\text{Al} + {}_2^4\text{He} \rightarrow {}_{15}^{30}\text{P} + ?$$
- Copy and complete the equation to identify a particle that is produced in the reaction. (1)
 - It is discovered that the reaction only takes place if the alpha particles have energies in excess of about 10^{-12} J . Use this information to calculate the closest distance of approach of the alpha particle and aluminium nucleus without it reacting. (3)
 - Explain why the reaction does not occur for the lower energy alpha particle. (1)

Stretch and challenge

- 18 An upper limit for the diameter of a carbon nucleus may be obtained from data similar to Geiger and Marsden's. In an alpha-particle scattering experiment, about 1 in 20 000 alpha particles were scattered by more than 150° . This is taken to mean that the particle had scored a 'direct hit' on the nucleus. The thickness of the carbon foil is $2 \mu\text{m}$.
- Given that the diameter of a carbon atom is $1.5 \times 10^{-10} \text{ m}$, calculate how many atoms thick the foil is.

- b)** Assuming that the probability of an alpha particle making a direct hit on the nucleus is proportional to the thickness of the foil, deduce what fraction of the alpha particles would have been scattered by an angle of 150° or more, had the foil been one atom thick.
- c)** Now calculate the ratio of the cross-sectional area of the nucleus to the cross-sectional area of the atom.
- d)** Hence work out the upper limit of the diameter of a carbon nucleus. Explain why the nucleus is likely to be smaller than this estimate.