24 PARTICLE PHYSICS

24.1 Alpha-particle scattering experiment

Specification reference: 6.4.1

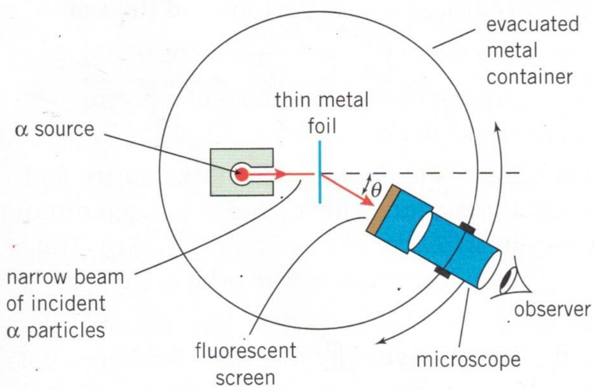
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → the alpha-particle scattering experiment
- → relative sizes of the atom and the nucleus.

Nuclear model

Englishman J. J. Thomson discovered the existence of the electron in 1897. He proposed that a neutral atom had an equal number of electrons and positive charges. How these charges were distributed was unknown at the time. In Thomson's 'plum-pudding' model, an atom contained negative electrons (the plums) embedded in a uniform sea of positive charge (the dough). All this changed in 1911 when Rutherford, Geiger, and Marsden – two New Zealanders and a German – experimentally showed that the positive charge of the atom existed in a tiny nucleus about 10^{-14} m in size, that is, most of the atom was empty space.



▲ **Figure 1** *Apparatus for the alpha-scattering experiment of Rutherford, Geiger, and Marsden*

Rutherford's alpha-scattering experiment

Figure 1 shows a simplified version of the arrangement used in Rutherford's experiments. A narrow beam of alpha particles, all of the same kinetic energy, from a radioactive source were targeted at a thin piece of gold foil which was only a few atomic layers thick. The alpha particles were scattered by the foil and detected on a zinc sulfide screen mounted in front of a microscope. Each alpha particle hitting this fluorescent screen produced a tiny speck of light. The microscope was moved around in order to count the number of alpha particles scattered through different values of the angle θ per minute, for θ from zero to almost 180°.

Observations and conclusions

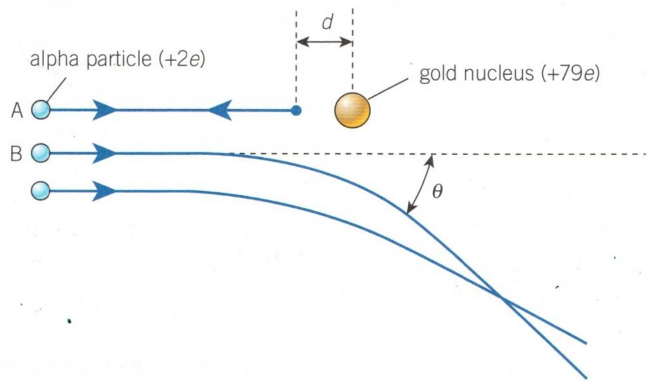
The scattering experiment led to the following two significant observations, which could not support Thomson's plum-pudding model of the atom.

- Most of the alpha particles passed straight through the thin gold foil with very little scattering. About 1 in every 2000 alpha particles was scattered.
- Very few of the alpha particles – about 1 in every 10 000 – were deflected through angles of more than 90°.

These significant observations can be explained in terms of a new model of the atom – the nuclear model. The first observation meant that most of the atom was empty space with most of the mass concentrated in a small region – the **nucleus**. The second observation led to the conclusion that the nucleus has a positive charge, because it repelled the few positive alpha particles that came near it. In fact, the charge on the nucleus is quantised and given by $+Ze$, where Z is the atomic number of the element (the proton number for the nucleus – see Topic 24.2, The nucleus) and e is the elementary charge 1.60×10^{-19} C.

Microscopic interactions

The scattering of the alpha particles from the gold nuclei can be modelled from Coulomb's law with the alpha particle having a charge $+2e$ and the gold nucleus having a charge $+Ze$.



▲ **Figure 2** *Scattering of alpha particles by the positive gold nucleus*

Figure 2 shows the paths of some alpha particles as they pass close to the heavy gold nucleus. The alpha particle A makes a head-on collision with the nucleus and rebounds back with a scattering angle 180°. The minimum distance between the alpha particle and the gold nucleus is d. The probability of such a collision is very small because of the tiny diameter of the nucleus. The alpha particle B makes an oblique collision with the nucleus and is scattered through an angle θ.

Sizes of the atom and the nucleus

Rutherford predicted the fraction of alpha particles that would be scattered through an angle θ. He found that departures from his predictions started to occur for more energetic alpha particles that managed to get much closer to the nucleus. From his experiments, Rutherford concluded that the nucleus had a radius of about 10^{-14} m.

In one of the experiments, Rutherford used alpha particles of kinetic energy 1.2×10^{-12} J (about 7.7 MeV). The distance d of closest approach between an alpha particle and the gold nucleus can be calculated using the idea of conservation of energy. At this distance, the alpha particle momentarily stops. Therefore

initial kinetic energy of alpha particle = electrical potential energy at distance d

$$1.2 \times 10^{-12} = \frac{Qq}{4\pi\varepsilon_0 d} \qquad (Q = Ze = 79e \text{ and } q = 2e)$$

$$1.2 \times 10^{-12} = \frac{79 \times 2 \times (1.60 \times 10^{-19})^2}{4\pi \times 8.85 \times 10^{-12} \times d}$$

$$d = 3.0 \times 10^{-14} \approx 10^{-14}\,\text{m}$$

This calculation gives an *upper limit* for the radius of the gold nucleus. More energetic alpha particles might get closer. In Topic 24.2, The nucleus, you will see that the order of magnitude value for the radius of a nucleus is about 10^{-15} m. The radius of most atoms is about 10^{-10} m. So the nucleus is about 10^5 times smaller than the atom. If a nucleus is represented by a dot of diameter 1 mm, then the outermost electron of the atom would be 100 m away!

Rutherford's modelling

One of Rutherford's predictions, based on electrostatic repulsion between the alpha particle and the gold nucleus, was that the number N of alpha particles scattered through an angle θ was inversely proportional to $\sin^4\left(\frac{\theta}{2}\right)$ (You do not need to recall this for this course). Table 1 shows some of the actual results collected by Geiger and Marsden, working under Rutherford's direction.

▼ **Table 1** *Number N of alpha particles scattered through angle θ*

θ/°	15	30	45	60	120	150
N	132 000	7800	1435	477	52	33

1 Suggest why only a small number of alpha particles were scattered through large angles.
2 Calculate the force experienced by an alpha particle at a distance of 10^{-14} m from the centre of the gold nucleus.
3 Use the table to show that N is inversely proportional to $\sin^4\left(\frac{\theta}{2}\right)$.

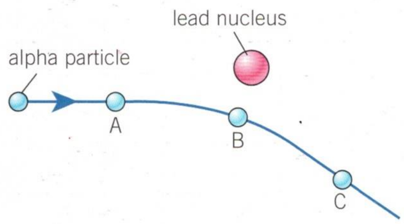
Summary questions

1 In Rutherford's alpha-scattering experiment, most of the alpha particles were not scattered. What can you conclude about the nature of atoms? *(1 mark)*

2 State the approximate radii of the atom and the nucleus. *(1 mark)*

3 In a visual model of the atom, the nucleus is represented by an apple of diameter 8 cm. Estimate the diameter of the atom in this model. *(2 marks)*

4 Figure 3 shows the path of an alpha particle close to the nucleus of lead. Draw arrows to represent the force on the alpha particle when at points A, B, and C. *(2 marks)*



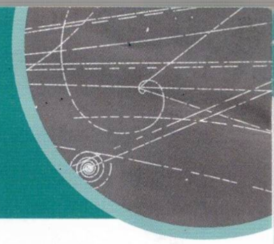
▲ **Figure 3**

5 Alpha particles of kinetic energy 8.8 MeV are fired at lead atoms. The charge on the nucleus of lead is 82e. Calculate:
 a the minimum distance the alpha particles approach to the nucleus of lead *(4 marks)*
 b the maximum electrostatic force experienced by the alpha particle. *(3 marks)*

6 A tiny droplet of oil diameter 1.0 mm is placed on water. The oil spreads out as a circular disc of thickness approximately one atom thick. Estimate the radius of this oil disc. *(3 marks)*

24.2 The nucleus

Specification reference: 6.4.1



Neutrons

In 1930, Bothe and Becker in Germany bombarded a beryllium target with alpha particles. They noticed that a very penetrating, non-ionising radiation was emitted from beryllium. They incorrectly assumed that they were observing gamma rays. In 1932 in Cambridge, Chadwick showed that the alpha particles hitting the beryllium nuclei were knocking **neutrons** from its nuclei. Chadwick was awarded the 1935 Nobel Prize for Physics for his discovery of the neutron. Neutrons carry no charge and exist in all nuclei except hydrogen.

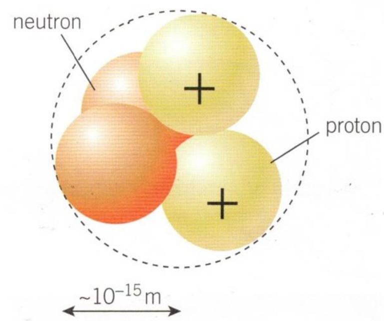
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → the simple nuclear model of the atom
- → protons, neutrons, and electrons
- → proton number, nucleon number, isotopes, notation for the representation of nuclei
- → the strong nuclear force and its short-range nature
- → radius of nuclei – $R = r_0 A^{\frac{1}{3}}$
- → mean densities of atoms and nuclei.

The nuclear model of the atom

The nucleus of an atom contains positive protons and uncharged neutrons. Figure 1 shows a helium nucleus. The proton and the neutron have approximately the same mass. The term **nucleon** is used to refer to either a proton or a neutron. The proton has a charge of $+e$, where e is the elementary charge. A neutral atom has the same number of electrons and protons.



▲ **Figure 1** *A helium nucleus (alpha particle) with two protons and two neutrons*

Isotopes

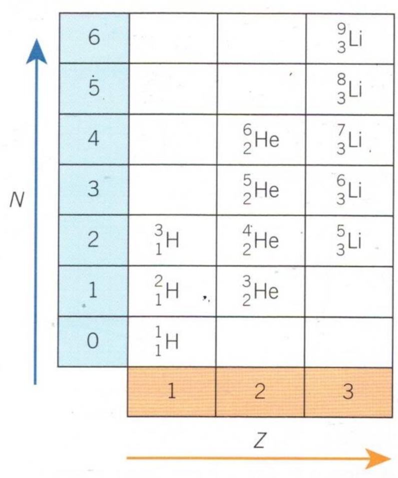
The nucleus of an atom for a particular element is represented as

$$^{A}_{Z}\mathrm{X}$$

where X is the chemical symbol for the element, A is the **nucleon number** (the total number of protons and neutrons), and Z is the **proton number** (also known as **atomic number**). The number of neutrons N in the nucleus is thus $N = (A - Z)$.

Isotopes are nuclei of the same element that have the same number of protons but different numbers of neutrons. All isotopes of an element undergo the same chemical reactions.

The grid in Figure 2 shows the isotopes of hydrogen (H), helium (He), and lithium (Li).



▲ **Figure 2** *Some isotopes shown by proton and neutron number on an N–Z grid*

Atomic mass units

The masses of atoms and nuclear particles are often expressed in **atomic mass units** (u). One atomic mass unit (1 u) is one-twelfth the mass of a neutral carbon-12 atom (Table 1). The experimental value of 1 u is about 1.661×10^{-27} kg.

▼ **Table 1** *The masses of some particles in atomic mass units (u), where 1 u = 1.661×10^{-27} kg.*

Particle	electron	proton	neutron	helium-4 nucleus	carbon-12 nucleus	iron-56 nucleus	uranium-235 nucleus
Mass / u	0.00055	1.00728	1.00867	4.00151	11.99671	55.79066	234.99343

Study tip

The approximate mass of a particle is its nucleon number in atomic mass units. For example, the mass of a carbon-12 nucleus ≈ 12 u and the mass of a uranium-235 nucleus ≈ 235 u.

Nuclear size and density

The radius of the nucleus depends on the nucleon number A of the nucleus. Fast-moving electrons have a de Broglie wavelength of about 10^{-15} m. Diffraction of such electrons has been used to determine the radii of isotopes. Experiments have shown that the radius R of a nucleus is given by the equation

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

where r_0 has an approximate value of 1.2 fm (1 fm = 10^{-15} m). The simplest nucleus is that of hydrogen – ${}^{1}_{1}\mathrm{H}$, with $A = 1$. You can therefore think of r_0 as roughly the radius of a proton.

The nucleus of an atom is very small, massive, and hence extremely dense. All nuclei have a density of about 10^{17} kg m^{-3} – about 10^{14} times denser than water. A spoonful of nuclear material would have a mass of about a thousand million tonnes. Ordinary matter, made of atoms and not just nuclei, has a density of around 10^3 kg m^{-3}.

Synoptic link

You first met the de Broglie equation in Topic 13.4, Wave–particle duality.

Worked example: Density of a helium nucleus

Calculate the approximate density of a helium-4 nucleus and of a helium atom.

Step 1: Calculate the volume of the helium-4 nucleus.

$$\text{volume of nucleus} = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(r_0 A^{\frac{1}{3}})^3 = \frac{4}{3}\pi r_0{}^3 A$$

$$\text{volume of nucleus} = \frac{4}{3}\pi \times (1.2 \times 10^{-15})^3 \times 4 = 2.895... \times 10^{-44}\,\text{m}^3$$

Step 2: The approximate mass of the helium-4 nucleus is 4 u, and density = $\frac{\text{mass}}{\text{volume}}$.

$$\text{density of nucleus} = \frac{4 \times 1.661 \times 10^{-27}}{2.895... \times 10^{-44}} = 2.3 \times 10^{17}\,\text{kg m}^{-3}\ \text{(2 s.f.)}$$

Step 3: The mass of the electrons is negligible, so the mass of the helium atom is about 4 u. It has a radius of about 10^{-10} m.

$$\text{density of atom} = \frac{4 \times 1.661 \times 10^{-27}}{\frac{4}{3}\pi \times (10^{-10})^3} = 1.6\,\text{kg m}^{-3}\ \text{(2 s.f.)}$$

Synoptic link

You can review this law in Topic 22.2, Coulomb's law.

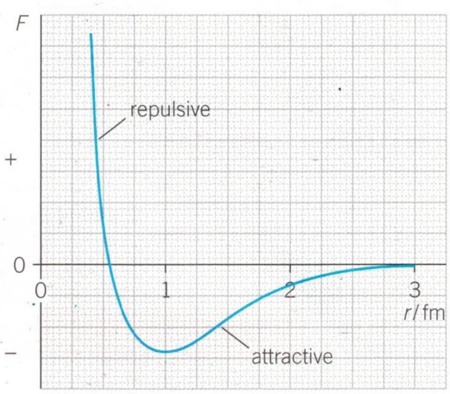
Nature of the strong nuclear force

In a helium-4 nucleus, the two protons are separated by a distance of about 10^{-15} m and exert a large repulsive electrostatic force on each other. According to Coulomb's law, the repulsive electrostatic force F is given by

$$F = \frac{Qq}{4\pi\varepsilon_0 r^2}$$

$$= \frac{(1.60 \times 10^{-19})^2}{4\pi \times 8.85 \times 10^{-12} \times (10^{-15})^2} \approx 230\,\text{N}$$

This is an extremely large repulsive force, so why do the protons not fly apart? The attractive gravitational force between the protons is far too small (about 10^{-34} N) to keep them together, so there must be another, much stronger force acting on the protons. This force is the **strong nuclear force**.



▲ **Figure 3** *A graph showing how the nuclear force F varies with separation r for two nucleons*

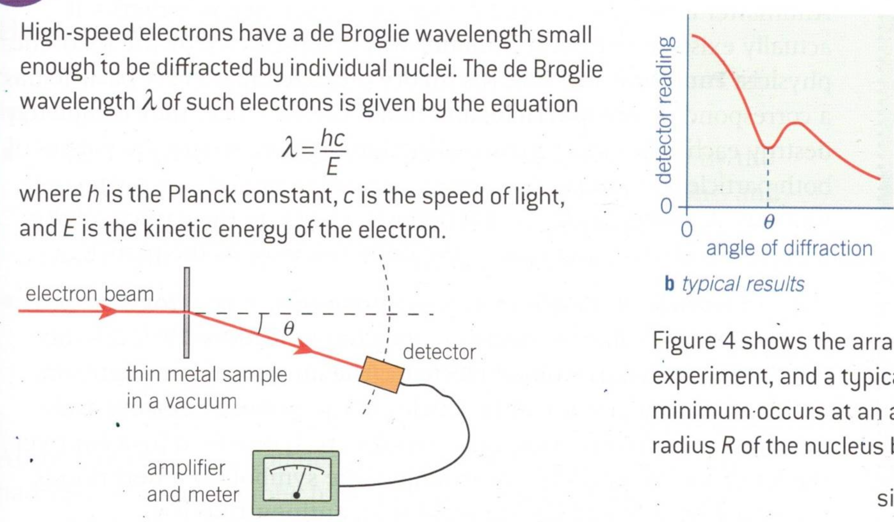
The strong nuclear force acts between all nucleons. It is a very short range force, effective over just a few femtometres. Figure 3 shows the variation of the strong nuclear force F between two nucleons with separation r. The force is attractive to about 3 fm and repulsive below about 0.5 fm.

Nuclear radii

High-speed electrons have a de Broglie wavelength small enough to be diffracted by individual nuclei. The de Broglie wavelength λ of such electrons is given by the equation

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

where h is the Planck constant, c is the speed of light, and E is the kinetic energy of the electron.



a *outline of experiment*

b *typical results*

Figure 4 *A high-speed electron diffraction experiment and a typical result*

Figure 4 shows the arrangement used to carry out the experiment, and a typical result. The first diffraction minimum occurs at an angle θ, which is related to the radius R of the nucleus by the equation

$$\sin\theta = \frac{0.61\lambda}{R}$$

1 Show that the radius R of a nucleus is given by the equation

$$R = \frac{0.61hc}{E\sin\theta}$$

2 Electrons of energy 420 MeV give a diffraction minimum angle of 44° for oxygen-16 nuclei. Calculate the radius R of the oxygen nucleus.

3 Compare your answer for R in the question above with the radius obtained using $R = r_0 A^{\frac{1}{3}}$.

Summary questions

1 State how many protons and neutrons there are in a helium-4 nucleus. *(1 mark)*

2 State how many protons, neutrons, and electrons there are in the atoms of the following isotopes:
a $^{6}_{2}He$; **b** $^{9}_{3}Li$; **c** $^{56}_{26}Fe$; **d** $^{235}_{92}U$. *(4 marks)*

3 Calculate the nuclear radii in fm of all the isotopes shown in question 2. *(4 marks)*

4 Calculate the approximate density of the uranium-235 nucleus. How does it compare with the value for helium-4 in the worked example? *(5 marks)*

5 A neutron star of mass 4.0×10^{30} kg has a radius of about 12 km. Calculate its mean density. Comment on the answer. *(3 marks)*

6 For two protons separated in the nucleus of an atom by a distance of about 10^{-15} m, calculate the ratio gravitational force on proton/electrostatic force on proton. *(4 marks)*

7 According to a student, the mean density of a nucleus is independent of its nucleon number A. Deduce whether or not this assumption is correct. *(3 marks)*