Chapter 12
Atomic structure

Worksheet

Worked examples

Practical: Simulation (applet) websites – Rutherford's -scattering experiment, and all known isotopes

End-of-chapter test

Marking scheme: Worksheet

Marking scheme: End-of-chapter test

Worksheet

speed of light in vacuum $c = 3.0 \quad 10^{8}\,\mathrm{m\,s^{-1}}$
Planck constant $h = 6.63 \quad 10^{-34}\,\mathrm{J\,s}$
mass of electron $= 9.1 \quad 10^{-31}\,\mathrm{kg}$
mass of neutron $= 1.7 \quad 10^{-27}\,\mathrm{kg}$

Intermediate level

1 State what may be concluded about the structure of the atom from the following observations made in the Rutherford -scattering experiment:

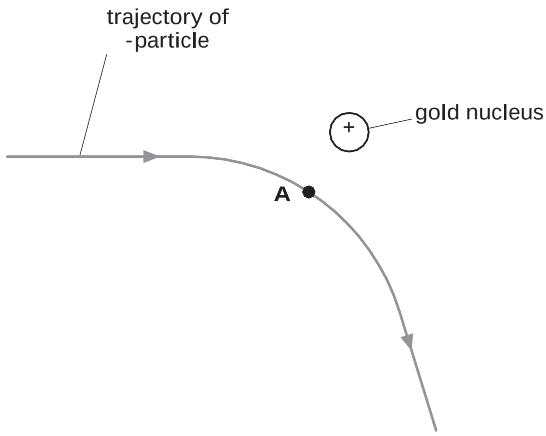
a Most of the -particles went straight through the gold foil without much scatter. [1]

b A very small percentage of the positively charged -particles were scattered through large angles by the gold foil. [2]

2 The diagram shows the trajectory of an -particle as it travels past the nucleus of a gold atom.

a Copy the diagram, adding arrows to show the directions and magnitudes of the forces experienced by the gold nucleus and the -particle when the -particle is at point **A**. [2]

b State a value for the typical size (diameter) of the nucleus. [1]



3 Define the following terms:

a proton (atomic) number; [1]

b nucleon (mass) number; [1]

c isotopes. [1]

4 A nuclide of carbon-14 has six protons and eight neutrons. The chemical symbol for carbon is C.

a What is the nucleon number for this nuclide? [1]

b How many electrons are there in a neutral atom of carbon-14? [1]

c Represent this nuclide in the form ${}^{A}_{Z}\mathrm{X}$. [1]

5 Represent each of the nuclides below in the form ${}^{A}_{Z}\mathrm{X}$:

a a uranium nucleus with 143 neutrons and 92 protons (chemical symbol: U); [2]

b an -particle, which has 2 protons and 2 neutrons (chemical symbol: He); [2]

c a lithium nucleus with 5 neutrons and 3 protons (chemical symbol: Li). [2]

Higher level

6 Name three techniques for investigating the crystalline structure of matter. [3]

7 High-speed electrons are diffracted by atomic nuclei.

a Suggest what electron diffraction demonstrates about the nature of high-speed electrons. [1]

b Suggest a typical wavelength for the high-speed electrons used to investigate the size of atomic nuclei. [1]

8 The spacing between the atoms in a solid is typically 2.0 10^{-10} m. For diffraction of either X-rays or particles by the solid, the incident wavelength must be comparable to or less than this spacing. For a wavelength of 2.0 10^{-10} m, calculate:

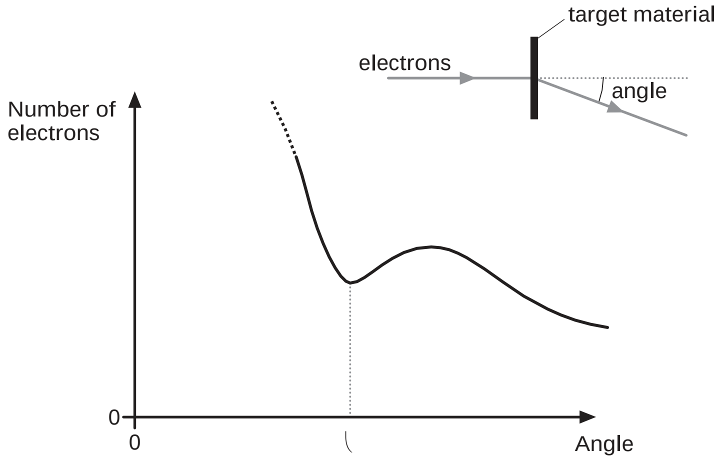
a the frequency of X-rays; [2]

b the speed of electrons; [2]

c the speed of neutrons. [2]

Extension

9 The diagram shows the typical diffraction pattern formed when high-speed electrons are diffracted by the nuclei of a target material.



The angle for the 'first diffraction minimum' is related to the diameter *d* of a single nucleus and the de Broglie wavelength ⌊ of a high-speed electron by the equation:

$$\sin \ = \frac{1.22⌊}{d}$$

The wavelength ⌊ of a high speed electron is related to its kinetic energy *E*, the Planck constant h and the speed of light in vacuum *c* by the equation:

$$⌊ = \frac{hc}{E}$$

a The angle is 52° for 420 MeV electrons fired into carbon. Determine the diameter of a nucleus of carbon. (1 eV = 1.6 10^{-19} J.) [4]

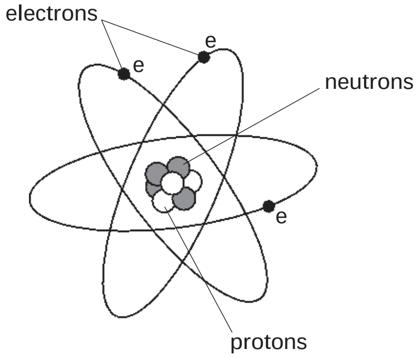
b The mass of a single nucleus of carbon is 2.0 10^{-26} kg. Determine the mean density of the carbon nucleus. [3]

c The density of matter is about 10^3 kg m^{-3}. What does your value for the density of the nucleus suggest about the structure of atoms? [2]

Total: $\frac{\quad}{38}$ Score: %

Worked examples

Example 1



One of the isotopes of lithium is ${}^{7}_{3}\mathrm{Li}$.

Determine the number of protons and neutrons within the nucleus of this isotope.

What is the new representation of the nuclide when two extra neutrons are added to the isotope ${}^{7}_{3}\mathrm{Li}$?

The 'lower' number denotes the number of protons, Z. Hence:

$Z = 3$

The nucleon number, A (the 'upper' number), for the isotope is 7. The number of neutrons, N, is therefore given by:

$N = A - Z = 7 - 3 = 4$

The nucleon number A is the total number of neutrons and protons. Hence:

$$A = N + Z$$

where N is the number of neutrons and Z is the proton number.

When two neutrons are added to the isotope, the total number of nucleons becomes 9. Therefore, the nucleon number will increase by 2. The new isotope of lithium is ${}^{9}_{3}\mathrm{Li}$.

> **Tip**
>
> The isotope is still that of lithium because the proton number Z is the same. There is no chemical difference between the isotopes of lithium.

Example 2

Scientists use the diffraction of neutrons to investigate the molecular structure of complex proteins. The neutrons have a wavelength comparable to the size of the protein molecules. Choose the appropriate wavelength from the list below and estimate the speed of the neutrons. (Mass of a neutron $= 1.7 \times 10^{-27}$ kg; Planck constant $h = 6.63 \times 10^{-34}$ J s.)

1.5×10^{-4} m 1.5×10^{-9} m 1.5×10^{-10} m

The correct wavelength λ from the list is 1.5×10^{-9} m.

The size of the molecules must be greater than the size of an atom (10^{-10} m).

The wavelength of the neutron is given by the de Broglie equation:

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

Hence:

$$v = \frac{h}{m\lambda} = \frac{6.63 \times 10^{-34}}{1.7 \times 10^{-27} \times 1.5 \times 10^{-9}}$$

$v = 260\ \mathrm{m\,s^{-1}}$

> **Tip**
>
> The de Broglie equation is studied in the 2822 module on Electrons and Photons. However, the specification for the 2824 module on Forces, Fields and Energy can legitimately ask questions related to this important equation.

Practical

Simulation (applet) websites – Rutherford's -scattering experiment, and all known isotopes

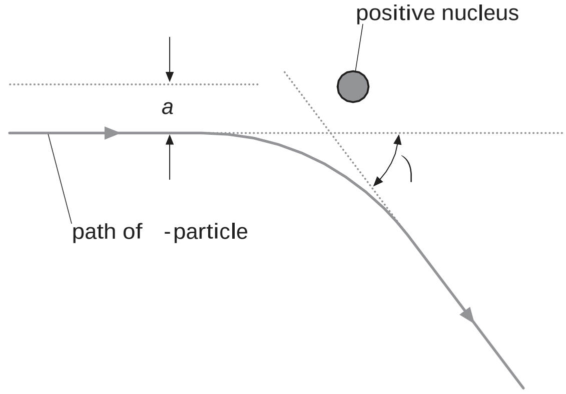
Introduction

The Internet provides free access to a range of simulations (applets) of experiments that are either difficult to perform in an A2 Physics laboratory or difficult to 'visualise'. The applets below may be used to support the work being done in the classroom.

Rutherford's -scattering experiment

http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/rutherford/rutherford.html

- This applet shows how a single -particle is scattered by a massive positive nucleus.
- The -particle is fired 'randomly' towards the nucleus.
- The applet may be used to provide a better understanding of how the scatter angle is related to the 'aiming distance' *a* (see diagram).



- Some possible questions:
  – What happens to the scatter angle as the 'aiming distance' decreases?
  – When do you get a scatter angle of 180°?

http://ap.polyu.edu.hk/Our%20Applets/RutherfordScattering/Scattering.html

- This applet is much more detailed. You can investigate how the proton number of the nucleus and the speed of the -particles affect the scattering of the -particles.
- The applet takes some time to produce the results. It is therefore best to start the simulation and then come back to the final conclusions.
- Some possible questions:
  – How is the scattering of the -particles affected by an increase in the proton number of the target nucleus?
  – How is the scattering of the -particles affected by their speed?

Isotopes

http://ie.lbl.gov/education/isotopes.htm

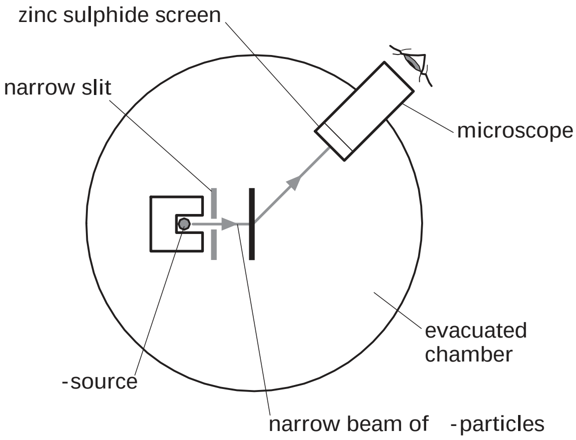
- This website lists all the known isotopes.
- At a click of the button, you can look up isotopes and investigate common features.
- Some possible questions:
  – How many isotopes does helium have?
  – What happens to the number of isotopes as the atomic (proton) number increases?

End-of-chapter test

Answer all questions.

speed of light in vacuum $c = 3.0 \quad 10^8$ m s^{-1}
Planck constant $h = 6.63 \quad 10^{-34}$ J s
mass of electron = $9.1 \quad 10^{-31}$ kg

1 The diagram shows the apparatus used by Rutherford in his -scattering experiment. Explain why:



a the gold foil and the -source were placed in a vacuum; [1]

b the gold foil had to be very thin. [1]

2 List the three key conclusions about the nature of the atom that can be drawn from the -scattering experiment. [3]

3 Two isotopes of oxygen are shown below:

$^{17}_{8}\text{O}$ $\quad$ $^{18}_{8}\text{O}$

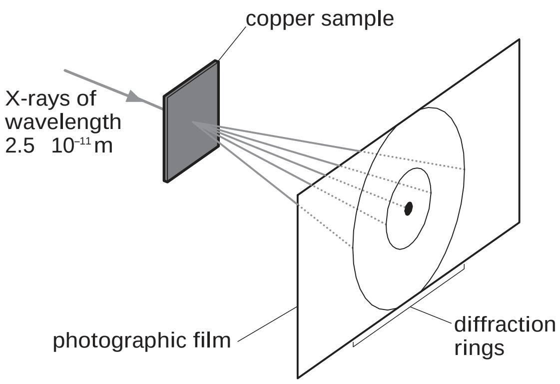
a What is an isotope? [1]

b State the number of protons within the nuclide $^{17}_{8}\text{O}$. [1]

c Name two ways in which the isotopes above are similar. [2]

d One extra neutron is added to the nuclide $^{18}_{8}\text{O}$. Write down the new nuclear representation of the nuclide. [1]

4 The diagram shows the diffraction 'rings' produced when X-rays of wavelength $2.5 \quad 10^{-11}$ m are diffracted by a thin sample of copper.



a What causes the diffraction of the X-rays? [1]

b State the approximate size (diameter) of an atom in metres. [1]

c A similar diffraction pattern is obtained when **electrons** are fired into the copper sample. Estimate the speed of an electron with a de Broglie wavelength the same as that for the X-rays above. [2]

d Explain why the diffraction pattern formed by the electrons of wavelength $2.5 \quad 10^{-11}$ m cannot be due to the atomic nuclei of copper. [1]

Total: $\frac{\quad}{15}$ Score: %

Marking scheme

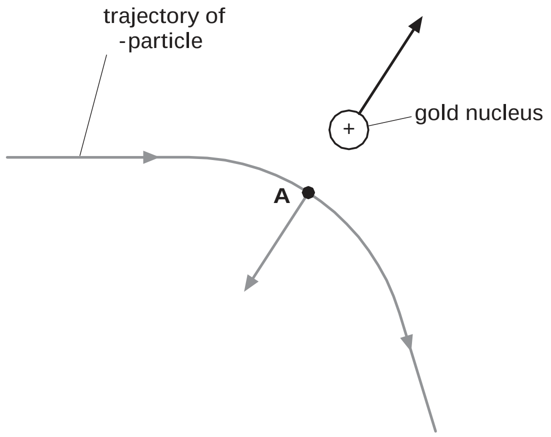
Worksheet

1 **a** Most of the atom is empty space (vacuum). [1]

b The atom has a positive nucleus because it repels the -particles. [1]

The massive nucleus is very small in diameter (<10^{-15} m) compared to the whole atom. [1]

2 **a**



Arrows in opposite in directions. [1]

Equal-sized arrows. [1]

b The size (diameter) of the nucleus is from 10^{-15} m to 10^{-14} m. [1]

3 **a** Proton number is the number of protons within the nucleus. [1]

b Nucleon number is the total number of protons and neutrons within the nucleus. [1]

c The isotopes of an element have nuclei with the same number of protons but different numbers of neutrons. [1]

4 **a** Nucleon number $A = 6 + 8 = 14$ [1]

b The number of electrons is equal to the number of protons; therefore a neutral atom of carbon-14 has 6 electrons. [1]

c ${}^{14}_{6}\mathrm{C}$ [1]

5 **a** $A = 143 + 92 = 235$ [1]; ${}^{235}_{92}\mathrm{U}$ [1]

b $A = 2 + 2 = 4$ [1]; ${}^{4}_{2}\mathrm{He}$ [1]

c $A = 5 + 3 = 8$ [1]; ${}^{8}_{3}\mathrm{Li}$ [1]

6 X-ray diffraction. [1]

Electron diffraction. [1]

Neutron diffraction. [1]

7 **a** Electrons travel through space as ‘waves’ (known as de Broglie or matter waves). [1]

b For diffraction, the de Broglie wavelength of an electron must be comparable to the size (diameter) of the nucleus. The high-speed electrons must have a wavelength of the order of 10^{-15} m. [1]

8 **a** $c = f \quad$ so $\quad f = \dfrac{3.0 \quad 10^{8}}{2.0 \quad 10^{-10}}$ [1]

$f = 1.5 \quad 10^{18}$ Hz [1]

b The de Broglie wavelength $\quad = \dfrac{h}{mv} \quad$ so $\quad v = \dfrac{h}{m} = \dfrac{6.63 \quad 10^{-34} \quad 10^{-}}{9.1 \quad ^{31} \quad 2.0 \quad 10^{-10}}$ [1]

$v = 3.64 \quad 10^{6}\,\mathrm{m\,s^{-1}} \quad 3.6 \quad 10^{6}\,\mathrm{m\,s^{-1}}$ [1]

c $\quad = \dfrac{h}{mv} \quad$ so $\quad v = \dfrac{h}{m} = \dfrac{6.63 \quad 10^{-34} \quad 10^{-}}{1.7 \quad ^{27} \quad 2.0 \quad 10^{-10}}$ [1]

$v = 1.95 \quad 10^{3}\,\mathrm{m\,s^{-1}} \quad 2.0 \quad 10^{3}\,\mathrm{m\,s^{-1}}$ [1]

9 **a** $\sin \quad = \dfrac{1.22}{d} \quad$ and $\quad = \dfrac{hc}{E}$

Therefore $\sin \quad = \dfrac{1.22hc}{Ed}$ [1]

$E = 420\,\mathrm{MeV} = 420 \quad 10^{6} \quad 1.6 \quad 10^{-19} = 6.72 \quad 10^{-11}$ J [1]

$d = \dfrac{1.22hc}{E \sin} = \dfrac{1.22 \quad 6.63 \quad 10^{-34} \quad 3.0 \quad 10^{8}}{6.72 \quad 10^{-11} \quad \sin 52°}$ [1]

$d = 4.58 \quad 10^{-15}\,\mathrm{m} \quad 4.6 \quad 10^{-15}\,\mathrm{m}$ [1]

b $\text{Density} = \dfrac{\text{mass}}{\text{volume}}$ [1]

$\text{density} = \dfrac{2.0 \quad 10^{-26}}{\frac{4}{3} \quad r^{3}} = \dfrac{2.0 \quad 10^{-26}}{\frac{4}{3} \quad (2.29 \quad 10^{-15})^{3}} \quad (r = \dfrac{d}{2})$ [1]

$\text{density} = 3.98 \quad 10^{17}\,\mathrm{kg\,m^{-3}} \quad 4.0 \quad 10^{17}\,\mathrm{kg\,m^{-3}} < 10^{17}\,\mathrm{kg\,m^{-3}}$ [1]

c Matter is composed of atoms. Most of the space of the atoms is vacuum. [1]

The nucleons are densely packed within the nuclei, hence the extremely high density. [1]

Marking scheme

End-of-chapter test

1 **a** So that the -particles could not collide with and be scattered by air molecules. [1]

b In order to reduce the chance of an -particle being scattered by several gold nuclei. [1]

2 The atom:

- contains a positively charged nucleus; [1]
- has a very small nucleus ($< 10^{-15}$ m) compared with the diameter of the atom; [1]
- has most of its mass in the nucleus. [1]

3 **a** Isotopes are nuclides of a particular element that have the same number of protons but different numbers of neutrons. [1]

b Eight protons. [1]

c Both belong to the same chemical element; [1]

and have the same number of protons. [1]

d The nucleon number will increase by 1. Hence the new nuclide is $^{19}_{8}$O. [1]

4 **a** Diffraction is due to ordered arrays of copper atoms with spacing between planes similar to the wavelength of the X-rays. [1]

b The size (diameter) of an atom is about 10^{-10} m. [1]

c $= \frac{h}{mv}$ so $v = \frac{h}{m} = \frac{6.63 \quad 10^{-34} \quad 10^{-}}{9.1 \quad ^{31} \quad 2.5 \quad 10^{-11}}$ [1]

$v = 2.91 \quad 10^{7}$ m s^{-1} 2.9 10^{7} m s^{-1} [1]

d The wavelength of the electrons is much larger than the size (diameter) of the nuclei ($< 10^{-15}$ m). Therefore the diffraction seen is due to layers of copper atoms and not to the atomic nuclei of copper. [1]