11.1 The nuclear atom and isotopes

Name: _____ Class: _____ Date: _____ **Total: 27 marks**

KEY WORDS nucleus • proton number • nucleon number • isotope • unified atomic mass unit

Objective

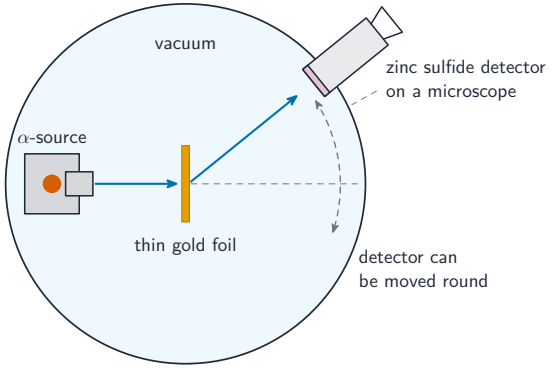
Answer exam questions on the **nuclear atom** : what the **α-particle scattering** α results prove, the model of protons, neutrons and orbital electrons, **nuclide** notation and **isotopes** , and masses in the **unified atomic mass unit** . Syllabus 11.1, learning outcomes 1 to 5 and 12.

You must be able to:

- infer from the α-scattering results that the atom has a nucleus, and that it is very small
- describe the nuclear atom: protons and neutrons in the nucleus, electrons in orbit around it
- use $^{A}_{Z}\mathrm{X}$ to count the protons, neutrons and electrons of an atom or an ion
- explain what isotopes are
- convert a mass between u and kg, and find the charge-to-mass ratio of a nucleus

1 Key knowledge and worked examples

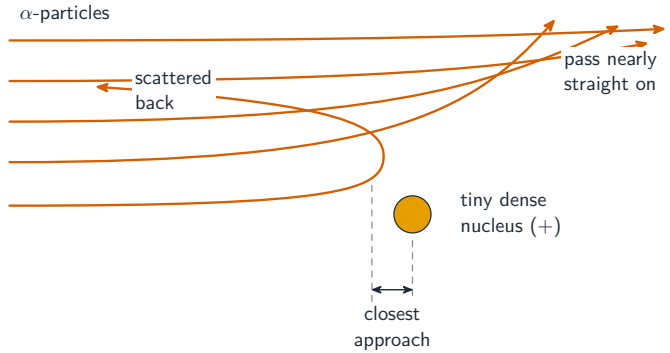
■ Key knowledge: the α-particle scattering experiment



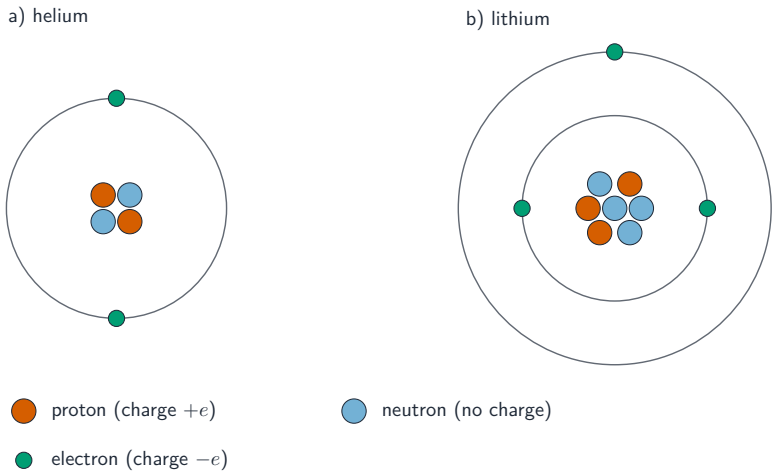
A beam of α-particles is fired at a thin gold foil in a vacuum, and a detector counts how many arrive at each angle. The mark scheme pairs each observation with one conclusion, so learn them as pairs.

observation	conclusion
almost all pass straight through	the atom is mostly empty space
a few are deflected through small angles	there is a concentrated positive charge
about 1 in 8000 turns through over 90°	charge and mass sit in a tiny nucleus

- The foil is **thin**, so each α-particle meets at most one nucleus.
- The chamber is **evacuated**, so the α-particles are not absorbed or scattered by air.



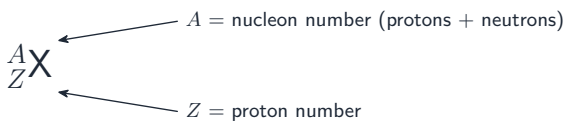
■ Key knowledge: the nuclear atom



particle	where	charge	mass
proton	nucleus	$+e$	about 1 u
neutron	nucleus	0	about 1 u
electron	in orbit	$-e$	about $\frac{1}{1840}$ u

- A nucleus is about 10^{-15} to 10^{-14} m across and an atom about 10^{-10} m, so the atom is tens of thousands of times wider than its nucleus.
- Almost all of the mass is in the nucleus, because a proton or a neutron is about 1840 times as massive as an electron.

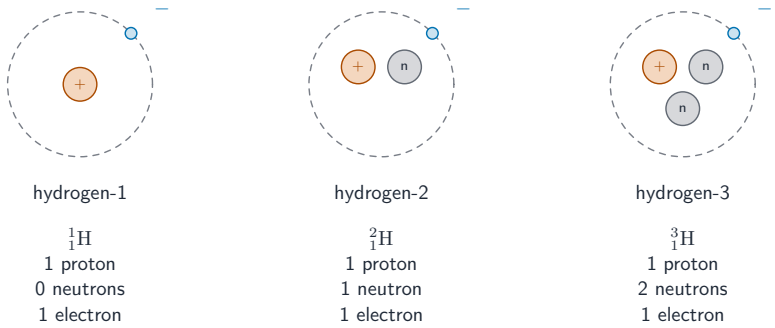
Key knowledge: nuclide notation and isotopes



symbol	name	what it counts
Z	**proton number**	protons; it fixes the element
A	**nucleon number**	protons plus neutrons
$N = A - Z$	neutron number	neutrons

- A **neutral atom** has Z electrons. An ion of charge $+ne$ has lost n of them, and one of charge $-ne$ has gained n.
- **Isotopes** are nuclides of the same element: the **same number of protons** but **different numbers of neutrons**.

Hydrogen isotopes (not to scale)



Worked example: counting the particles

Find the numbers of protons, neutrons and electrons in the ion $^{56}_{26}\mathrm{Fe}^{3+}$.

1. **Protons** – the proton number: $Z = 26$.
2. **Neutrons** – the nucleon number minus the proton number:
$$N = A - Z = 56 - 26 = 30$$
3. **Electrons** – the neutral atom has Z, and a charge of $+3e$ means three have been lost:
$$n_{\mathrm{e}} = Z - 3 = 26 - 3 = 23$$

Key knowledge: the unified atomic mass unit

- 1 u is **one twelfth of the mass of an atom of carbon-12**, and $1\ \mathrm{u} = 1.66 \times 10^{-27}$ kg.
- A proton and a neutron each have a mass of about 1 u, so a nucleus of nucleon number A has a mass of about A u.

Worked example: a mass in kg, and a charge-to-mass ratio

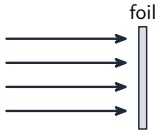
An α-particle is a nucleus of $^{4}_{2}\mathrm{He}$: two protons and two neutrons.

1. **Mass** – about A u, converted to kilograms:
$$m = A \times 1\ \mathrm{u} = 4 \times 1.66 \times 10^{-27}\ \mathrm{kg} = 6.64 \times 10^{-27}\ \mathrm{kg}$$
2. **Charge-to-mass ratio** – the charge is $2e$, from the two protons:
$$\frac{Q}{m} = \frac{2e}{m} = \frac{2 \times 1.60 \times 10^{-19}\ \mathrm{C}}{6.64 \times 10^{-27}\ \mathrm{kg}} = 4.8 \times 10^{7}\ \mathrm{C\ kg^{-1}}$$
3. **Running it backwards** – a nucleus of 40 nucleons has the same ratio. Its mass is
$$m = A \times 1\ \mathrm{u} = 40 \times 1.66 \times 10^{-27}\ \mathrm{kg} = 6.64 \times 10^{-26}\ \mathrm{kg}$$
and its charge is Ze, so
$$Z = \frac{(Q/m) \times m}{e} = \frac{(4.8 \times 10^{7}\ \mathrm{C\ kg^{-1}})(6.64 \times 10^{-26}\ \mathrm{kg})}{1.60 \times 10^{-19}\ \mathrm{C}} = 19.9$$
4. **Round to a whole number** – a count of protons is a whole number, so $Z = 20$ and the nuclide is $^{40}_{20}\mathrm{Ca}$. Keep every figure until this last step.

2 Practice

Now use the methods above.

2.1 State **two** conclusions about the atom that were drawn from the α-particle scattering experiment. [2]



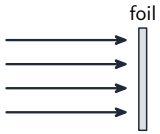
2.2 For a neutral atom of $^{14}_{6}C$, state the numbers of protons, neutrons and electrons. [2]

$^{14}_{6}C$

2.3 Define **isotopes**. [1]

isotopes

2.4 In the α-scattering experiment, explain why the gold foil must be **thin** and why the apparatus must be in a **vacuum**. [2]



2.5 State the numbers of protons, neutrons and electrons in the ion $^{35}_{17}Cl^{-}$. [3]

$^{35}_{17}Cl^{-}$

2.6 Calculate the mass, in kg, of a nucleus of $^{40}_{20}Ca$. [2]

$^{40}_{20}Ca$

3 Exam-style questions

3.1 Which statement about two isotopes of the same element is correct? [1]

isotopes

- ☐ **A** They have the same nucleon number but different proton numbers.
- **B** They have the same proton number but different numbers of neutrons.
- **C** They have the same number of neutrons but different numbers of protons.
- **D** Their neutral atoms have different numbers of electrons.

3.2 The mass of a certain nucleus is 3.99×10^{-26} kg. What is its nucleon number? [1]

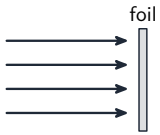
- ☐ **A** 12
- **B** 16
- **C** 24
- **D** 40

3.99×10^{-26} kg

3.3 In the α-particle scattering experiment, a beam of α-particles is directed at a thin gold foil.

(a) Describe what is observed for most of the α-particles, and state what this shows about the atom. [2]

(b) A very small fraction of the α-particles are deflected through more than 90°. Explain what this shows about the charge, the mass and the size of the nucleus. [3]



3.4 The unified atomic mass unit is 1.66×10^{-27} kg and the elementary charge is 1.60×10^{-19} C.

(a) State what is meant by the **unified atomic mass unit**. [1]

(b) Calculate the mass, in kg, of a nucleus of $^{7}_{3}\text{Li}$. [2]

1.66×10^{-27} kg

1.60×10^{-19} C

(c) A different nucleus has 27 nucleons and a charge-to-mass ratio of 4.6×10^{7} C kg^{-1}. Determine its number of protons and its number of neutrons. [3]

(d) The charge-to-mass ratio of a $^{4}_{2}\text{He}$ nucleus is 4.8×10^{7} C kg^{-1}. Explain why the nucleus in (c) has a slightly smaller ratio. [2]

Solutions

Each answer shows the steps, then the **result**.

2.1

- any two: the atom is **mostly empty space**; it has a **tiny nucleus**; the nucleus is **positively charged**; most of the atom's **mass** is in the nucleus

2.2

- protons $= Z = 6$, and a neutral atom has as many electrons, 6
- the neutron number is the nucleon number minus the proton number

$$N = A - Z = 14 - 6 = \mathbf{8}$$

2.3

- nuclides of the **same element**, with the same number of protons but **different numbers of neutrons**

2.4

- thin: so that each α-particle is scattered by **one nucleus at most** and is not absorbed in the foil
- vacuum: so that the α-particles are not **absorbed or scattered by air**, in which they travel only a few centimetres

2.5

- protons $= Z = \mathbf{17}$
- neutrons
$$N = A - Z = 35 - 17 = \mathbf{18}$$
- a charge of $-e$ means one electron has been gained

$$n_\mathrm{e} = Z + 1 = 17 + 1 = \mathbf{18}$$

2.6

- the mass of a nucleus is about A u

$$m = A \times 1\ \mathrm{u} = 40 \times 1.66 \times 10^{-27}\ \mathrm{kg} = \mathbf{6.64 \times 10^{-26}}\ \mathrm{kg}$$

3.1 B

- isotopes have the same proton number, so they are the same element, and different numbers of neutrons
- **A** describes two different elements; **D** is wrong because a neutral atom has Z electrons, the same for every isotope

3.2 C

- the mass of a nucleus is about A u, so

$$A = \frac{m}{1\ \mathrm{u}} = \frac{3.99 \times 10^{-26}\ \mathrm{kg}}{1.66 \times 10^{-27}\ \mathrm{kg}} = 24$$

3.3

(a) almost all of the α-particles pass **straight through** the foil, undeflected

- so the atom is **mostly empty space**

(b) such a large deflection needs a strong repulsion, so the nucleus carries a concentrated **positive charge**

- the α-particle is turned back, so the nucleus is **much more massive** than the α-particle
- it happens very rarely, so the nucleus is **very small** compared with the atom

3.4

(a) one twelfth of the mass of an atom of **carbon-12**

(b) the mass of a nucleus is about A u

$$m = A \times 1\ \mathrm{u} = 7 \times 1.66 \times 10^{-27}\ \mathrm{kg} = \mathbf{1.16 \times 10^{-26}}\ \mathrm{kg}$$

(c) the mass of the nucleus

$$m = A \times 1\ \mathrm{u} = 27 \times 1.66 \times 10^{-27}\ \mathrm{kg} = 4.48 \times 10^{-26}\ \mathrm{kg}$$

- its charge is Ze, so

$$Z = \frac{(Q/m) \times m}{e} = \frac{(4.6 \times 10^{7}\ \mathrm{C\ kg^{-1}})(4.48 \times 10^{-26}\ \mathrm{kg})}{1.60 \times 10^{-19}\ \mathrm{C}} = 12.9$$

- a whole number of protons, $Z = \mathbf{13}$, and then

$$N = A - Z = 27 - 13 = \mathbf{14}$$

(d) the ratio depends only on the number of protons per nucleon

- helium has 2 protons in 4 nucleons, exactly a half; this nucleus has 13 in 27, less than a half, because heavier nuclei have more neutrons than protons