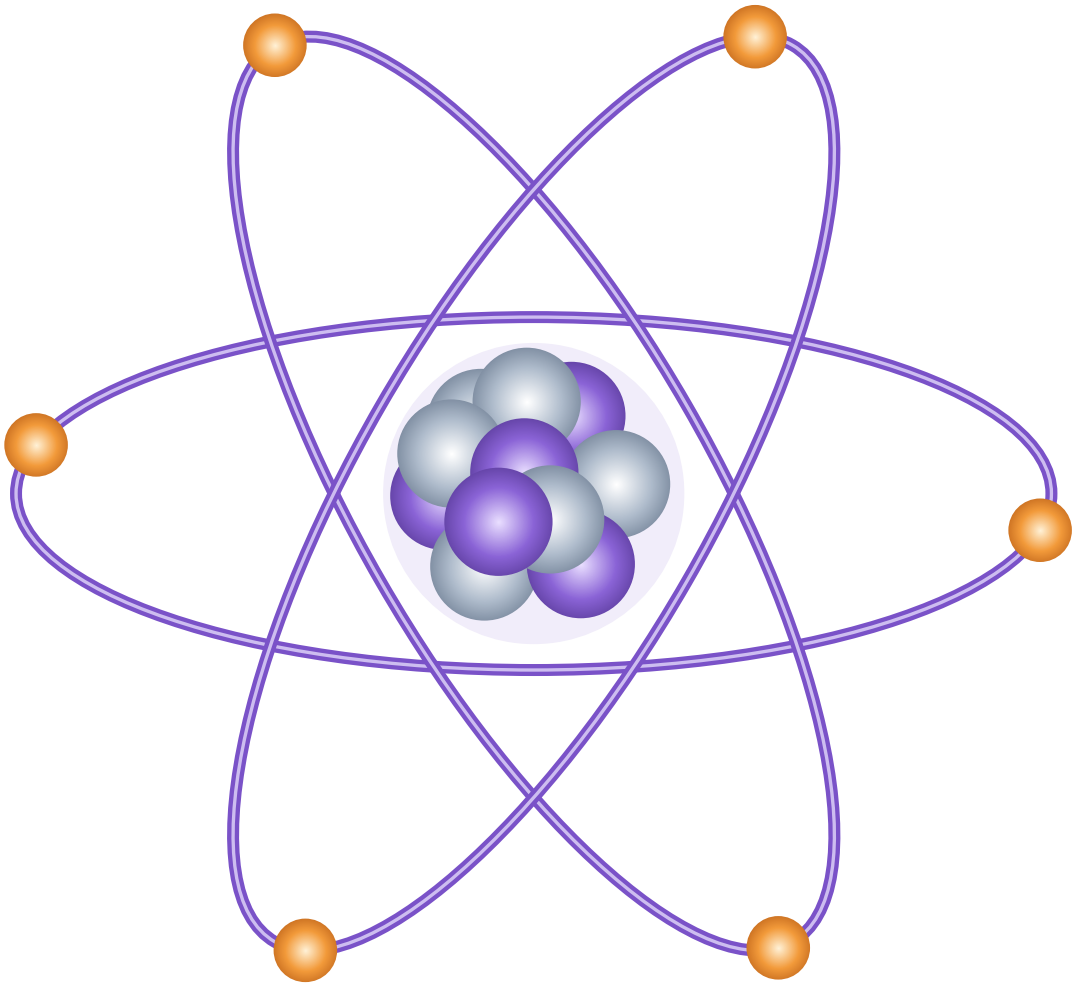
CHEMISTRY • HIGHER LEVEL

CHAPTER 2

Atomic Structure: The Nuclear Model



CHAPTER 2 / THE NUCLEAR MODEL

Atomic Structure: The Nuclear Model

Particulate nature of matter

All substances are made up of tiny, invisible particles. Depending on the substance, these can be **atoms,** molecules or ions.

Atom

The smallest particle of an element that still has the properties of that element.

Evidence for small particles

- Ammonia particles move from left to right and **hydrogen chloride** particles from right to left.
- A white, powdery ring of **ammonium chloride** forms where they meet.
- Hydrochloric acid is a solution of **hydrogen chloride** gas in water.



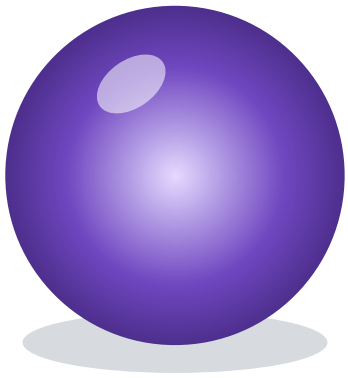
The Greek philosophers (~400 BC)

- First proposed that matter consists of tiny particles that cannot be broken down into simpler particles.
- Called these particles **atomos,** meaning **indivisible.** The word atom comes from this word.

Dalton's atomic theory (1808)

- John Dalton wrote a book explaining an atomic theory based on experiments with gases.
- All matter is made of very small particles called **atoms.**
- All **atoms** are **indivisible:** they cannot be broken down into simpler particles.
- Atoms were pictured as small, solid spheres, like snooker balls. Experiments towards the end of the 19th century began to question the theory.

Dalton's atom



A small, solid, indivisible sphere

Chapter objectives

Appreciate the key discoveries leading to the nuclear model. Understand how sub-atomic particles are arranged. Understand properties of **protons, neutrons** and **electrons.**

Discovery dates in Section 2.2 do not have to be remembered.

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Cathode rays & the electron

William Crookes (1875)

- Investigated an electric current passing through gases.
- Passed a current through air at low pressure in a vacuum tube.
- Rays came from the negative electrode, the **cathode,** and cast a Maltese-cross shadow at the far end. He called them **cathode rays.**
- The rays are invisible. Glass glows (fluoresces) when they strike it, except where the cross blocks them.
- Crookes did not know that the rays consisted of tiny charged particles.

Robert Millikan (1909)

- At the University of Chicago, used an oil drop experiment to measure the size of the electron's charge: 1.6×10^{-19} coulomb.
- Thomson's **charge-to-mass ratio** and Millikan's result allowed electron mass to be calculated: 9.1×10^{-31} kg.
- Received the 1923 Nobel Prize in Physics.

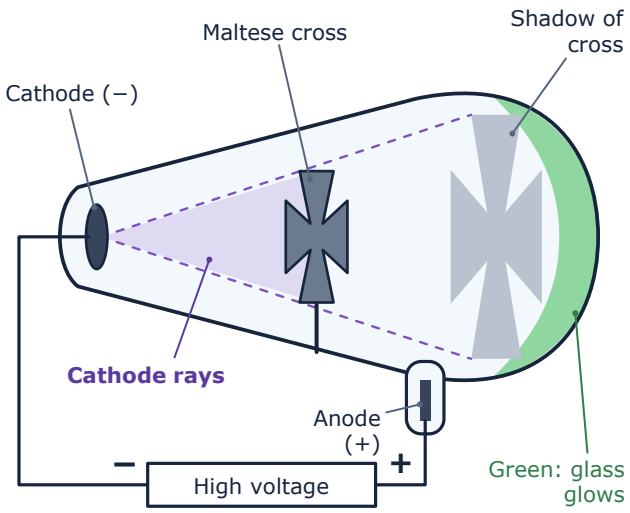
J. J. Thomson (1897)

- Investigated Crookes' **cathode rays** at Cambridge University's Cavendish Laboratory.
- Passed a narrow **cathode**-ray beam through a small hole in the positive electrode and between two parallel metal plates.
- The beam struck a fluorescent screen, producing a glowing spot.
- No charge on the plates: the beam travelled straight.
- Positive charge on the top plate: the spot moved upwards towards it.
- Unlike charges attract, so Thomson concluded that the particles were **negatively charged.** He called them **electrons.**
- The high voltage dragged **electrons** out of **cathode atoms.** They travelled towards the positive electrode.
- Measured the electron's **charge-to-mass ratio.** Received the 1906 Nobel Prize in Physics.

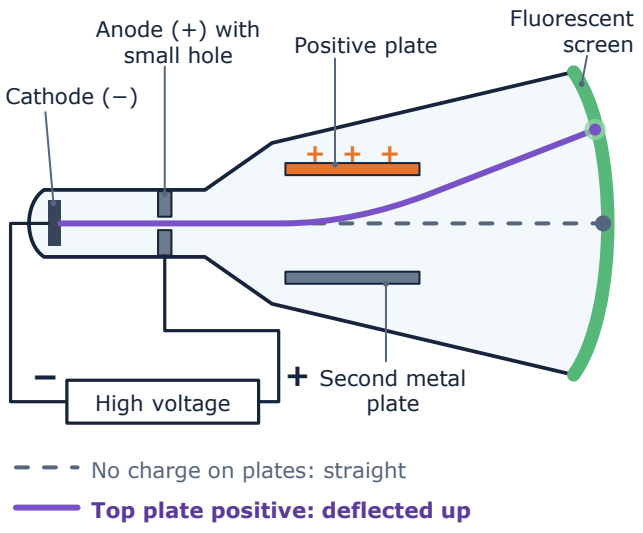
Cathode rays

Streams of **negatively charged** particles called **electrons.**

Crookes' tube



Thomson's apparatus



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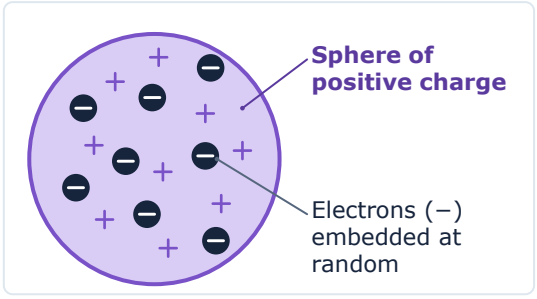
Plum pudding & the gold foil experiment

Thomson's plum-pudding model (1898)

- An atom is like a sphere of positive charge.
- Electrons are embedded at random in the sphere.
- Resembles raisins in a pudding or cake.
- Did not explain why **atoms** were **neutral** and had no experimental evidence to support it.



Rutherford's experiment (1909)

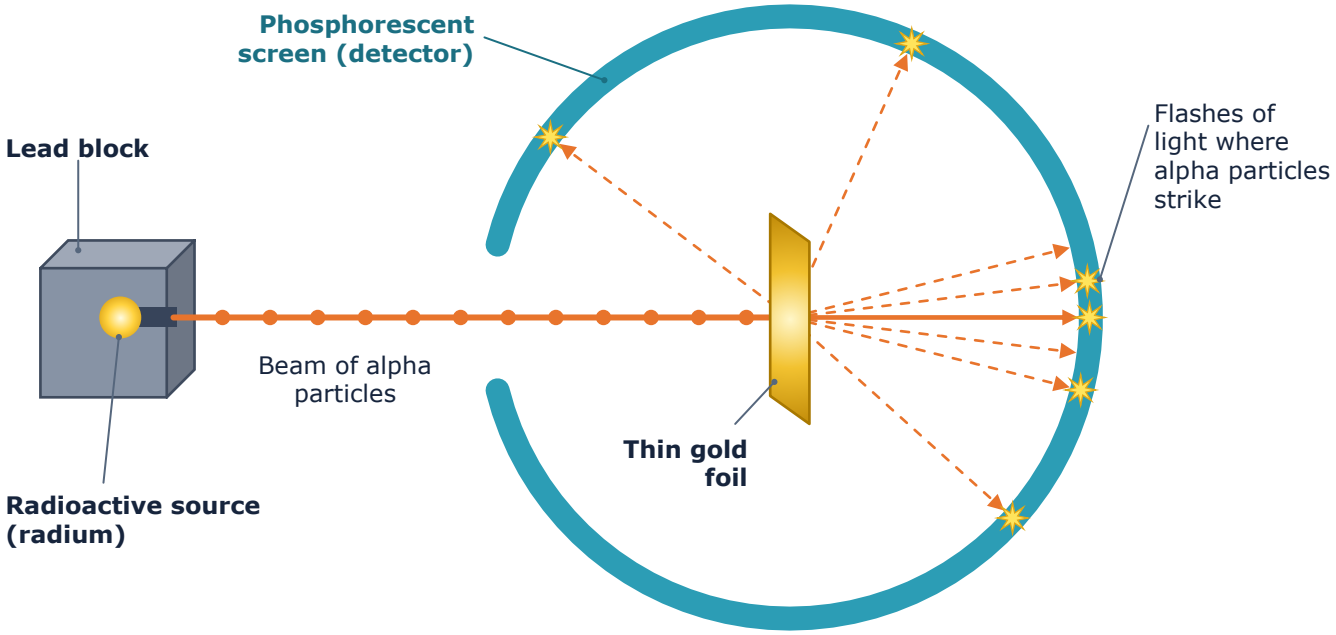
- Ernest Rutherford, from New Zealand, worked at Manchester University with two research students.
- Studied alpha particles given off by radioactive substances and directed them at a thin piece of gold foil.
- Used a **phosphorescent screen** to detect alpha particles: impacts produced little flashes of light, viewed through a microscope.
- The results showed that Thomson's model was not correct.
- Rutherford received the 1908 Nobel Prize in Chemistry for work on radioactivity.

Alpha particles

Positively charged groups of two **neutrons** and two **protons** stuck together: the **nucleus** of a helium atom.

Expected result

If positive charge were spread evenly throughout the atom, most alpha particles would pass through undeflected. A few would pass through with only slight deflections.



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Rutherford's results & the nucleus

Observations and conclusions

Observation	Conclusion
Most alpha particles pass straight through the gold foil.	Most of the atom is empty space.
Some alpha particles are deflected at large angles.	They are repelled when passing near the small, positive nucleus.
A small number of alpha particles are reflected back along their own paths.	A small number collide head-on with the nucleus.

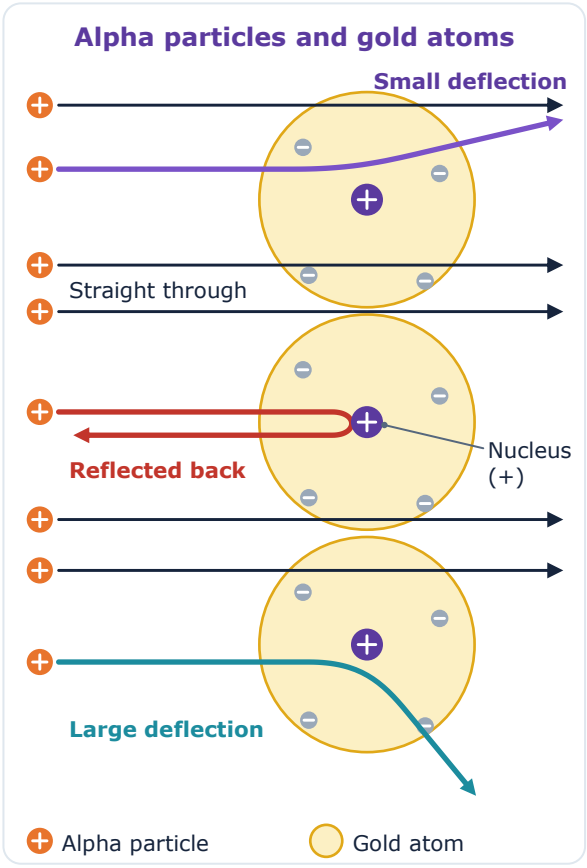
Rutherford compared this surprise to firing a 15-inch shell at tissue paper and having it come back and hit you.

Nucleus

A small, dense core containing the positive charge and mass of the atom.

Explanation

- Positive alpha particles and the positive **nucleus** repel each other.
- Large deflections occur when alpha particles pass very close to the high concentration of positive charge in the **nucleus.**
- Only a small number are reflected back because only a small number score a direct hit on the small **nucleus.**



Size of the nucleus

The nuclear diameter is approximately **1/100,000** of the atom's diameter. If the atom were the size of Croke Park, the **nucleus** would be like a marble at its centre.

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The proton & Rutherford's nuclear model

Discovery of the proton

- Bombardment of **atoms** such as oxygen and nitrogen with alpha particles released small, **positively charged** particles.
- Rutherford named these particles **protons** and explained that lighter nuclei were broken up to release them.
- This did not happen with heavier **atoms** such as gold: their large positive nuclear charge repelled the alpha particles before the nuclei could break up.

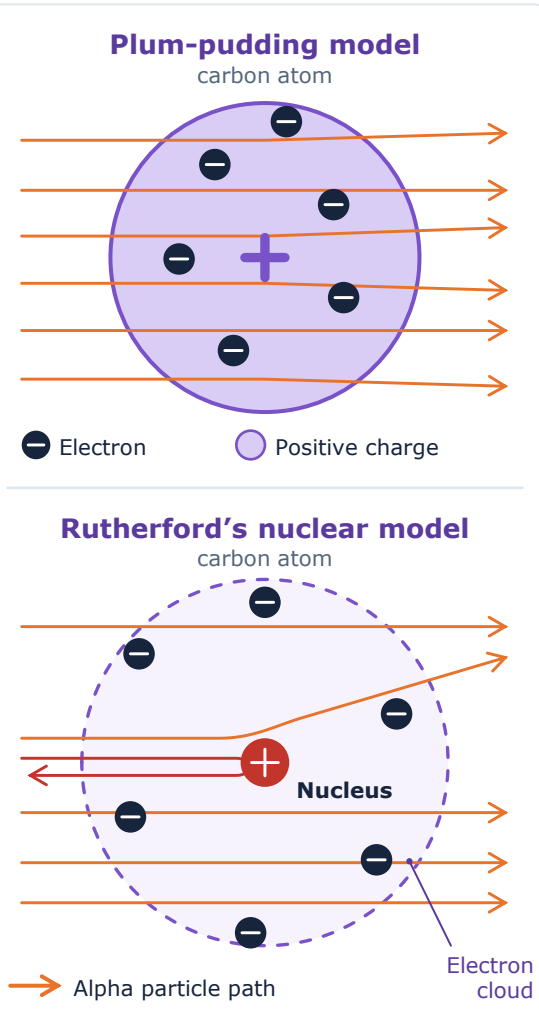
> **Electron cloud**
> The space surrounding the **nucleus** in which **electrons** are scattered.

Assumptions of the nuclear model

- Atoms have a small, dense, positive core called the **nucleus.** Most of the atom's mass is concentrated there.
- Positive particles called **protons** are located in the **nucleus.**
- The atom is mostly empty space.
- Electrons are scattered in the space surrounding the **nucleus,** called the **electron cloud.** They move around it, but their exact motion is not described.

Limitations

- Like charges repel: the model does not explain why repulsion between **protons** does not cause the **nucleus** to fly apart.
- Opposite charges attract: the model does not explain why **electrons** do not fall into the **nucleus.**
- Most **atoms** are stable.



Rutherford's model replaced Thomson's plum-pudding model. It located positive charge and most mass in a small central nucleus.

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The neutron & the updated nuclear model

James Chadwick's experiment (1932)

- A student of Rutherford, Chadwick bombarded **beryllium** with alpha particles.
- Radiation consisting of particles came from the **beryllium.**
- The particles were **neutral** and hard to detect. They were penetrating enough to knock **protons** out of **paraffin wax.**
- Chadwick concluded that alpha particles were knocking **neutral** particles out of the **beryllium nucleus.**
- Their mass was about the same as a proton's. He called them **neutrons.**
- Neutrons were discovered after **electrons** and **protons** because their lack of charge made them difficult to detect.
- Chadwick received the 1935 Nobel Prize in Physics.

Assumptions of the updated model

- Most mass is concentrated in a small, dense, positive **nucleus.**
- Protons and **neutral** particles called **neutrons** are in the **nucleus.**
- The atom is mostly empty space.
- Electrons are scattered in the surrounding **electron cloud.** Their movement is proposed, but their exact motion is not described.

Remaining limitation

- Opposite charges attract: moving **electrons** should lose energy, spiral into the **nucleus** and cause the atom to collapse.
- The model cannot explain why **electrons** stay in motion around the **nucleus** without crashing into it.
- Most **atoms** are stable.

Neutrons in the nucleus

Help to cement **positively charged protons** together so that the **nucleus** does not fall apart through proton–proton repulsion.

PRACTICE / QUESTIONS BASED ON THE SUPPLIED PAGES

Sample Questions

Q1 Matter & atoms

Define the particulate nature of matter and an atom. Name the white substance formed where ammonia and hydrogen chloride meet.

Q2 Dalton & Crookes

State Dalton’s two atomic assumptions. Describe the Maltese-cross observation and what happens when cathode rays strike glass.

Q3 Thomson’s experiment

Describe the beam path with uncharged plates and a positively charged top plate. Explain what Thomson concluded about the particles.

Q4 Millikan

State what Millikan measured and the value obtained. Explain how the electron’s mass was then calculated and state its value.

PRACTICE / QUESTIONS BASED ON THE SUPPLIED PAGES

Sample Questions

Q5 Plum pudding & alpha particles

State the two assumptions of the plum-pudding model. State the composition of an alpha particle and how Rutherford detected alpha particles.

Q6 Scattering evidence

Give three observations from the gold foil experiment and the conclusion associated with each. State the nuclear-to-atomic diameter ratio.

Q7 The nuclear model

State Rutherford’s four nuclear-model assumptions and its two limitations. Explain how the bombardment of lighter atoms led to the proton’s discovery.

Q8 Chadwick & the updated model

Outline Chadwick’s beryllium/paraffin-wax experiment. State the neutron’s charge and comparative mass, how the model was updated, and its remaining limitation.

ANSWERS / KEY POINTS FROM THE SUPPLIED PAGES

Worked Solutions

Q1 Matter & atoms

All substances consist of tiny invisible particles: atoms, molecules or ions. An atom is the smallest particle of an element that retains its properties.

The white substance is ammonium chloride.

Q2 Dalton & Crookes

Dalton: all matter consists of very small atoms; atoms are indivisible and cannot be broken into simpler particles.

Crookes: a Maltese cross casts a shadow. Glass glows where cathode rays strike it, but not where the cross blocks them.

Q3 Thomson's experiment

Uncharged plates: the beam travels straight. Positive top plate: the spot moves upwards towards it.

Unlike charges attract, so cathode rays contain negatively charged particles, called electrons.

Q4 Millikan

Measured the size of the electron's charge: 1.6×10^{-19} coulomb.

Combining this with Thomson's charge-to-mass ratio allowed electron mass to be calculated: 9.1×10^{-31} kg.

Q5 Plum pudding & alpha particles

The atom is a sphere of positive charge with electrons embedded at random.

An alpha particle contains two protons and two neutrons. Impacts on a phosphorescent screen produce flashes, viewed through a microscope.

Q6 Scattering evidence

Most pass straight through: the atom is mostly empty space.

Some have large deflections: they pass near the small positive nucleus and are repelled. Few return: a small number collide head-on with the nucleus.

Nuclear diameter is approximately 1/100,000 of atomic diameter.

Q7 The nuclear model

Small dense positive nucleus holds most mass; protons are in it; most of the atom is empty space; electrons occupy the surrounding electron cloud.

Does not explain why proton repulsion fails to break the nucleus apart or why electrons do not fall into it.

Alpha bombardment breaks up lighter nuclei, releasing small positive particles called protons.

Q8 Chadwick & the updated model

Alpha particles bombard beryllium. Neutral particles from its nucleus knock protons out of paraffin wax. Their mass is about the same as a proton's.

Neutrons join protons in the nucleus and help cement them together.

The updated model still cannot explain why moving electrons do not spiral into the nucleus.