Cambridge (CIE) IGCSE Physics

Your notes

The Nuclear Model of the Atom

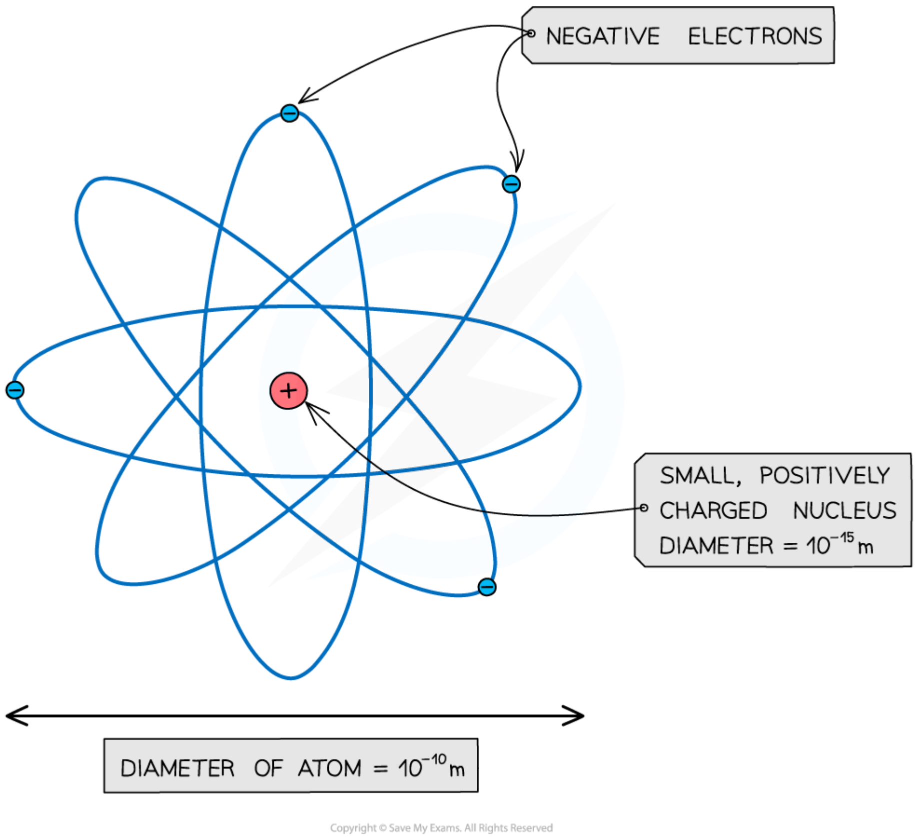
Contents

Your notes

Atomic structure

- Atoms are the building blocks of **all matter**
- They consist of a small dense **positively** charged nucleus and **negatively** charged electrons in orbit around the nucleus

Atomic structure



An atom: is a small positive nucleus, surrounded by orbiting negative electrons

- Atoms are incredibly small, with a radius of only 1×10^{-10} m
  - This means that about one hundred million atoms could fit side by side across your thumbnail
- The radius of the nucleus is over 10,000 times smaller than the whole atom, but it contains almost **all of the mass** of the atom

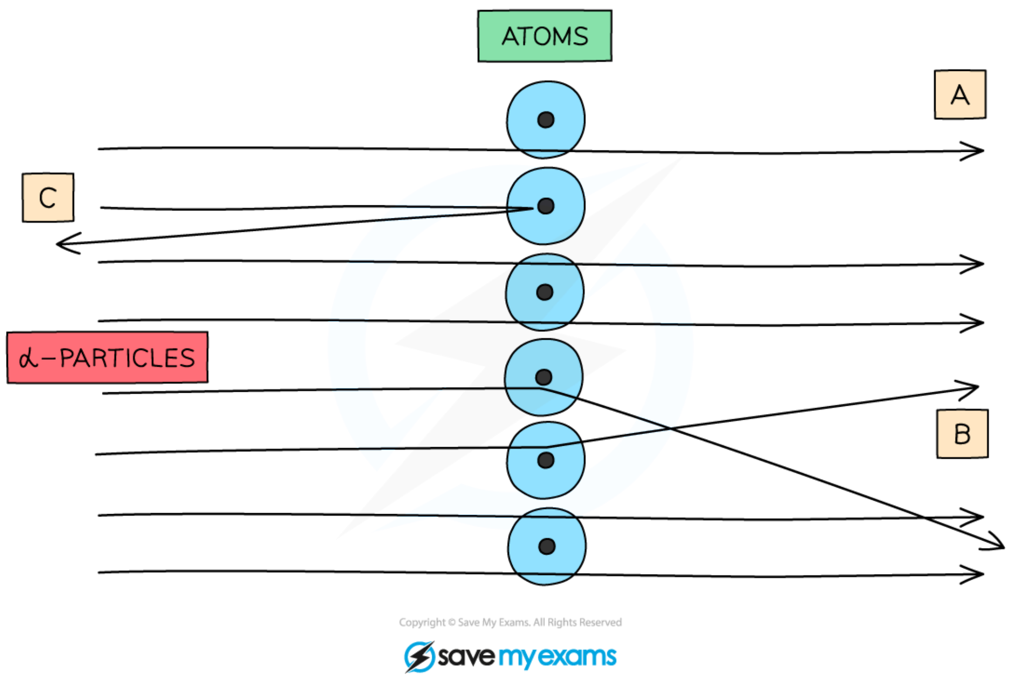
Rutherford's alpha scattering experiment

Extended tier only

- In Rutherford's alpha scattering experiment the scattering of alpha (α) particles by a sheet of thin metal supports the **nuclear model** of the atom, by providing evidence for:
  - a very **small nucleus** surrounded by **mostly empty space**
  - a **nucleus** containing most of the **mass** of the atom

- a nucleus that is **positively charged**
- In 1909 a group of scientists were investigating the Plum Pudding model of atomic structure
  - Physicist, **Ernest Rutherford** was instructing two of his students, Hans Geiger and Ernest Marsden to carry out the alpha scattering experiment
- They directed a beam of **alpha particles** (He^{2+} ions) at a thin gold foil
  - They expected the alpha particles to **travel through** the gold foil, and maybe change direction a small amount
- As shown in the diagram, instead they discovered that :
  - Most of the alpha particles **passed straight through** the foil because the atom is mostly **empty space** (A)
  - Some of the alpha particles were **deflected** (changed direction**)** as they passed through the foil because they came close to the positively charged nucleus, which repelled the positively charged alpha particles (B)
  - A few of the alpha particles **bounced back** off the gold foil because the nucleus is tiny
- This bouncing back could not be explained by the Plum Pudding model of atomic structure, so a new model had to be created
  - This was the first evidence of the nuclear atom as atomic structure

Rutherford's alpha scattering experiment results



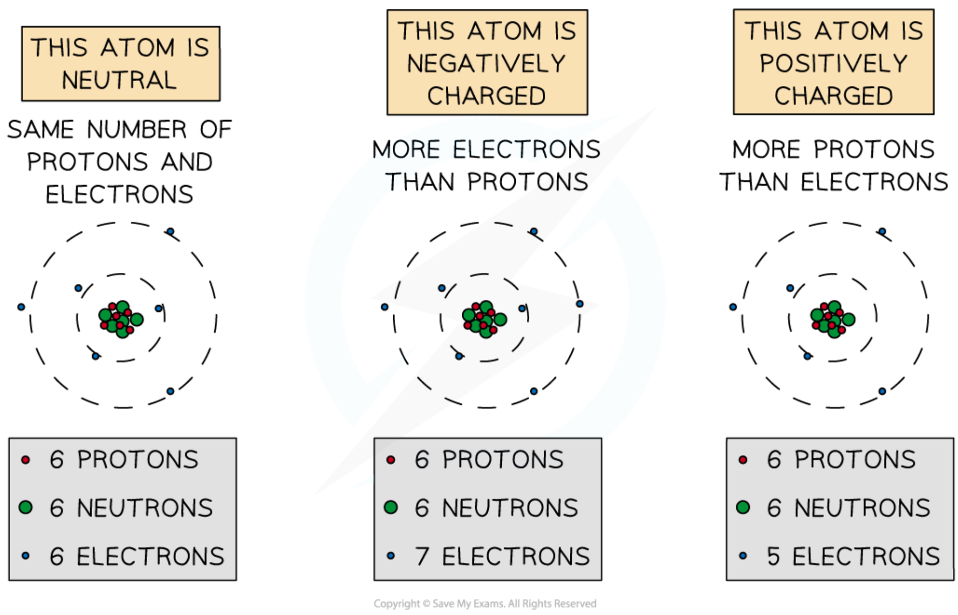
When α-particles are fired at thin gold foil, most of them go straight through but a very small number bounce straight back

Atoms & ions

- An ion is an **electrically charged** atom or group of atoms formed by the **loss** or **gain** of **electrons**
  - An atom will lose or gain electrons to become more stable
- A stable atom is normally electrically neutral

- This means it has the same number of protons (positive charge) and electrons (negative charge)
- Positive ions are therefore formed when atoms **lose** electrons
  - There will be more protons than electrons
- Negative ions are therefore formed when atoms **gain** electrons
  - There will be more electrons than protons

The atomic structure of ions



The difference between positive and negative ions

Examiner Tips and Tricks

You may hear the term 'net charge'. This just means the 'overall' charge of the atom. If an atom has 5 protons, 5 neutrons and 6 electrons, it has a **net** negative charge because it's a negative ion (more electrons than protons).

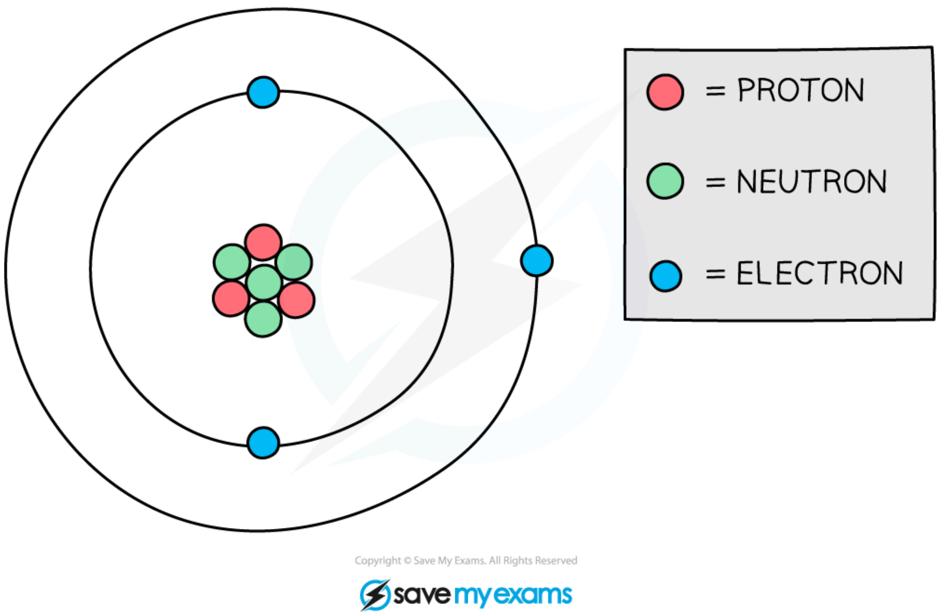
Remember which way around the charges are by **p**roton being **p**ositive.

Your notes

Composition of the nucleus

- A nucleus is composed of:
  - positively charged **protons**
  - neutrally charged **neutrons**
- Hence a nucleus has an **overall positive** charge

Structure of the atom



Protons and neutrons are found in the nucleus of an atom

Examiner Tips and Tricks

Be careful with your terminology:

- Atom = nucleus (proton and neutron) **and** electrons
- Nucleus = protons and neutrons at the centre of the atom

Describing the nucleus

Proton number, Z

- The number of protons in an atom is called its **proton** number (it can also be called the **atomic** number)
  - Elements in the periodic table are ordered by their atomic number
  - Therefore, the number of protons determines which element an atom is
- The atomic number of a particular element is always the same

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- For example:
  - Hydrogen has an atomic number of 1. It always has just one proton
  - Sodium has an atomic number of 11. It has 11 protons
  - Uranium has an atomic number of 92. It has 92 protons
- The atomic number is also equal to the number of electrons in an atom
  - This is because atoms have the same number of electrons and protons in order to have no overall charge

Nucleon number, A

- The total number of particles in the nucleus of an atom is called its **nucleon number** (or **mass** number)
- The mass number is the number of protons **and** neutrons in the atom

Calculating the number of neutrons

- The number of neutrons can be found by **subtracting** the **atomic** number from the **mass** number

$$\text{number of neutrons} = \text{nucleon number} - \text{proton number}$$

- For example, if a sodium atom has a mass number of 23 and an atomic number of 11, then the number of neutrons would be 23 – 11 = 12

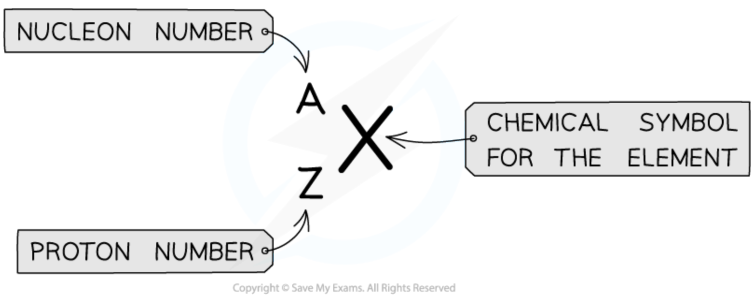
Examiner Tips and Tricks

You may have noticed that the number of electrons is not part of the mass number. This is because electrons have a **tiny** mass compared to neutrons and protons. We say their mass is negligible when compared to the particles in the nucleus.

Nuclide notation

- Atomic symbols are written in a specific notation called **ZXA** or **nuclide notation**
  - The top number A represents the **nucleon** number
  - The lower number Z represents the **proton** number

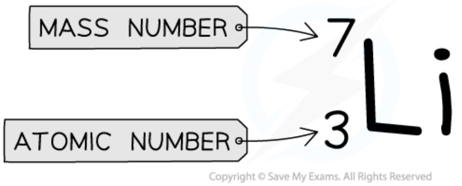
Nuclide notation



Atomic symbols in AZX nuclide notation describe the constituents of nuclei

- A nuclide is a group of atoms containing the same number of protons and neutrons
  - For example, 5 atoms of oxygen are all the same nuclide but are 5 separate atoms
- An example of nuclide notation is:

Example of lithium nuclide notation



Atomic symbols, like the one above, describe the constituents of nuclei

Worked Example

The element symbol for gold is Au. How many protons, neutrons and electrons are in the gold atom?

$$^{197}_{79}\mathrm{Au}$$

	Protons	Neutrons	Electrons
A	79	79	79
B	197	79	118
C	118	118	79
D	79	118	79

Answer: D

Step 1: Determine the atomic and mass number

- The gold atom has an atomic number of 79 (lower number) and a mass number of 197 (top number)

Step 2: Determine the number of protons

- The **atomic** number is equal to the number of **protons**
- The atom has 79 protons

Step 3: Calculate the number of neutrons

- The mass number is equal to the number of protons and neutrons
- The number of neutrons is equal to the mass number minus the atomic number

$$197 - 79 = 118$$

- The atom has 118 neutrons

Step 4: Determine the number of electrons

- An atom has the **same** number of **protons and electrons**
- The atom has 79 electrons

Examiner Tips and Tricks

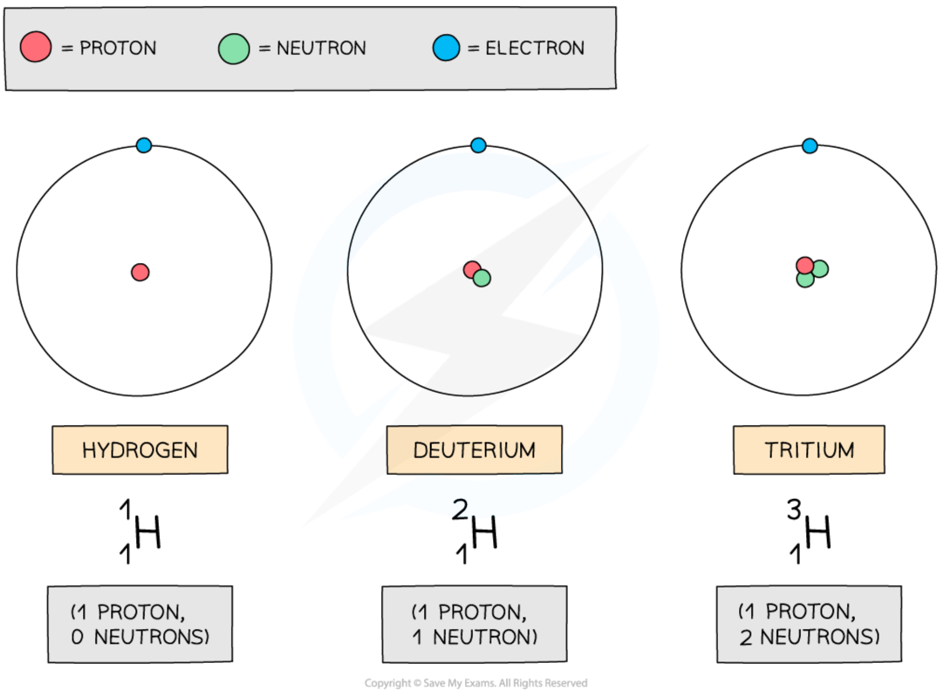
You may recognise this notation from the periodic table in chemistry when mass number and proton number are more commonly used. In physics, you are more likely to see nucleon number and proton number. The periodic table is ordered by atomic number.

Your notes

Isotopes

- Although the number of protons in a particular element is always the same, the number of **neutrons** can be different
- **Isotopes** are atoms of the same element that have an equal number of protons but a **different** number of **neutrons**
  - This means that each element can have more than one isotope
- Isotopes tend to be more **unstable** due to their imbalance of protons and neutrons
  - This means they're more likely to decay
- In the diagram below are three isotopes of Hydrogen:

Isotopes of hydrogen



Hydrogen has three isotopes, each with a different number of neutrons

- Isotopes occur naturally, but some are more rare than others
- For example, about 2 in every 10,000 Hydrogen atoms is Deuterium
  - Tritium is even more rare (about 1 in every billion billion hydrogen atoms)

Worked Example

Which of the following elements are isotopes of each other?

A	$^{35}_{17}Cl$ and $^{35}_{18}Cl$
B	$^{238}_{92}U$ and $^{235}_{92}U$

C	${}^{12}_{6}C$ and ${}^{14}_{8}\mathrm{C}$
D	${}^{16}_{8}\mathrm{O}$ and ${}^{14}_{7}\mathrm{N}$

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Answer: **B**

- In nuclide notion, the top number is the **nucleon** number (number of protons and neutrons) and the bottom number is the **proton** number (number of protons)
- Isotopes are two of the same elements
    - This eliminates option **D** since one is oxygen (O) and the other nitrogen (N)
- Which have the same number of protons
    - This eliminates option **C** and **A**
    - Their proton numbers are different for the same element
- But a different number of neutrons
    - Therefore, the correct answer is **B**

Your notes

Relative charge

- **Charge** can be positive or negative
- Protons, neutrons and electrons have different properties and different charges
  - **Protons** have a **positive** charge
  - **Electrons** have a **negative** charge
  - **Neutrons** have **no charge**
- **Relative charge** can be used to compare these properties
  - Relative charge is the **ratio** of the charge of a particle compared to the fundamental charge
  - Because relative charge is a ratio, it has **no units**
- **Fundamental charge** is equal to the **magnitude** of the charge on a proton and an electron = **1.6×10^{-19} C**
- The relative charge of a proton is

$$\text{proton} = \frac{1.6 \times 10^{-19}\ \text{C}}{1.6 \times 10^{-19}\ \text{C}} = +1$$

- The relative charge of an electron is

$$\text{electron} = \frac{-1.6 \times 10^{-19}\ \text{C}}{1.6 \times 10^{-19}\ \text{C}} = -1$$

- The relative charge of a neutron is

$$\text{neutron} = \frac{0\ \text{C}}{1.6 \times 10^{-19}\ \text{C}} = 0$$

Table of relative charges

Particle	Relative charge
Proton	+1
Neutron	0
Electron	-1

Examiner Tips and Tricks

You don't need to know how to calculate relative charge, but you do need to understand what it is. You do also need to remember what the relative charges are for each subatomic particle.

Nuclear charge

Extended tier only

- Nuclear charge is the **relative charge** of the **nucleus**

Your notes

- This is determined by the **proton number** of the atom
- Relative charge is calculated by:
  $\text{nuclear charge} = \text{number of protons in the nucleus} \times \text{relative charge of a proton}$
- An element of carbon has a proton number of 6
  - So the relative charge of carbon is 6 × (+1) = 6

Worked Example

What is the relative charge of the chromium nucleus $^{52}_{24}\text{Cr}$?

Answer:

Step 1: Determine the number of protons

- The number of protons is the proton number
- This is the Z number in the AZX notation

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

- This chromium nucleus has 24 protons

$$^{52}_{24}\text{Cr}$$

Step 2: State the relative mass of 1 proton

- 1 proton has a relative charge of +1

Step 3: Multiply relative charge of 1 proton by the number of protons

- This nucleus of chromium therefore has a relative charge of +24

Examiner Tips and Tricks

Charge can be either positive (+) or negative (–). Usually, when a number is positive, we don't write the + sign, but when dealing with relative charge, we do.

Nuclear mass

Extended tier only

- Nuclear mass or the relative mass of an atom, is the **relative mass** of the **nucleus**
  - This is because the mass of electrons orbiting the nucleus is negligible
- A relative mass of 1 = 1.67×10^{-27} kg
- The relative mass of an atom is determined by the **nucleon number** of the atom
- It is calculated by:

$$\text{relative mass of atom} = \text{number of protons and neutrons in the nucleus} \times \text{relative mass of a proton or a neutron}$$

- An element of carbon has a nucleon number of 12
  - So the relative mass of carbon is 12 × 1 = 12 atomic mass units or **amu**

Your notes

Table of relative mass

Particle	Relative mass
Proton	1
Neutron	1
Electron	$\frac{1}{2000}$ negligible

Worked Example

What is the relative mass of the chromium nucleus $^{52}_{24}\text{Cr}$?

Answer:

Step 1: Determine the number of protons and neutrons

- The number of protons and neutrons is the mass (nucleon) number
- This is the A number in the AZX notation

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

- This chromium nucleus has 52 protons and neutrons

$$^{52}_{24}\text{Cr}$$

Step 2: State the relative mass of 1 proton and 1 neutron

- 1 proton has a relative mass of 1
- 1 neutron has a relative mass of 1

Step 3: Multiply relative charge of 1 proton and 1 neutron by number of protons and neutrons

- This nucleus of chromium therefore has a relative mass of 52

Examiner Tips and Tricks

The relative mass of a nucleus only includes the protons and neutrons. However, this is pretty much the relative mass of the whole atom because electrons have negligible (very little) mass in comparison to the proton and neutron.

Fission & fusion

- Nuclear fission & fusion are **nuclear reactions** that change the nucleus of an atom to produce high amounts of energy from the energy **stored** in the nucleus of an atom

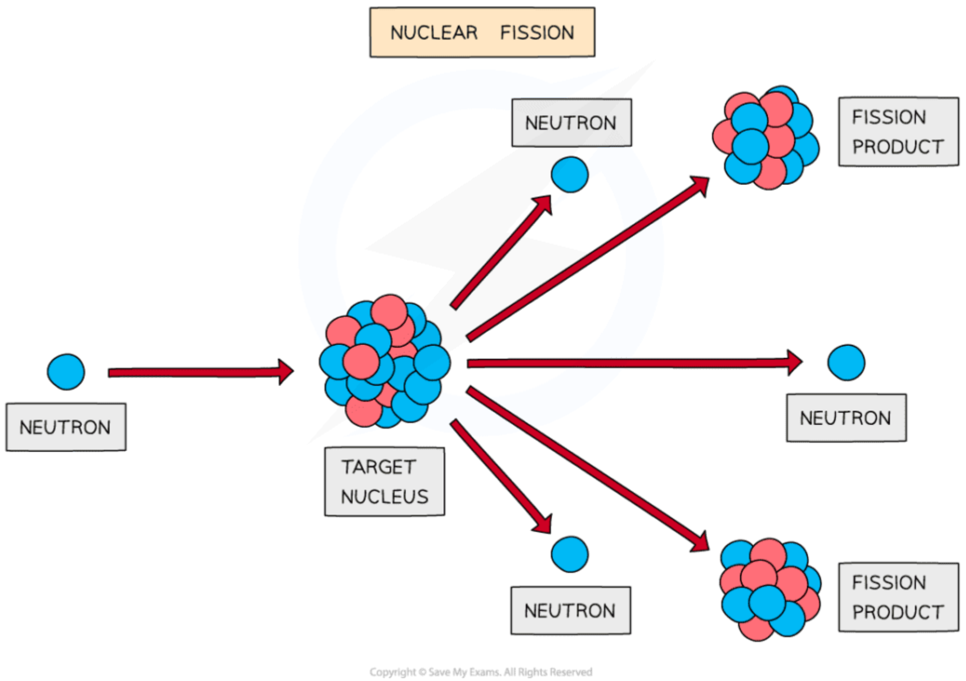
Nuclear fission

- Nuclear fission is defined as:

The splitting of a large, unstable nucleus into two smaller nuclei

- During fission:
  - A neutron collides with an unstable nucleus
    - The neutron and the nucleus are the **reactants**
  - The nucleus splits into **two smaller nuclei** (called daughter nuclei) and **two or three neutrons**
    - The daughter nuclei and the neutrons are the **products** of the reaction
  - Gamma rays are also emitted

Nuclear fission process



A neutron is fired into the target nucleus, causing it to split

Nuclear fission nuclide equations

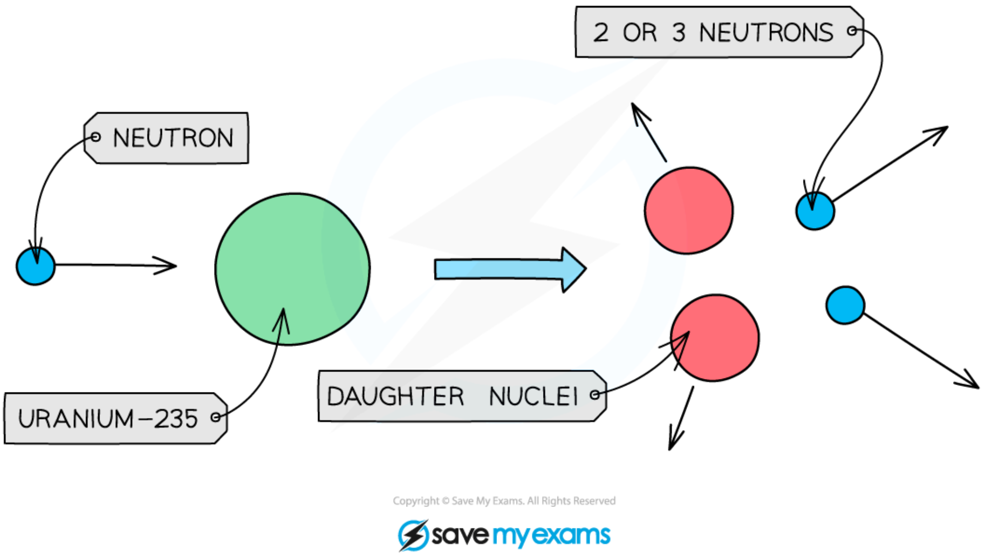
- An example of a nuclide equation for the fission of uranium-235 is:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3\ ^{1}_{0}\text{n} + \text{energy}$$

- Where:

- $^{235}_{92}U$ is an unstable isotope of uranium
- $^{1}_{0}n$ is a neutron
- $^{92}_{36}Kr$ is an unstable isotope of krypton
- $^{141}_{56}Ba$ is an unstable isotope of barium

Nuclear fission of uranium-235



Large nuclei can decay by fission to produce smaller nuclei and neutrons with a lot of kinetic energy

Nuclear fission mass and energy values

- **Energy is conserved** in a nuclear fission reaction
- In the example:

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3\,{}^{1}_{0}n + \text{energy}$$

- The sum of the nucleon (top) numbers of the reactants (left-hand side) is equal to the sum of the nucleon numbers of the products (right-hand side):

$$235 + 1 = 92 + 141 + (3 \times 1)$$

- The same is true for the proton (bottom) numbers:

$$92 + 0 = 36 + 56 + (3 \times 0)$$

- The products of fission move away very **quickly**
  - During a fission reaction, energy is transferred from **nuclear energy** store of the parent nucleus to the kinetic energy store of the products
- The mass of the products is **less** than the mass of the original nucleus
  - This is because the remaining mass has been converted into **energy,** which is released during the fission process
- Large isotopes with a large nucleon number, such as **uranium** and **plutonium,** both undergo fission and are used as fuels in nuclear power stations

Your notes

Nuclear fusion

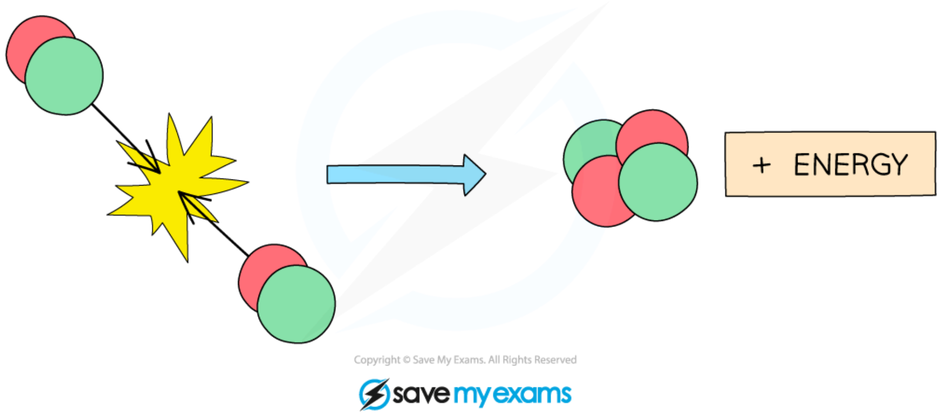
Your notes

- Nuclear fusion is defined as:

When two light nuclei join to form a heavier nucleus

- Stars use nuclear fusion to produce **energy**
  - In most stars, hydrogen nuclei (**light nuclei**) are fused together to form a helium nucleus (**heavier nucleus**) and massive amounts of **energy** is produced

Nuclear fusion of hydrogen



Two hydrogen nuclei fuse to form a helium nucleus

- Nuclear fusion requires extremely high **temperature** and **pressure**
  - So fusion is very hard to reproduce on Earth

Nuclear fusion nuclide equations

- An example of a nuclide equation for fusion is:

$$^{2}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + \text{energy}$$

- Where:
  - $^{2}_{1}\mathrm{H}$ is deuterium (isotope of hydrogen with 1 proton and 1 neutron)
  - $^{1}_{1}\mathrm{H}$ is hydrogen (with one proton)
  - $^{3}_{2}\mathrm{He}$ is an isotope of helium (with two protons and one neutron)

Nuclear fusion mass and energy values

- The energy produced during nuclear fusion comes from a very small amount of a particle's mass **converted** into energy
- Therefore, the mass of the product (fused nucleus) is **less** than the mass of the two original nuclei (reactants)
  - The remaining mass has been converted into the **energy** released when the nuclei fuse
- The amount of **energy released** during nuclear fusion is **huge**:
  - The energy from 1 kg of hydrogen that undergoes fusion is equivalent to the energy from burning about 10 million kilograms of coal

Your notes

Worked Example

A nuclide equation for nuclear fission is stated as:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{96}_{37}\mathrm{Rb} + {}^{137}_{55}\mathrm{Cs} + N\,^{1}_{0}\mathrm{n}$$

Calculate the number of neutrons, *N* emitted in this reaction.

Answer:

Step 1: Calculate the sum of the nucleon numbers of the reactants

- The reactants are on the left-hand side of the equation
- The nucleon numbers are the top numbers in the nuclide notation

$$235 + 1 = 236$$

Step 2: Calculate the sum of the nucleon numbers of the products

- The products are on the right-hand side of the equation

$$96 + 137 + (N \times 1) = 233 + N$$

Step 3: Equate the total nucleons of the reactants and products

$$236 = 233 + N$$

Step 4: Rearrange for the number of neutrons, N

$$N = 236 - 233 = 3$$