OCR A Level Physics

Your notes

The Nuclear Atom

Contents

Alpha Particle Scattering Experiment

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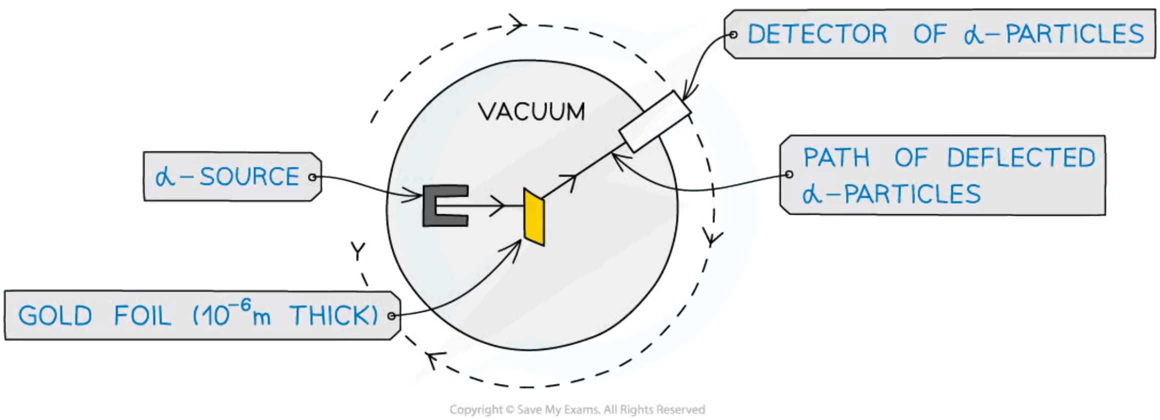
Alpha Particle Scattering Experiment

- Evidence for the structure of the atom was discovered by Ernest Rutherford in the beginning of the 20th century from the study of **α-particle scattering**
- The experimental setup consists of alpha particles fired at thin gold foil and a detector on the other side to detect how many particles deflected at different angles



α-particle scattering experiment set up

- α-particles are the nucleus of a helium atom and are positively charged

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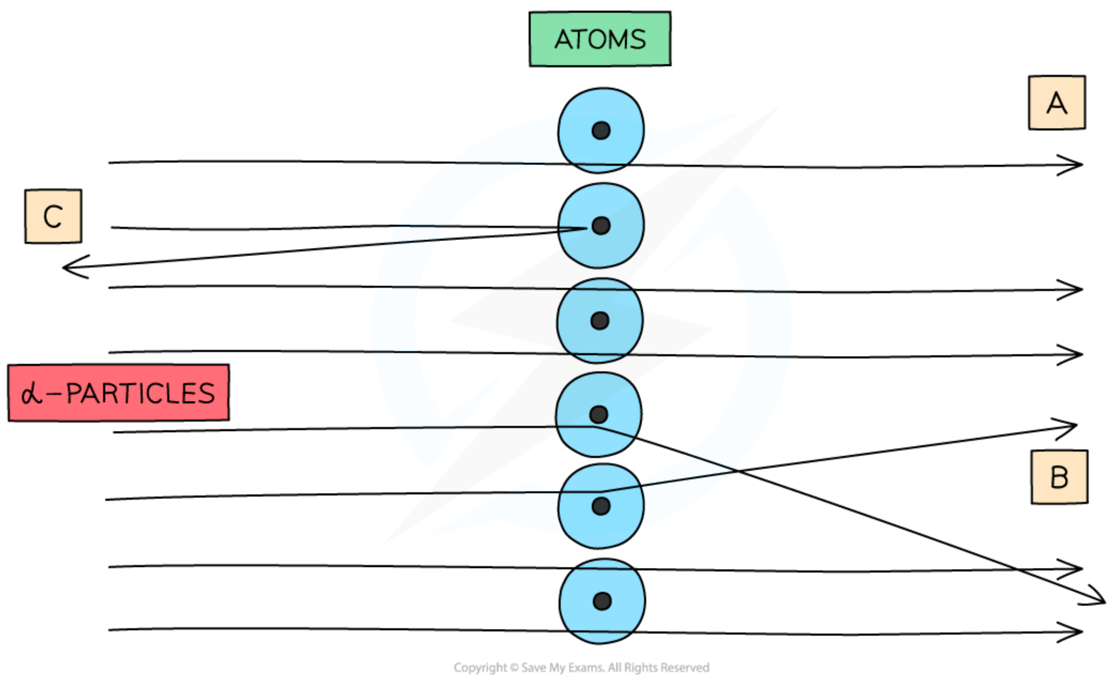

When α-particles are fired at thin gold foil, most of them go straight through but a small number bounce straight back

What did the Alpha Particle Scattering Experiment Show?

- The Rutherford alpha particle scattering experiment showed that:
- **The majority of α-particles went straight through (A)**
  - This suggested the atom is mainly empty space
- **Some α-particles deflected through small angles of < 10° (B)**
  - This suggested there is a positive nucleus at the centre (since two positive charges would repel)
- **Only a small number of α-particles deflected straight back at angles of > 90° (C)**
  - This suggested the nucleus is extremely small and this is where the mass and charge of the atom is concentrated
  - It was therefore concluded that atoms consist of ***small dense positively charged nuclei***

- Since atoms were known to be neutral, the negative electrons were thought to be on a positive sphere of charge (plum pudding model) before the nucleus was theorised

- Now it is known that the negative electrons are orbiting the nucleus. Collectively, these make up the atom

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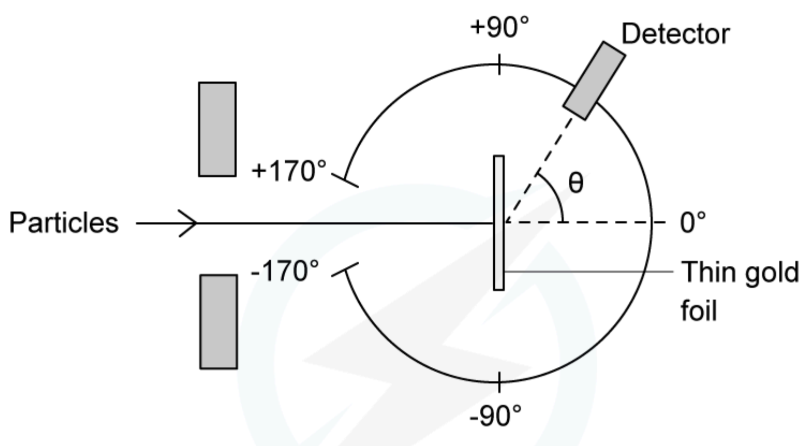
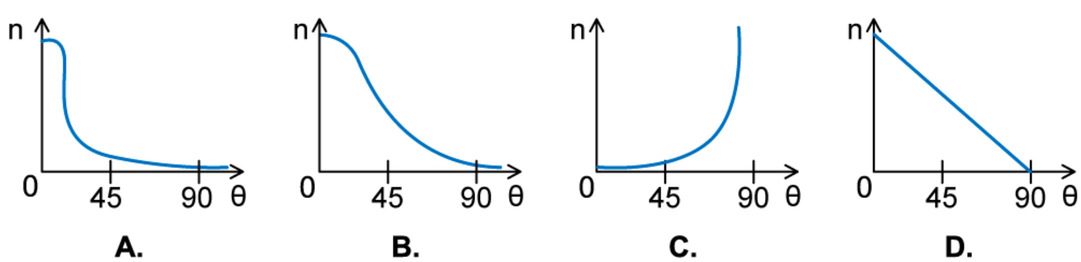
Worked Example

In an α-particle scattering experiment, a student set up the apparatus below to determine the number n of α-particle incident per unit time on a detector held at various angles θ.



Which of the following graphs best represents the variation of n with θ from 0 to 90°?



Answer: A

- The Rutherford scattering experiment directed parallel beams of α-particles at gold foil
- The observations were:
  - Most of the α-particles went straight through the foil
  - The largest value of n will therefore be at small angles
  - Some of the α-particles were deflected through small angles

- n drops quickly with increasing angle of deflection θ
- These observations fit with graph **A**

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Atomic Structure

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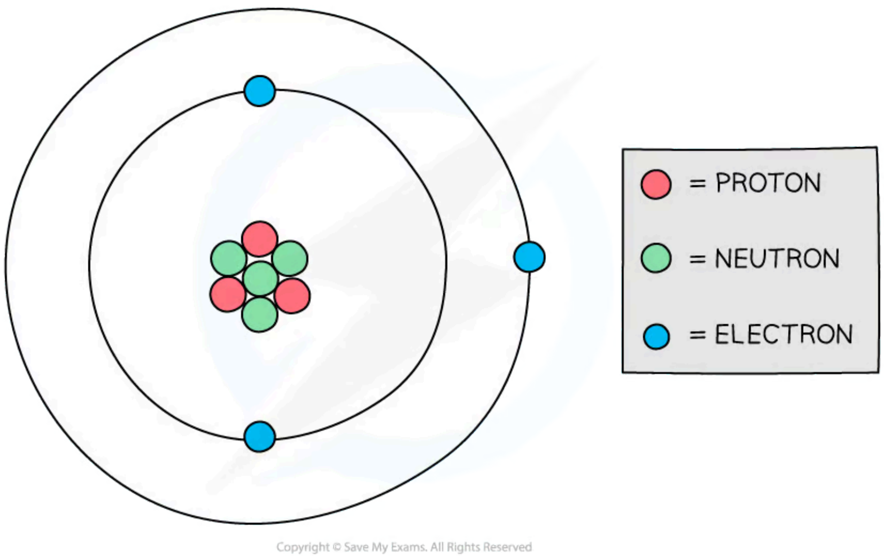
Atomic Structure

- The atoms of all elements are made up of three types of particles: protons, neutrons and electrons.



Protons and neutrons are found in the nucleus of an atom while electrons orbit the nucleus

- The properties of each particle in SI units are shown in the table below:

Particle	Charge / C	Mass / kg
Proton	$+1.60 \times 10^{-19}$	$1.67(3) \times 10^{-27}$
Neutron	0	$1.67(5) \times 10^{-27}$
Electron	-1.60×10^{-19}	9.11×10^{-31}

- It is important to know the **relative masses** and **charges** that **protons**, **neutrons** and **electrons** have in relation to each other

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- The relative properties of each particle are shown in the table below:

PARTICLE	RELATIVE CHARGE	RELATIVE MASS
PROTON	+1	1
NEUTRON	0	1
ELECTRON	−1	1/2000 (NEGLIGIBLE)

- A stable atom is **neutral** (it has no charge)
- Since protons and electrons have the same charge, but opposite signs, a stable atom has an equal number of both for the overall charge to remain neutral

Examiner Tips and Tricks

Remember not to mix up the 'atom' and the 'nucleus'. The 'atom' consists of the nucleus and electrons. The 'nucleus' just consists of the protons and neutrons in the middle of the atom, not the electrons.

Relative Sizes of the Atom and Nucleus

Relative Sizes

- From Rutherford's Alpha Scattering Experiment we know that most of an atom is made up of empty space

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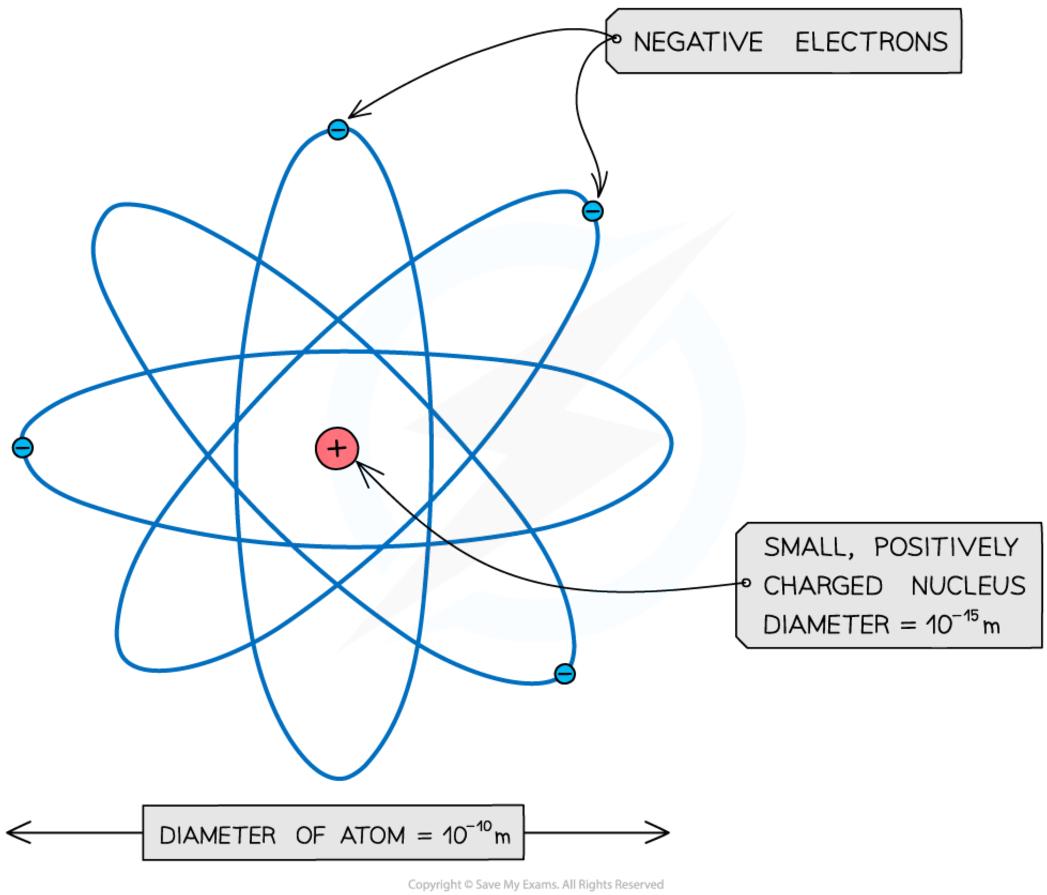


An atom: a small positive nucleus, surrounded by negative electrons

- The atom is around 100,000 times larger than the nucleus!
  - The diameter of an atom is 1×10^{-10} m
  - The diameter of a nucleus is 1×10^{-15} m
  - So, $1 \times 10^{-15} \times 100{,}000 = 1 \times 10^{-10}$

Closest Approach Method

- In the Rutherford scattering experiment, alpha particles are fired at a thin gold foil
- Some of the alpha particles are found to come straight back from the gold foil
- This indicates that there is **electrostatic repulsion** between the alpha particles and the gold nucleus

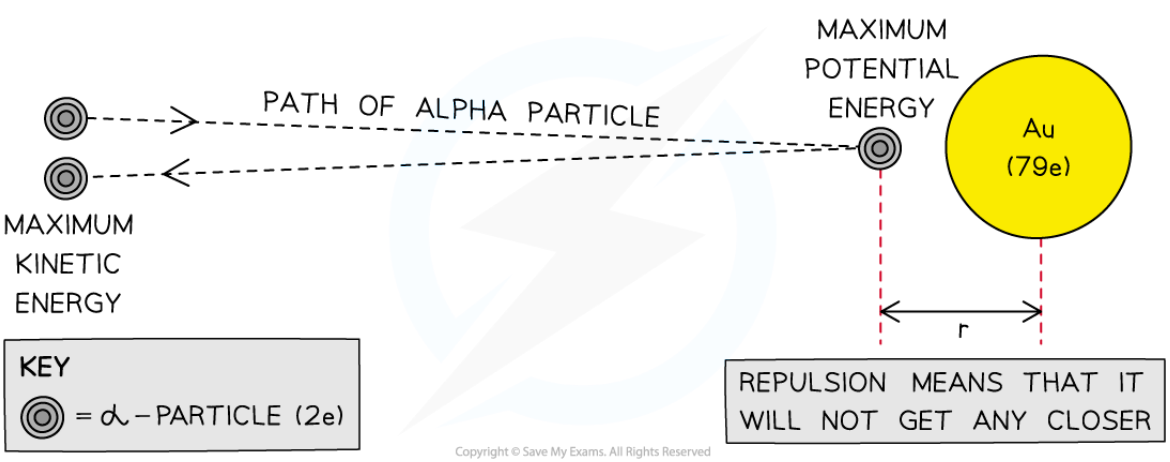
$$E_k = eV = \frac{1}{2}mv^2$$

- At the point of closest approach, r, the repulsive force reduces the speed of the alpha particles to zero momentarily
- At this point, the initial kinetic energy of an alpha particle, E_k, is **equal** to electric potential energy, E_p
- The radius of the closest approach can be found be equating the initial kinetic energy to the electric potential energy

$$E_p = \frac{Qq}{4\pi\varepsilon_0 r}$$

- Equating the two equations gives:

$$E_k = E_p = \frac{1}{2}mv^2 = \frac{Qq}{4\pi\varepsilon_0 r}$$



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Examiner Tips and Tricks

It is important to understand that the nucleus is tiny compared to the size of the atom around it.

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AZX Notation & Isotopes

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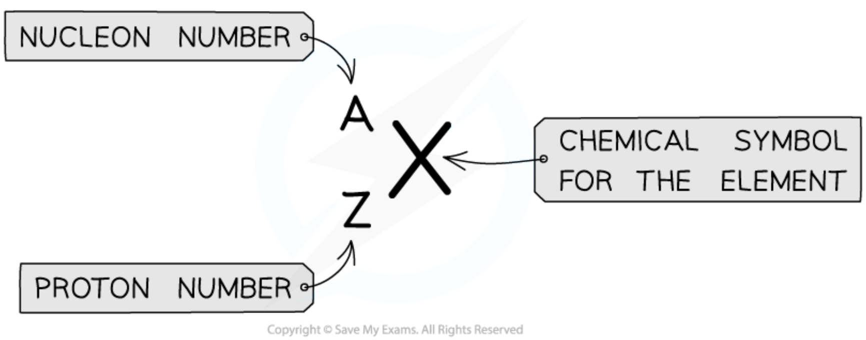
AZX Notation & Isotopes

AZX Notation

- 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
- Atomic symbols are written in a specific notation called **nuclide** or **AZX notation**



Atomic symbols in AZX Notation describe the constituents of nuclei

- The top number A represents the **nucleon** number or the **mass** number
  - **Nucleon number (A)** = total number of **protons and neutrons** in the nucleus
- The lower number Z represents the **proton** or **atomic** number
  - **Proton number (Z)** = total number of **protons** in the nucleus
- Note: In Chemistry, the nucleon number is referred to as the mass number and the proton number as the atomic number. The periodic table is ordered by atomic number

Isotopes

- Although all atoms of the same element always have the same number of protons (and hence electrons), the number of neutrons can vary
- An isotope is defined as:

  An atom (of the same element) that has an equal number of protons but a different number of neutrons

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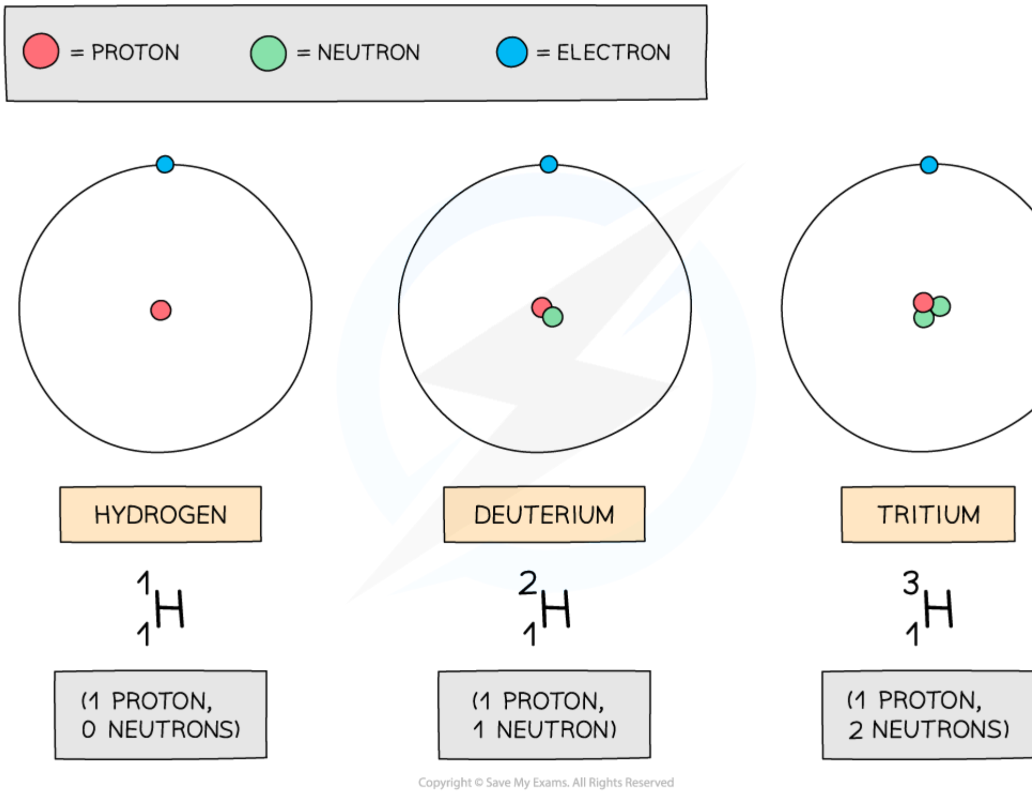
- Hydrogen has two isotopes: **deuterium** and **tritium**



The three atoms shown above are all forms of hydrogen, but they each have different numbers of neutrons

- The neutron number of an atom is found by subtracting the proton number from the nucleon number
- Since nucleon number includes the number of neutrons, an isotope of an element will also have a **different nucleon / mass number**
- Since isotopes have an imbalance of neutrons and protons, they are **unstable**
  - This means they decay and emit radiation to achieve a more stable form
  - This can happen from anywhere between a few nanoseconds to 100,000 years

Differences Between Isotopes

- The number of neutrons in an atom does not affect the chemical properties of an atom, such as its charge, but only its mass
  - This is because neutrons have no charge but do have mass

- The charge of the nucleus of a particular element is **always the same**
- In the periodic table, the mass number of Chlorine is often given as 35.5

			4 He HELIUM 2
14 N NITROGEN 7	16 O OXYGEN 8	19 F FLUORINE 9	20 Ne NEON 10
31 P PHOSPHORUS 15	32 S SULFUR 16	35.5 Cl CHLORINE 17	40 Ar ARGON 18

This section of a periodic table shows Chlorine as having a mass number of 35.5, but other elements have an integer mass number

- The mass number of chlorine is given as 35.5 because it has 2 isotopes, one with a mass number of 35 and the other with a mass number of 37
- Chlorine-35 is about three times more abundant than chlorine-37, so the given mass number of chlorine is closer to 35 than 37 because the mass number is a **weighted average**, therefore it takes into account the proportion of each isotope present
- The number of electrons and protons in different isotopes remains the **same**
- Some isotopes are **unstable** as they have an imbalance of protons and neutrons

Worked Example

One of the rows in the table shows a pair of nuclei that are isotopes of one another.

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	Nucleon number	Number of neutrons
A	39 35	19 22
B	37 35	20 18
C	37 35	18 20
D	35 35	20 18

Which row is correct?

Answer: B

Step 1: State the properties of isotopes

Isotopes are nuclei with the same number of protons but different number of neutrons

The nucleon number is the sum of the protons and neutron

Therefore, an isotope has a different nucleon number too

Step 2: Calculate number of protons in the first nucleus

Nucleon number: 37

Neutrons: 20

Protons = 37 – 20 = 17

Step 3: Calculate number of protons in the second nucleus

Nucleon number: 35

Neutrons: 18

Protons = 35 – 18 = 17

Step 4: Conclusion

Therefore, they have the same number of protons but different numbers of neutrons and are isotopes of each other

The correct answer is therefore option **B**

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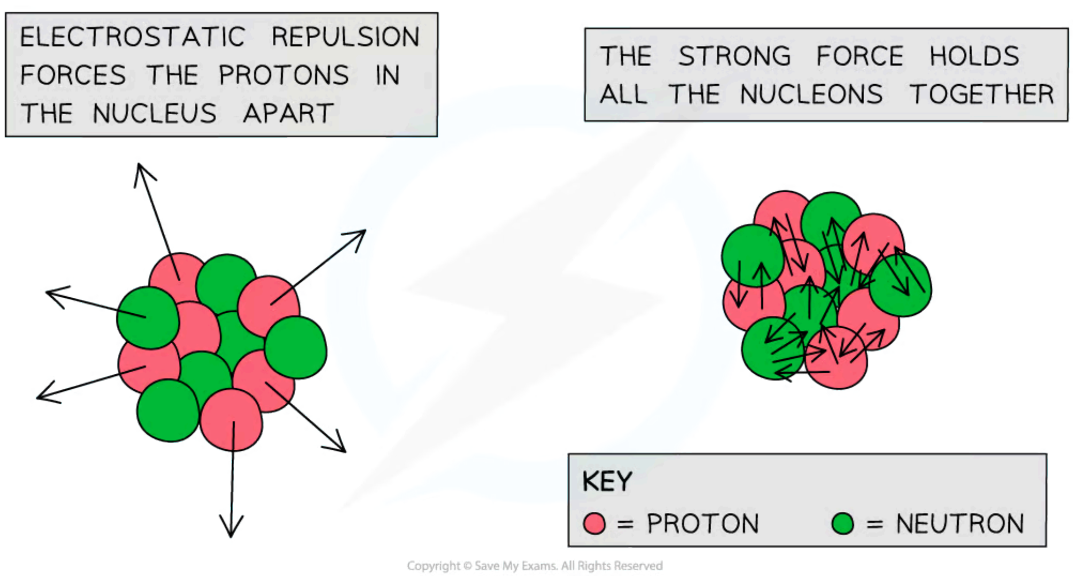
The Strong Nuclear Force

The Strong Nuclear Force

- In the nucleus, there are electrostatic forces between the protons due to their electric charge and gravitational forces due to their mass
- Comparatively, gravity is a very weak force and the electrostatic repulsion between protons is therefore much stronger than their gravitational attraction
- If these were the only forces, the nucleus wouldn't hold together
- Therefore, the force that does hold the nucleus together is called the **strong nuclear force**
- The strong nuclear force keeps the nucleus stable since it holds quarks together
- Since protons and neutrons are made up of quarks, the strong force keeps them bound within a nucleus



Whilst the electrostatic force is a repulsive force in the nucleus, the strong nuclear force holds the nucleus together

Range of the Strong Nuclear Force

- The strength of the strong nuclear force between two nucleons varies with the separation between them

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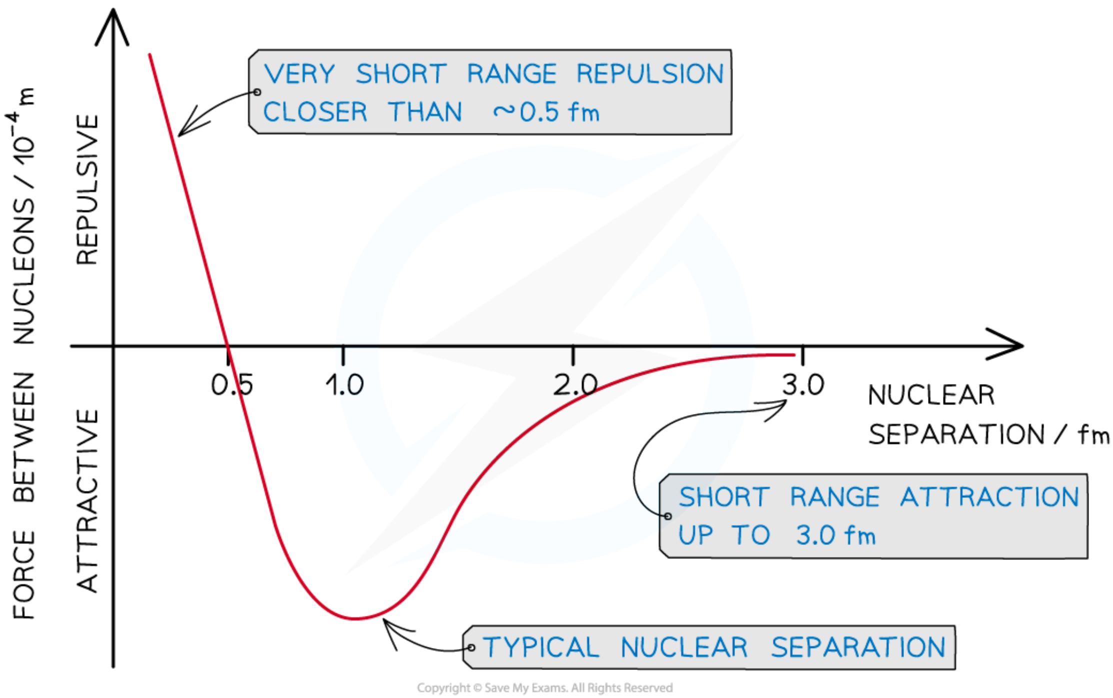
- This can be plotted on a graph which shows how the force changes with separation



The strong nuclear force is repulsive before a separation of ~ 0.5 fm and attractive up till ~ 3.0 fm

- The key features of this graph are that the strong nuclear force is:
  - **Repulsive** closer than around 0.5 fm
  - **Attractive** up to around 3.0 fm
  - Reaches a **maximum** attractive value at around 1.0 fm (the typical nuclear separation)
  - Becomes **zero** after 3.0 fm
- In comparison to other fundamental forces, the strong force therefore has a very small range (only up to 3.0 fm)

Examiner Tips and Tricks

- You may see the strong nuclear force also referred to as the **strong interaction**
- Remember to write that after 3 fm, the strong force becomes 'zero' or 'has no effect' rather than it is ‘negligible’.

- Recall that 1 fm = 1×10^{-15} m

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Nuclear Radius & Density

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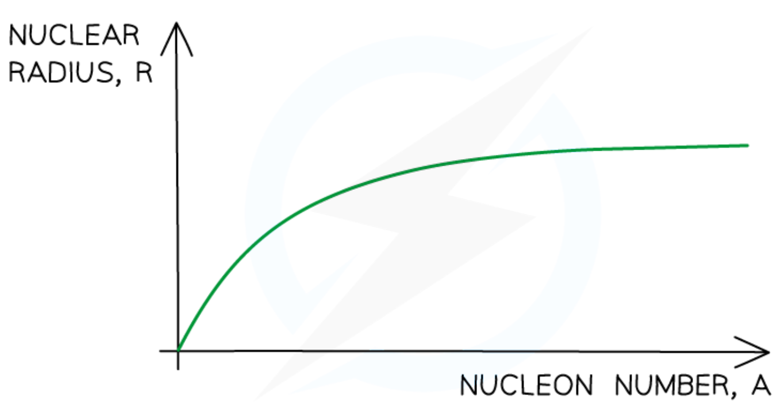
Nuclear Radius

- The radii of some nuclei are shown in the table below:

Element	Nuclear radius R / 10^{-15} m	Mass number A
Carbon	2.66	12
Silicon	3.43	28
Iron	4.35	56
Tin	5.49	120
Lead	6.66	208

- In general, nuclear radii are of the order 10^{-15} m or 1 fm
- The nuclear radius, *R*, varies with nucleon number, *A* as follows:



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- **The key features of this graph are:**
  - The graph starts with a steep gradient at the origin
  - Then the gradient gradually decreases to almost horizontal
- This means that
  - As more nucleons are added to a nucleus, the nucleus gets bigger
  - However, the number of nucleons A is **not** proportional to its size r

Calculating the Nuclear Radius

- The radius of nuclei depends on the nucleon number, A of the atom
- This makes sense because as more nucleons are added to a nucleus, more space is occupied by the nucleus, hence giving it a larger radius
- The exact relationship between the radius and nucleon number can be determined from experimental data
- By doing this, physicists were able to deduce the following relationship:

$$\mathbf{R = r_0 A^{1/3}}$$

- Where:
  - R = nuclear radius (m)
  - A = nucleon / mass number
  - R_0 = constant of proportionality = 1.2 fm = 1.2×10^{-15} m (the radius of a proton)

Mean Densities of Atoms and Nuclei

Equation for Nuclear Density

- Assuming that the nucleus is spherical, its volume is equal to:

$$V = \frac{4}{3}\pi R^3$$

- Where R is the nuclear radius, which is related to mass number, A, by the equation:

$$R = R_0 A^{\frac{1}{3}}$$

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- Where R_0 is a constant of proportionality
- Combining these equations gives:

$$V = \frac{4}{3}\pi\left(R_0 A^{\frac{1}{3}}\right)^3 = \frac{4}{3}\pi R_0^3 A$$

- This shows that the nuclear volume, *V*, is proportional to the mass of the nucleus, *A*

$$V \propto A$$

- Mass (m), volume (V), and density (ρ) are related by the equation:

$$\rho = \frac{m}{V}$$

- The mass, *m*, of a nucleus is equal to:

$$m = Au$$

- Where:
  - *A* = the mass number
  - *u* = atomic mass unit
- Using the equations for mass and volume, nuclear density is equal to:

$$\rho = \frac{Au}{\frac{4}{3}\pi R_0^3 A} = \frac{3u}{4\pi R_0^3}$$

- Since the mass number *A* cancels out, the remaining quantities in the equation are all constant
- Therefore, this shows the density of the nucleus is:
  - Constant
  - Independent of the radius
- The fact that nuclear density is constant shows that nucleons are evenly separated throughout the nucleus regardless of their size

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Worked Example

Calculate the approximate density of a lithium nucleus.

Assume the atomic mass of lithium to be 7u.

Answer:

Step 1: Write down the equations:

- Density: $density = \frac{mass}{volume} = \frac{Au}{{}^4/_3\ \pi\ R^3}$
- Volume of a sphere: $V = \frac{4}{3}\pi\ R^3$
- From the data booklet: nuclear radius, $R = r_0\ A^{1/3}$
  - Where:
    - r_o = constant = 1.2×10^{-15}
    - A = mass number = 7 for lithium

Step 2: Combine equations:

- $V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (r_o A^{1/3})^3 = \frac{4}{3}\pi r_o^3 A$

Step 3: Calculate the volume of the nucleus:

- $V = \frac{4}{3}\pi r_o^3 A = \frac{4}{3}\pi \times (1.2 \times 10^{-15})^3 \times 7 = 5.07 \times 10^{-44}$ m^3

Step 4: Calculate mass of lithium nucleus:

- Mass = Au = $7 \times (1.661 \times 10^{-27}) = 1.1627 \times 10^{-26}$ kg

Step 5: Calculate the density:

- Density = $\frac{\text{mass}}{\text{volume}} = \frac{1.1627 \times 10^{-26}}{5.07 \times 10^{-44}} = 2.29 \times 10^{17}$ kg m^{-3}

Step 6: Finalise your answer:

- The density of a lithium nucleus is 2.3×10^{17} kg m^{-3} (2 s.f.)

Examiner Tips and Tricks

Don't let all the powers and letters confuse you. Work through each step of a question one by one. It is just mass/volume to get the density with a little bit of substitution!

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