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2.1.1-Atomic-Structure

PHYSICS

AQA A Level Revision Notes

EXAM PAPERS PRACTICE

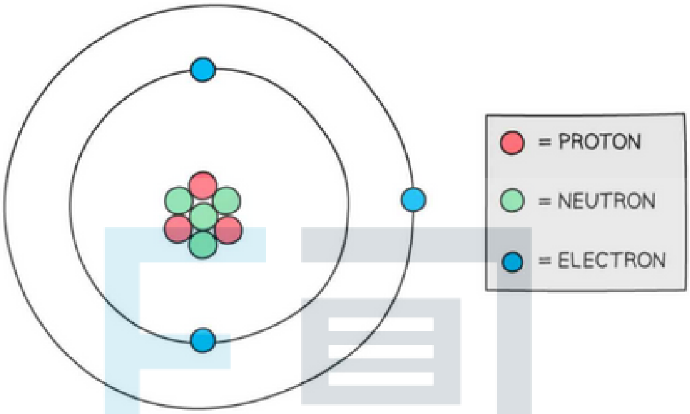
A Level Physics AQA

2.1 Atomic Structure & Decay Equations

CONTENTS

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}

- 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

Exam Tip

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.

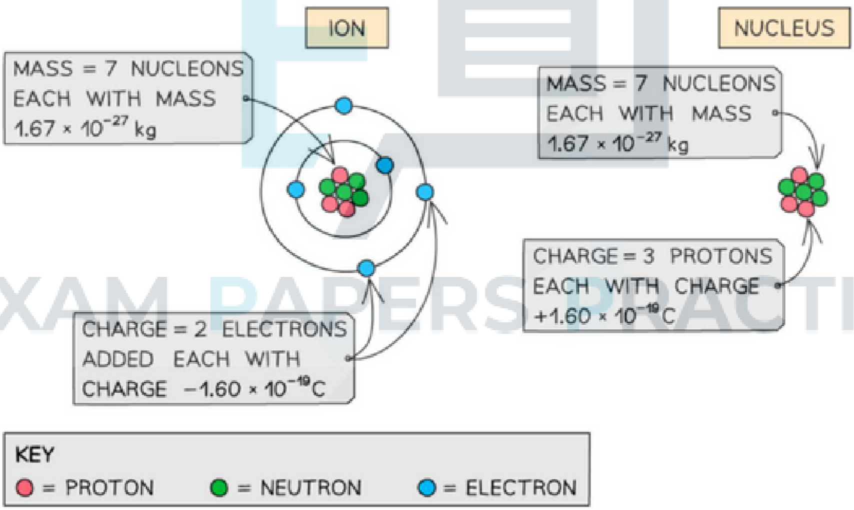
- In physics 'specific' means a characteristic of a property of a specific substance ie. per unit mass, length, area, volume etc.
  - For example, **specific** heat capacity refers to the thermal energy per unit mass of a substance
- In the same way, the specific charge of a particle is the ratio of its charge to its mass, which can be calculated using the equation:

$$\text{Specific charge} = \frac{\text{charge}}{\text{mass}} = \frac{Q}{m}$$

- Specific charge is measured in units of **coulombs per kilogram** ($C\ kg^{-1}$)
- Values for the specific charge of the electron and proton are given on the datasheet as the 'charge / mass ratio'
  - The specific charge of the electron = $(e / m_e) = 1.76 \times 10^{11}\ C\ kg^{-1}$
  - The specific charge of the proton = $(e / m_p) = 9.58 \times 10^{7}\ C\ kg^{-1}$

Calculating Specific Charge

- You may be asked to find the specific charge of an ion or a nucleus
  - Charge of a proton or electron, $e = 1.60 \times 10^{-19}$ C
  - Mass of a proton, m_p (or neutron, m_n) $= 1.67 \times 10^{-27}$ kg
- To calculate the specific charge of an ion:
  - Charge = Total number of electrons added / removed × (1.60×10^{-19} C)
  - Mass = Total number of nucleons × (1.67×10^{-27} kg)
- To calculate the specific charge of a nucleus:
  - Charge = Total charge of the protons × (1.60×10^{-19} C)
  - Mass = Total number of nucleons × (1.67×10^{-27} kg)
- The number of nucleons is given by the mass number of the ion or nucleus



How the total charge and mass are calculated depends on whether you are calculating the specific charge for an ion or a nucleus

Worked Example

An atom of $^{24}_{12}$Mg gains 2 electrons. What is the specific charge of the ion?

Step 1: Write the specific charge equation

$$\text{Specific charge} = \frac{Q}{m}$$

Step 2: Determine the number of protons

The atomic number is 12, therefore there are 12 protons in this ion

Step 3: Determine the number of neutrons

Number of neutrons = the mass number – atomic number

24 – 12 = 12 neutrons

Step 4: Calculate the total mass

Total mass = nucleon (mass) number × mass of one nucleon

$$24 \times (1.67 \times 10^{-27}) = 4.0 \times 10^{-26} \text{ kg}$$

Step 5: Calculate the total charge

Total charge = number of electrons × (-1.60×10^{-19})

$$2 \times (-1.60 \times 10^{-19}) = -3.2 \times 10^{-19} \text{ C}$$

Step 6: Substitute in values

$$\text{Specific charge} = \frac{-3.2 \times 10^{-19}}{4.0 \times 10^{-26}} = -8.0 \times 10^{6}\ \text{C kg}^{-1}$$

Exam Tip

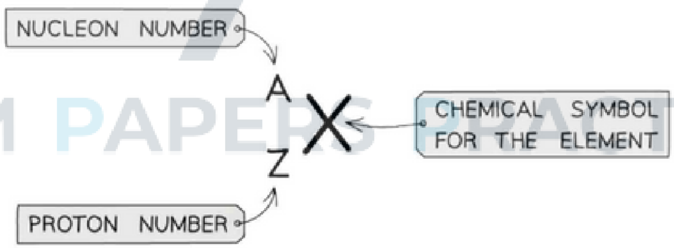
Sometimes you might be asked if the specific charge is positive or negative for an ion. Since the electron has a negative charge, the rules are as follows:

- If there is a gain in electrons, the specific charge will be **negative**.
- If there is a loss of electrons, the specific charge will be **positive**.

2.1.2 Nucleon & Proton Number

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

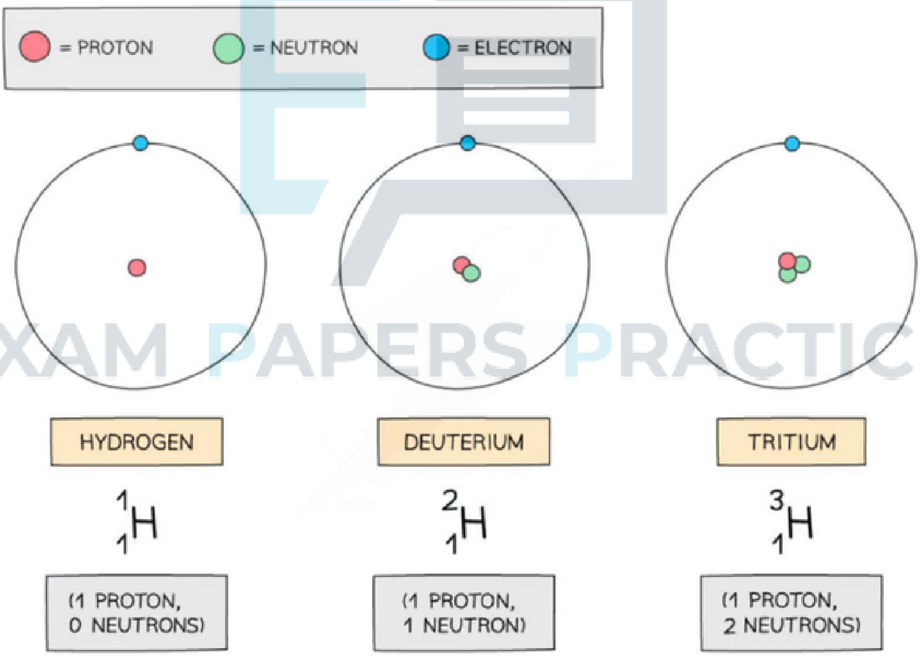
- The top number A represents the **nucleon** number or the **mass** number
  - **Nucleon number (A)** = total number of **protons and neutrons** in the nucleus
- The lower number Z represents the **proton** or **atomic** number
  - **Proton number (Z)** = total number of **protons** in the nucleus
- 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**

- 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 constantly decay and emit radiation to achieve a more stable form
  - This can happen from anywhere between a few nanoseconds to 100,000 years

Isotopic Data

- Isotopic data is defined as:

The relative amounts of different isotopes of an element found within a substance

- It is used to identify an **isotopic signature** within organic and inorganic materials
- Isotopic data is often used for determining the age of archaeological findings and is used in **radioactive dating**
- Carbon-14 is a naturally occurring isotope most often used for this, since it is present in all living beings and undergoes radioactive decay
- When a plant or animal dies, the natural decay of this isotope means the concentration of the carbon-14 in its tissue gradually reduces
- Since carbon-14 has a long half-life of around 6000 years, the half-life can be used to determine the age of the plant or animal when it died

Worked Example

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

	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: 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 protons in the first nucleus

Nucleon number: 37

Neutrons: 20

Protons = 37 – 20 = 17

Step 3: Calculate protons in the second nucleus

Nucleon number: 35

Neutrons: 18

Protons = 35 – 18 = 17

Step 4: Conclusion

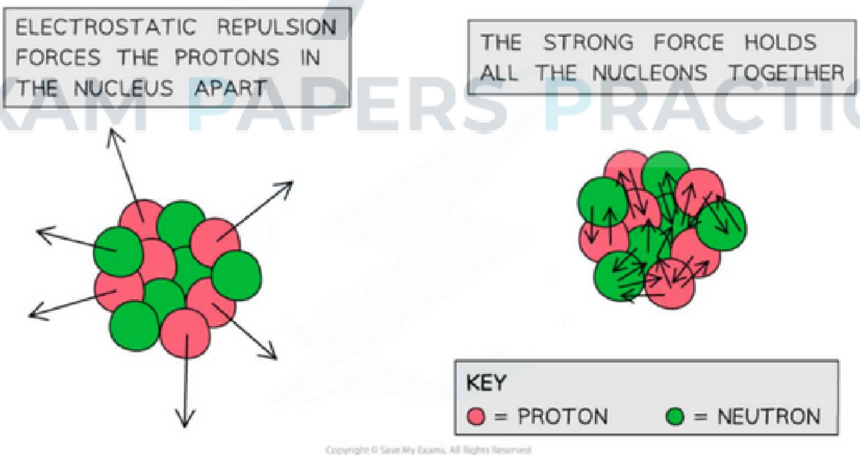
Therefore, they have the same number of protons but different numbers of neutrons and are isotopes of each other

The correct answer is therefore option **B**

2.1.3 Strong Nuclear Force

Strong Nuclear Force

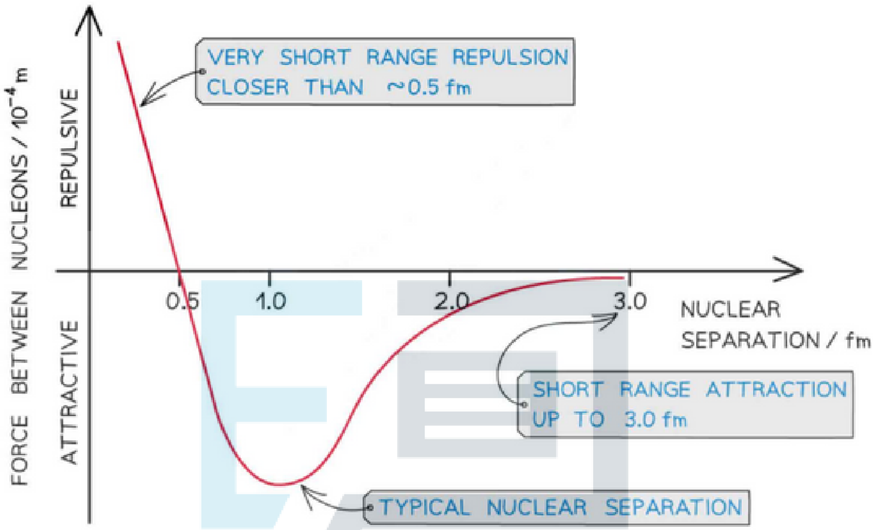
- In the nucleus, there are electrostatic forces between the protons due to their electric charge and gravitational forces due to their mass
- Comparatively, gravity is a very weak force and the electrostatic repulsion between protons is therefore much stronger than their gravitational attraction
- If 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
- 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)

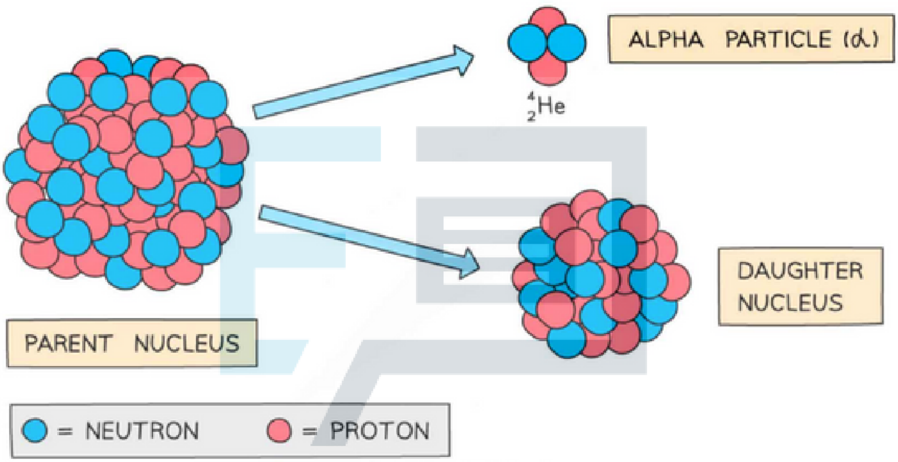
Exam Tip

- 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

α & β Decay Equations

Alpha Decay

- Alpha decay is common in large, unstable nuclei with too many protons
- The decay involves a nucleus emitting an alpha particle and decaying into a different nucleus
- An alpha particle consists of **2 protons and 2 neutrons** (the nucleus of a Helium atom)



Alpha decay produces a daughter nucleus and an alpha particle (helium nucleus)

- When an unstable nucleus (the parent nucleus) emits radiation, the constitution of its nucleus changes
- As a result, the isotope will change into a different element (the daughter nucleus)
- Alpha decay can be represented by the following radioactive decay equation:

$$^{A}_{Z}X \longrightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}\alpha$$

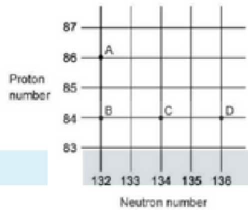
$$\text{e.g.} \quad ^{212}_{84}Po \longrightarrow \, ^{208}_{82}Pb + \, ^{4}_{2}\alpha$$

Alpha decay equation

- When an alpha particle is emitted from a nucleus:
  - The nucleus loses 2 protons: **proton number decreases by 2**
  - The nucleus loses 4 nucleons: **nucleon number decreases by 4**

Worked Example

The radioactive nucleus $^{222}_{86}\text{Rn}$ undergoes alpha decay into a daughter nucleus Po.



(a)

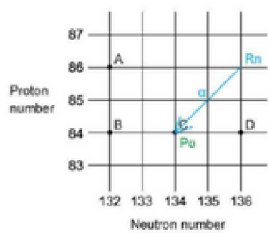
Which letter in the diagram represents the daughter product?

(b)

What is the nucleon number and proton number of Po?

(a) Answer: C

- The number of neutrons in $^{222}_{86}\text{Rn}$ is 222 – 86 = 136
- In alpha decay, the parent nucleus loses a helium nucleus (2 protons, 2 neutrons)
  - Proton number: 86 decreases to 84
  - Neutron number: 136 decreases to 134



- Therefore, the correct answer is **C**

(b)

- The equation for alpha decay is as follows:

$$^{A}_{Z}X \longrightarrow \, ^{4}_{2}\alpha + \, ^{A-4}_{Z-2}Y$$

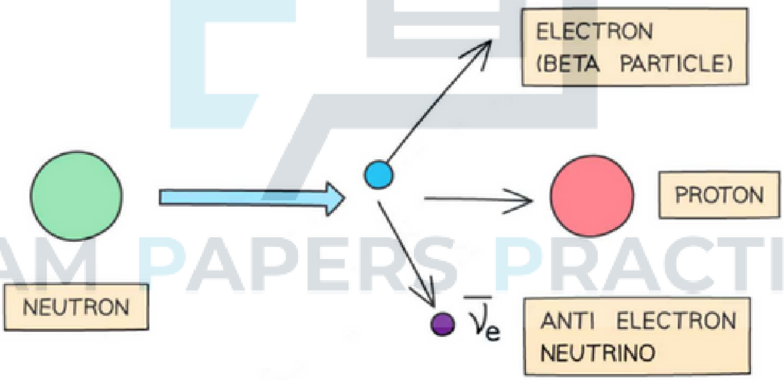
$$^{222}_{86}Rn \longrightarrow \, ^{4}_{2}\alpha + \, ^{218}_{84}Po$$

- Hence the daughter nucleus Po has
  - Nucleon number = 222 – 4 = 218
  - Proton number = 86 – 2 = 84

Beta-Minus Decay

- A beta-minus, β^-, particle is a high energy electron emitted from the nucleus

- β^- decay is when a **neutron turns into a proton emitting an electron and an anti-electron neutrino**



$$n \longrightarrow p + e^- + \bar{\nu}_e$$

- When a β^- particle is emitted from a nucleus:
  - The number of protons increases by 1: **proton number increases by 1**
  - The total number of nucleons stays the same: **nucleon number remains the same**

$$^{A}_{Z}X \rightarrow \ ^{A}_{Z+1}Y + \ ^{0}_{-1}\beta + \ ^{0}_{0}\overline{\nu}_e$$

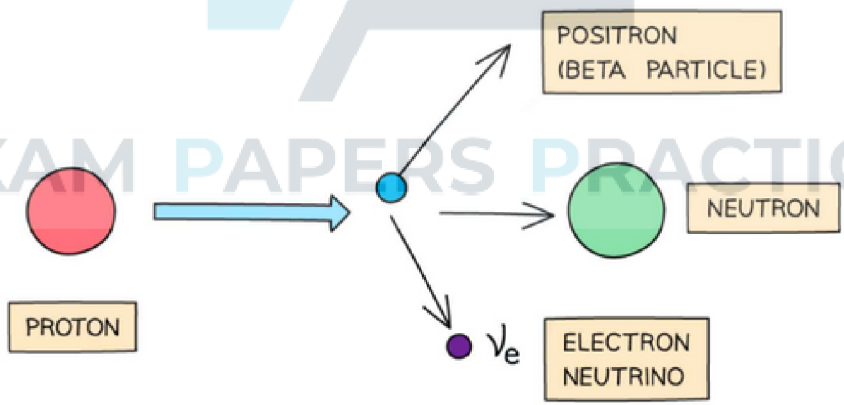
$$\text{e.g.} \quad ^{14}_{6}C \rightarrow \ ^{14}_{7}N + \ ^{0}_{-1}\beta + \ ^{0}_{0}\overline{\nu}_e$$

Equation for beta minus emission

- The new nucleus formed from the decay is called the "daughter" nucleus (nitrogen in the example above)

Beta-Plus Decay

- A beta-plus, β^+, particle is a high energy positron emitted from the nucleus
- β^+ decay is when a **proton turns into a neutron emitting a positron (anti-electron) and an electron neutrino**



$$p \rightarrow n + e^+ + \nu_e$$

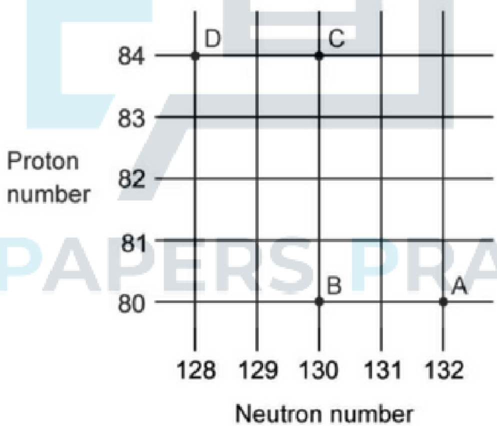
- When a β^+ particle is emitted from a nucleus:
  - The number of protons decreases by 1: **proton number decreases by 1**
  - The total number of nucleons stays the same: **nucleon number remains the same**

$$^{A}_{Z}X \longrightarrow \, ^{A}_{Z-1}Y + \, ^{0}_{+1}\beta + \, ^{0}_{0}\nu_e$$

e.g. $$^{6}_{6}C \longrightarrow \, ^{6}_{5}B + \, ^{0}_{+1}\beta + \, ^{0}_{0}\nu_e$$

Worked Example

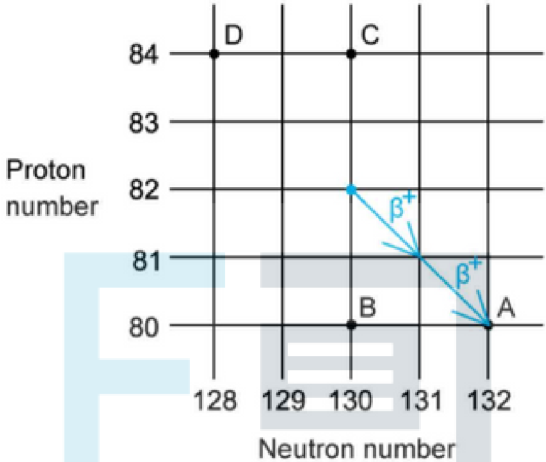
A radioactive substance with a nucleon number of 212 and a proton number of 82 decays by β-plus emission into a daughter product which further decays by β-plus emission into a granddaughter product.



Which letter in the diagram represents the granddaughter product?

Answer: A

- The number of neutrons in the parent nucleus is 212 – 82 = 130
- In beta-plus decay, a proton turns into a neutron
  - Proton number: 82 decreases to 80
  - Neutron number: 130 increases to 132



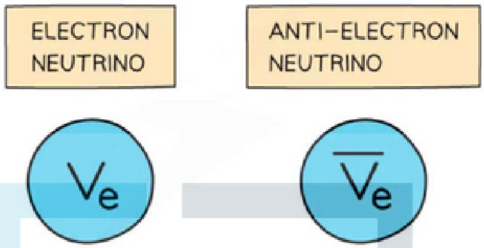
- Therefore, the correct answer is **A**

Exam Tip

Remember to avoid the common mistake of confusing the number of neutrons with the nucleon number. In alpha decay, the nucleon (protons and neutrons) number decreases by 4 but the number of neutrons only decreases by 2.

Neutrino Emission

- An electron neutrino is a type of subatomic particle with no charge and negligible mass which is also emitted from the nucleus
- The anti-neutrino is the antiparticle of a neutrino
  - Electron anti-neutrinos are produced during β- decay
  - Electron neutrinos are produced during β+ decay



- Although the neutrino has no charge and **negligible mass**, its existence was hypothesised to account for the conservation of **energy in beta decay**

Exam Tip

One way to remember which particle decays into which depends on the type of beta emission, think of beta '**p**lus' as the '**p**roton' that turns into the neutron (plus an electron neutrino)

2.1.5 Particles, Antiparticles & Photons

Antimatter

- The universe is made up of **matter** particles (protons, neutrons, electrons etc.)
- All matter particles have antimatter counterparts
  - **Antimatter particles are identical to their matter counterpart but with the opposite charge**
- This means if a particle is positive, its antimatter particle is negative and vice versa
- Common matter-antimatter pairs are shown in the diagram below:

Matter-Antimatter Table

Matter	Charge	Antimatter	Charge
Electron e^-	−1	Positron e^+	+1
Proton p	+1	Anti-proton $\bar{p}$	−1
Neutron n	0	Anti-neutron $\bar{n}$	0
Neutrino ν	0	Anti-neutrino $\bar{\nu}$	0

- Apart from electrons, the corresponding antiparticle pair has the same name with the prefix **'anti-'** and a line above the corresponding matter particle symbol
- A neutral particle, such as a neutron or neutrino, **is its own antiparticle**

Properties of Antiparticles

- Although antimatter particles have the opposite charges to their matter counterparts, they still have **identical mass and rest mass-energy**
  - The rest mass-energy of a particle is the energy equivalent to the mass of the particle at rest
- The datasheet provides the masses in kg and rest-mass energies in MeV for a proton, neutron, electron and neutrino
- These masses are identical for their corresponding antiparticles (antiproton, antineutron, positron and antineutrino respectively)

Mass & Rest Mass Energy Table

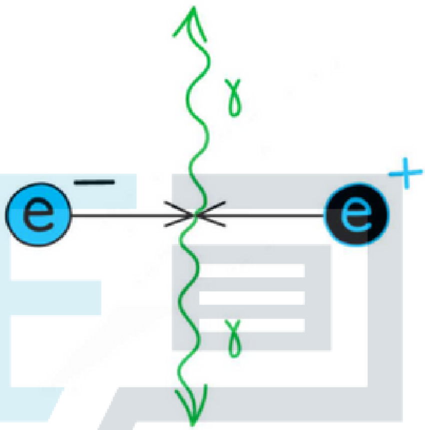
Particle/ Antiparticle	Mass (kg)	Rest Mass Energy (MeV)
Proton/ antiproton	$1.67(3) \times 10^{-27}$	938.257
Neutron/ antineutron	$1.67(5) \times 10^{-27}$	939.551
Electron/ positron	9.11×10^{-31}	0.510999
Neutrino/ antineutrino	0	0

Annihilation & Pair Production

Annihilation

- When a particle meets its antiparticle pair, the two will **annihilate**
- Annihilation is:

When a particle meets its equivalent anti-particle they both are destroyed and their mass is converted into energy in the form of two gamma ray photons



When an electron and positron collide, their mass is converted into energy in the form of two photons emitted in opposite directions

- The minimum energy of **one** photon after annihilation is the total rest mass energy of **one** of the particles is:

$$E_{min} = hf_{min} = E$$

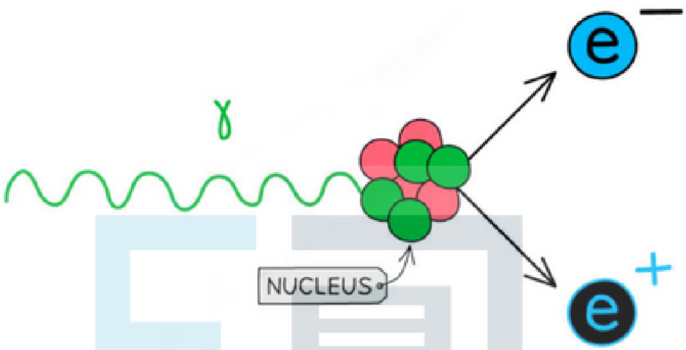
- Where:
  - E_{min} = minimum energy of one of the photons produced (J)
  - h = Planck's Constant (J s)
  - f_{min} = minimum frequency of one of the photons produced (Hz)
  - E = rest mass energy of one of the particles (J)

- To conserve momentum, the two photons will move apart in **opposite** directions
- As with all collisions, the mass and energy is still conserved

Pair Production

- Pair production is the opposite of annihilation
- Pair production is:

When a photon interacts with a nucleus or atom and the energy of the photon is used to create a particle-antiparticle pair



When a photon with enough energy interacts with a nucleus it can produce an electron-positron pair

- This means the energy of the photon must be above a certain value to provide the total rest mass energy of the particle-antiparticle pair
- The minimum energy for a photon to undergo pair production is the total rest mass energy of the particles produced:

$$E_{min} = hf_{min} = 2E$$

- Where:
  - E_{min} = minimum energy of the incident photon (J)
  - h = Planck's Constant (J s)
  - f_{min} = minimum frequency of the photon (Hz)
  - E = rest mass energy of one of the particles (J)

- To conserve momentum, the particle and anti-particle pair move apart in **opposite** directions
- Remember for both calculations, the frequency f is also defined by the wave equation

WAVE SPEED = FREQUENCY × WAVELENGTH

-

$$v = f \times \lambda$$

Using this equation, the wavelength λ can also be calculated

- Remember that v is c (the speed of light) for gamma ray photons

Worked Example

Calculate the maximum wavelength of one of the photons produced when a proton and antiproton annihilate each other.

Step 1: Write down the known quantities

Rest mass energy of a proton (and antiproton) = 938.257 MeV

$$1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$$

Step 2: Write the equation for the minimum photon energy

$$E_{min} = hf_{min} = E$$

Step 3: Write energy in terms of wavelength

$$f_{min} = \frac{c}{\lambda_{max}}$$

$$E_{min} = \frac{hc}{\lambda_{max}} = E$$

Step 4: Rearrange for wavelength

$$\lambda_{max} = \frac{hc}{E}$$

Step 5: Substitute in values

$$\lambda_{max} = \frac{(6.63 \times 10^{-34}) \times (3.0 \times 10^{8})}{938.257 \times (1.60 \times 10^{-13})} = 1.32 \times 10^{-15} \text{ m}$$

Exam Tip

Since the Planck constant is in Joules (J) remember to always convert the rest mass-energy from MeV to J.