2.3 Conservation Laws and Particle interactions

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

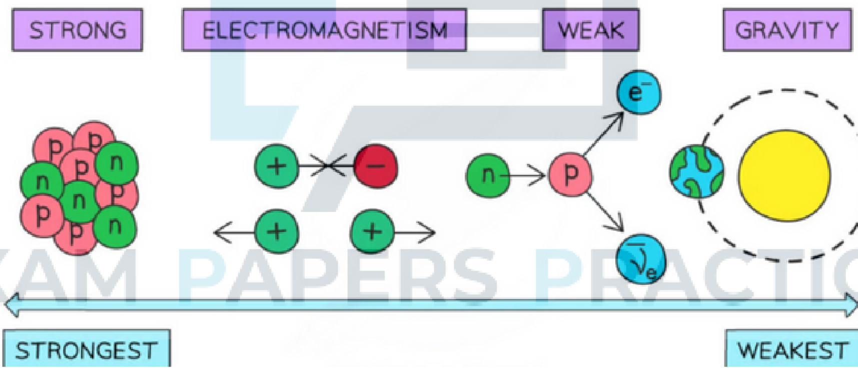
2.3 Conservation Laws & Particle Interactions

CONTENTS

The Four Fundamental Interactions

- There are four fundamental interactions, or fundamental forces, that exist. These are:
  - **Gravity**
  - **Electromagnetism**
  - **Strong Nuclear (or Strong Interaction)**
  - **Weak Nuclear**

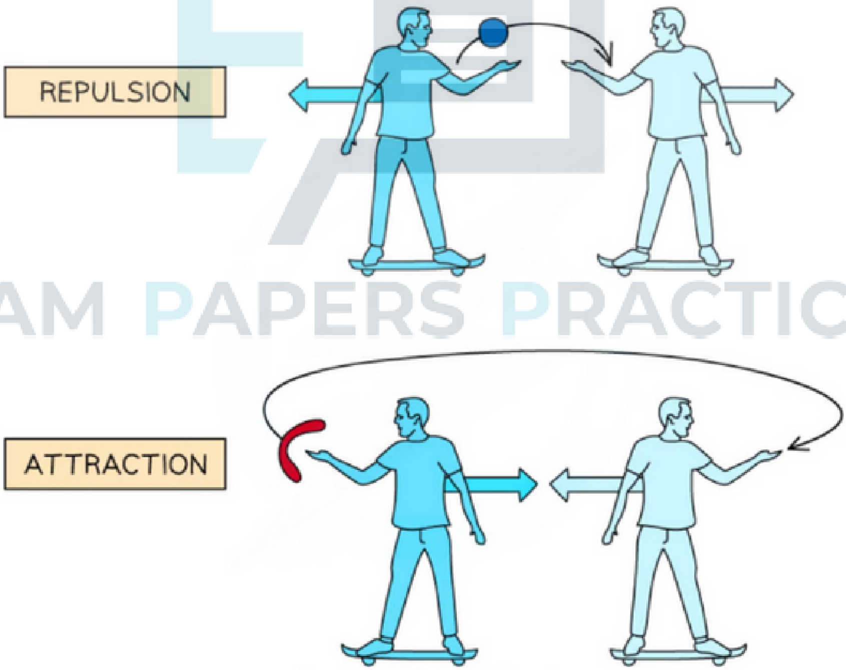
- Gravity is the weakest of these forces, whilst the strong interaction is the strongest (hence the name)
- They also have different ranges:
  - The electromagnetic and gravitational interactions have an infinite range
  - The weak force has a range of up to 10^{-18} m
  - The strong force has a range of ~ 10^{-15} m



Exchange Particles

- When two particles interact, there cannot be instantaneous action at a distance
  - This means one particle needs to "know" that the other is there

- This is the idea behind **exchange** (or **virtual**) particles
- When two particles exert a force on each other, a virtual particle is created
- Virtual particles only exist for a short amount of time and carry the fundamental force between each particle
- A force can be **attractive** or **repulsive**. An analogy of exchange particles would be:
  - Two people are on skateboards and a ball is passed between them. Due to this, they start to move away from each other. The ball represents an exchange particle creating **repulsion**
  - However, if one person throws a boomerang to the other, they will start to move closer together. The boomerang represents an exchange particle creating **attraction**



Both skateboarders can create repulsion or attraction by throwing a ball or boomerang between them. The ball and boomerang represent exchange particles.

- Each fundamental interaction is transmitted by its own exchange particle
  - These are also called **gauge bosons**

Table of Exchange Particles

Fundamental Interaction	Exchange Particle
Strong	pion(π^+, π^-, π^0) (between nucleons) gluon (between quarks)
Weak	W^+, W^-, Z^0
Electromagnetic	Photon, γ

- Since gravity is so weak, it only has a noticeable effect on large masses, therefore, gravity does not play a part in particle interactions
- The theorised exchange particle for the gravitational force is the graviton, however, this has not yet been discovered

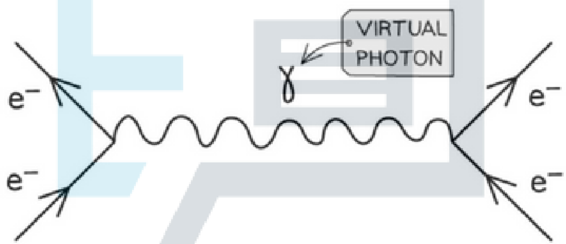
Exam Tip

You will be expected to remember which exchange particle mediates which fundamental interaction for your exam. This is particularly important when drawing Feynman diagrams, as the correct exchange particle will be expected to be on them.

The Electromagnetic Force

- The electromagnetic force is only between charged particles
- The exchange particle that carries this force is the **virtual photon, γ**
- Properties of the photon are:
  - It has no mass
  - It has no charge
  - It is its own antiparticle

- Electromagnetic interactions occur whenever two charged particles interact with each other
- For example, when two charged particles, such as electrons, are repelled by each other, a virtual photon is exchanged between them to produce this repulsion



Feynman diagram of electromagnetic repulsion between two electrons shown by the exchange of a virtual photon

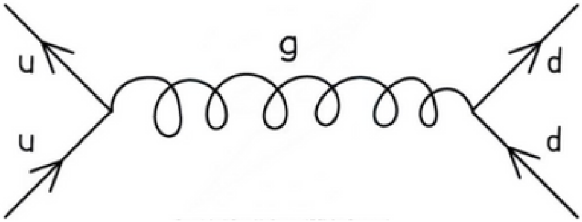
- The electromagnetic force is also responsible for binding electrons to atoms
  - This is due to the attractive force between the negative electrons and positive nucleus

Hadrons & The Strong Nuclear Force

- Hadrons are particles that are made up of quarks
  - Hence they are subject to the **strong** interaction

- The exchange particle of the strong interaction is either:
  - The **pion** (between nucleons)
  - The **gluon** (between quarks)

- This means that leptons cannot interact with the strong force, since they are not made up of quarks



Feynman diagram of the interaction between an up and down quark. The gluon is the exchange particle between them.

2.3.3 The Weak Interaction

The Weak Interaction

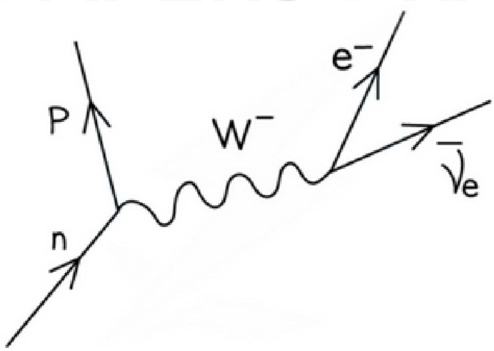
- The weak interaction is responsible for the radioactive decay of atoms
- The exchange particle that carries this force is the **W⁻**, **W⁺** or **Z^0** boson
  - The type of exchange particle depends on the type of interaction

β decay

- β^- and β^+ decay are examples of the weak interaction in action
- In β^- decay, a **neutron** turns into a **proton** emitting an **electron** and an **anti-electron neutrino**

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

- The W^- boson is the exchange particle in this interaction

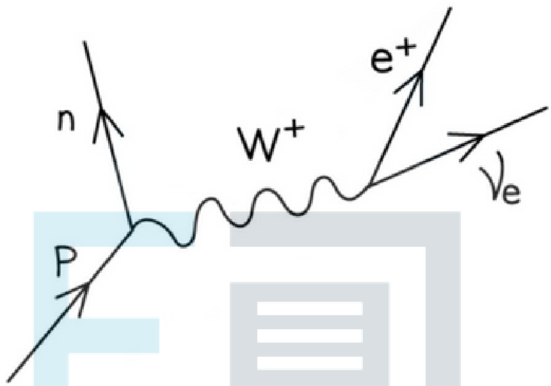


Feynman diagram showing beta minus decay. The W^- boson is the exchange particle

- In β^+ decay, a **proton** turns into a **neutron** emitting a **positron** and an **electron neutrino**

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

- The W^+ boson is the exchange particle in this interaction



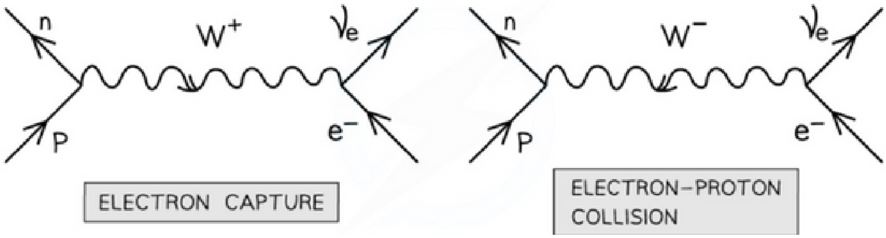
Feynman diagram showing beta plus decay. The W^+ boson is the exchange particle

Electron Capture & Electron–Proton Collisions

- Electrons and protons are attracted to each other via the electromagnetic interaction
  - However, when they interact with each other, it is the weak interaction that facilitates the collision
- Both electron capture and electron-proton collisions have the same decay equation

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

- Electron capture is when **an atomic electron is absorbed by a proton in the nucleus** resulting in the release of a neutron and an electron neutrino
  - This decay is mediated by the W^+ boson
- Electron-proton collisions are similar; when **an electron collides with a proton**, a neutron and an electron neutrino are emitted
  - This decay is mediated by the W^- boson



Feynman diagrams for electron capture and an electron-proton collision. These are equal except for the sign of the W boson

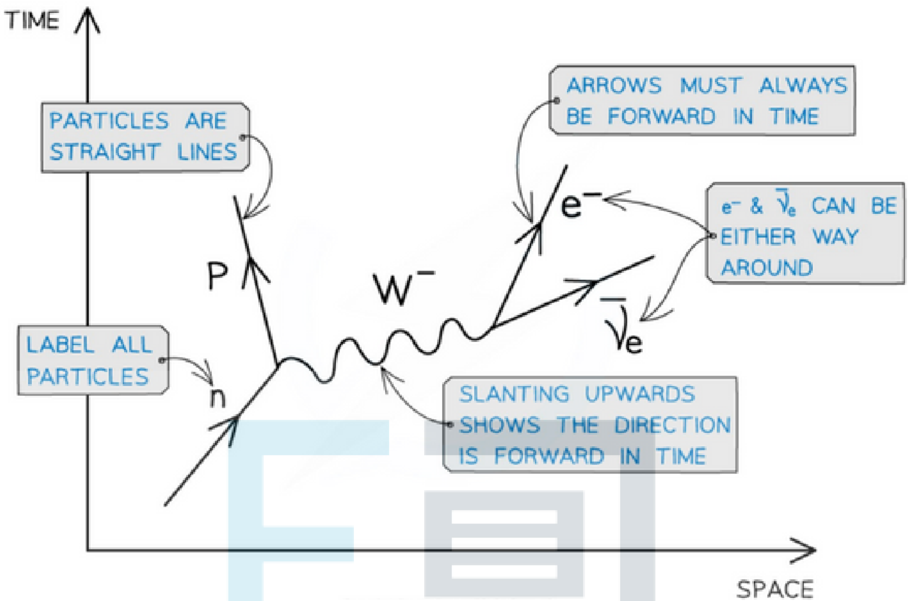
Exam Tip

Notice that the sign of the W boson matches that of the beta decay. The W^- boson is exchanged in beta **minus** decay and W^+ **boson is exchanged** in beta **plus** decay.

2.3.4 Feynman Diagrams

Feynman Diagrams

- Feynman diagrams are a clear way of representing particle interactions in terms of their incoming and outgoing particles and exchange particles
- Although there are many variations of Feynman diagrams, they follow a set of rules:
  - The vertical axis represents **time**
  - The horizontal axis represents **space**
  - Gauge bosons are represented by a wavy or dashed lines or a helix
  - All other particles are represented by **straight** lines
  - Each line (apart from neutral gauge bosons) can have an **arrow** with its direction forward in time
  - The total charge, baryon number and lepton number **must** be **conserved** at each vertex
  - Particle lines must **not** cross over



Feynman diagrams follow a set of rules which are needed to interpret them accurately

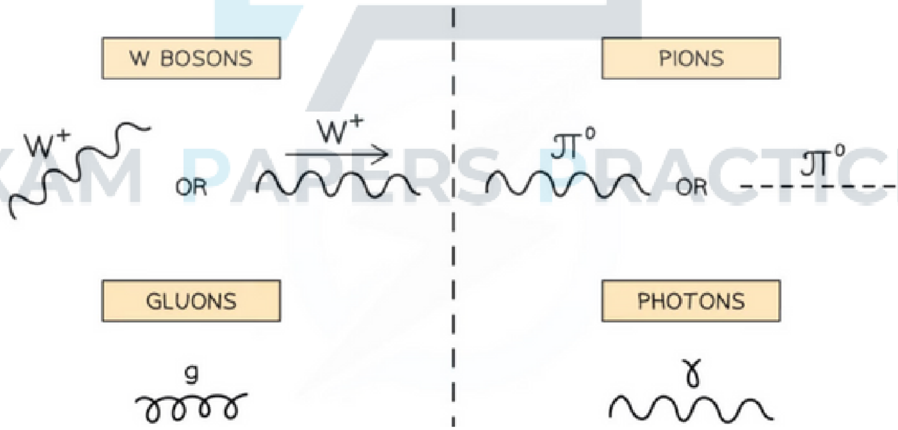
- Feynman diagrams show nothing about the actual path of the particles, so the angles in the diagram are of no significance
- Note that you might find the following variations of Feynman diagrams:
  - The vertical axis representing space and the horizontal axis representing time
  - Anti-particles represented as moving backwards in time
- However, it is best to stick to the rules given for this syllabus which have time on the vertical and space on the horizontal axis and all particles moving forward in time

Exchange Particles

- Gauge bosons are represented differently in each Feynman diagram depending on the type of interaction
- Charged exchange particles (W^+ and W^-) sometimes have an arrow with their direction indicated

- Representing exchange particles:
  - In the weak interaction, W and Z bosons are represented by a wavy line
  - The W^+ and W^- can have an arrow showing their direction (left or right) or must be slanted upwards, meaning that they are forward in time
  - Pions are represented by a wavy or dashed line
  - Photons are represented by a wavy line
  - Gluons are represented by a helix

- The sign of the W particle depends on the other particles involved in the decay
  - The $\mathbf{W^+}$ particle 'carries away' a **positive** charge
  - The $\mathbf{W^-}$ particle 'carries away' a **negative** charge
- The charge must always be **conserved** at each vertex
- Therefore, in the Feynman diagram above where a neutron turns into a proton, the W^- **carries away** a negative charge from the neutral neutron, leaving a positive charge of the proton
  - The negative charge is then carried over to the vertex with the electron and anti-neutrino
  - Since the combined charge of an electron and anti-neutrino is negative, this vertex has now 'gained' a negative charge



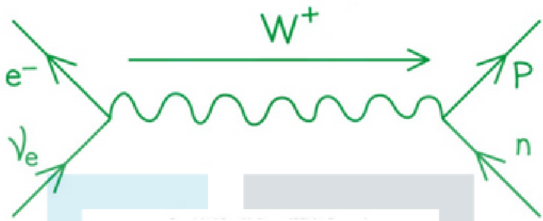
The gauge bosons are depicted by a wavy or dashed line, or a helix depending on the type of interaction

Worked Example

A neutron interacts with a neutrino in the following way:

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

Draw the Feynman diagram that corresponds to the neutron and neutrino interaction represented in the equation.



- The vertical axis represents time and the horizontal axis represents space
- All particles are labelled correctly
- All particles are represented by straight lines and arrows pointing forward in time
- W^+ boson represented by a wavy line with an arrow pointing towards the neutron-proton vertex

Exam Tip

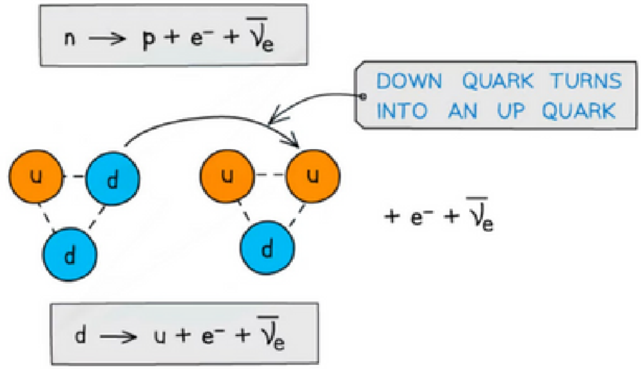
The most common exam mistakes when asked to draw Feynman diagrams are missing out arrows indicating the direction of charged gauge bosons or particles. Although you are not required to sketch and label the space and time axes, all particles must be labelled accurately.

Quark Transformation in β decay

- β decay occurs because of the weak interaction between quarks

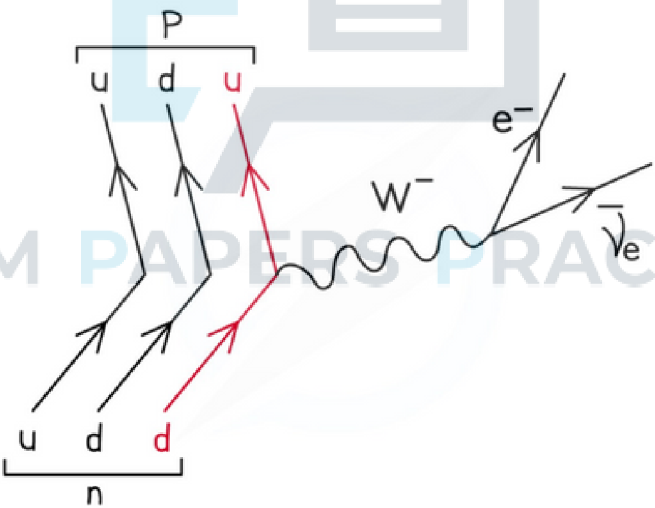
Quark Composition: β^- decay

- β^- decay is when a neutron turns into a proton emitting an electron and anti-electron neutrino
- More specifically, a neutron turns into a proton because a **down** quark turns into an **up** quark



Beta minus decay is when a down quark turns into an up quark

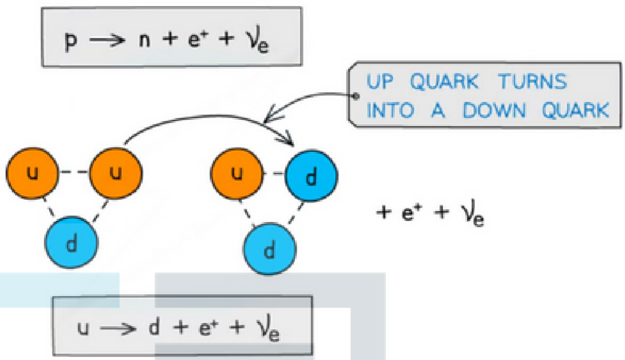
- The W^- boson 'carries away' the negative charge of the down quark which provides the negative charge for the electron and anti-neutrino



In beta minus decay, the weak interaction turns a down quark into an up quark

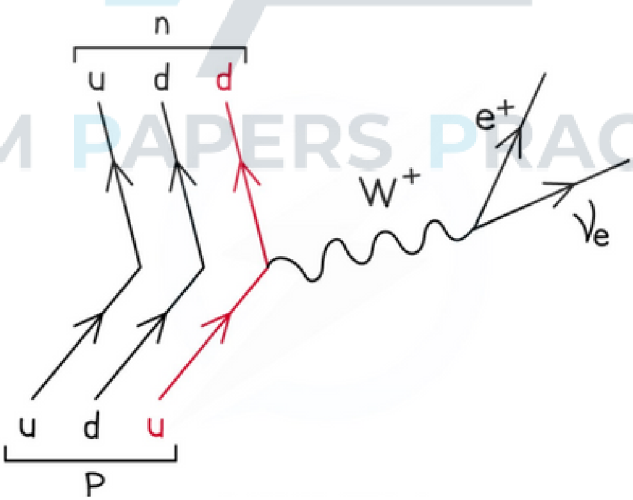
Quark Composition: β^+ decay

- β^+ decay is when a proton turns into a neutron emitting an positron and an electron neutrino
- More specifically, a proton turns into a neutron because an **up** quark turns into a **down** quark



Beta plus decay is when an up quark turns into a down quark

- The W^+ boson 'carries away' the positive charge of the up quark which provides the positive charge for the positron and neutrino



In beta plus decay, the weak interaction turns an up quark into a down quark

Application of Conservation Laws

- All particle interactions must obey a set of conservation laws. These are conservation of:
  - Charge, ***Q***
  - Baryon number, ***B***
  - Lepton Number, ***L***
  - Strangeness, ***S***
  - Energy (or mass-energy)
  - Momentum

- However, strangeness does not need to be conserved in weak interactions. It can change by either 0, +1 or −1
- Quantum numbers such as ***Q***, ***B***, ***L*** and ***S*** can only take discrete values (ie. 0, +1, −1, 1/2)
- To know whether a particle interaction can occur, check whether each quantum number is equal on both sides of the equation
  - If even one of them, apart from strangeness in weak interactions, is not conserved then the interaction cannot occur

	K^+	$\rightarrow$	μ^+	+	ν_μ	
Q	+1	=	+1	+	0	CONSERVED ✓
B	0	=	0	+	0	CONSERVED ✓
L	0	=	−1	+	+1	CONSERVED ✓
S	+1	=	0	+	0	NOT CONSERVED ✗

Example of a working out what is conserved in Kaon decay. This decay must be through the weak interaction since S is not conserved

Worked Example

The lambda nought particle Λ^0 is made up from the quarks uds. Show, in terms of the conservation of charge, strangeness, baryon number and lepton number whether the following interaction is permitted

$$\Lambda^0 \rightarrow \pi^- + e^+ + \nu_e$$

Step 1: Determine conservation of charge

$$0 = -1 + 1 + 0$$

Charge is conserved

Step 2: Determine conservation of strangeness

Λ^0 has an s quark, so must have a strangeness of −1

$$-1 = 0 + 0 + 0$$

Strangeness is not conserved

Step 3: Determine conservation of baryon number

Λ^0 is a baryon since it has 3 quarks, so must have a baryon number of +1

$$+1 = 0 + 0 + 0$$

Baryon number is not conserved

Step 4: Determine conservation of lepton number

Λ^0 is a baryon, so must have a lepton number of 0

$$0 = 0 + (-1) + 1$$

Lepton number is conserved

Step 5: Conclusion

Since the baryon number is not conserved, this interaction is **not permitted**

Worked Example

The equation for β^- decay is

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

Using the quark model of beta decay, prove that the charge is conserved in this equation.

STEP 1	β^- DECAY IS WHEN A DOWN QUARK CHANGES TO AN UP QUARK THIS CHANGES A NEUTRON INTO A PROTON
STEP 2	CHARGE OF THE LEFT HAND SIDE OF THE EQUATION THE QUARK COMPOSITION OF A NEUTRON IS udd
STEP 3	ADDING UP THE QUARK CHARGES: +2/3 – 1/3 – 1/3 = 0 THE LEFT HAND SIDE HAS A CHARGE OF 0
STEP 4	CHARGE ON THE RIGHT HAND SIDE OF THE EQUATION THE QUARK COMPOSITION OF A PROTON IS uud
STEP 5	ADD UP THE QUARK CHARGES: +2/3 + 2/3 – 1/3 = +1
STEP 6	THE ELECTRONS CHARGE IS –1 THE ANTI–NEUTRINOS CHARGE IS 0 THE RIGHT HAND SIDE HAS A CHARGE OF +1 – 1 + 0 = 0
STEP 7	SINCE THE CHARGES ARE EQUAL ON BOTH SIDES, IT IS CONSERVED IN THE BETA DECAY EQUATION

Exam Tip

Note:

- Quantum numbers for any exotic particles will be given in the question
- All the rest can be found on the datasheet or can be deduced using the information provided