A2 Level Physics

Chapter 8 – Nuclear and Particle Physics

8.2.1 Fundamental Particles

Notes

Particles and Antiparticles

For every particle there is an antiparticle (e.g. the positron is the antiparticle of the electron).

A particle and its antiparticle have:

- The same mass
- Equal, but opposite charge

All particles are referred to as matter, while antimatter refers to antiparticles.

Some examples/properties of particle-antiparticle pairs are shown in the table below:

Particle/Antiparticle	Symbol	Relative Charge	Mass (kg)
Proton	p	+1	1.67×10^{-27}
Antiproton	$\overline{p}$	-1	
Neutron	n	0	1.67×10^{-27}
Antineutron	$\overline{n}$		
Electron	e^-	-1	9.11×10^{-31}
Positron	e^+	+1	
Neutrino	v_e	0	0
Antineutrino	$\overline{v_e}$		

Particles and Antiparticles

Neutrinos and antineutrinos are so small that they are thought to have no mass and no rest energy.

In 1928, British physicist Paul Dirac mathematically predicted the presence of antimatter. His equation described a particle that was nearly identical to an electron except for the fact that it was positively charged (i.e. positron).

Carl Anderson was the first to detect these positrons in 1932.

Antiprotons and antineutrons were first discovered in accelerator particle collision experiments in the 1950s, and antiparticles have been discovered for all known particles since then.

When cosmic rays collide with molecules in the atmosphere, many antiparticles are created naturally.

The various types of particles identified are categorised or classified based on their nature and interaction.

There are 4 types of interaction:

- **Strong interaction**

This is the force that holds nucleons together i.e. hadrons.

- **Weak Interaction**

This is responsible for the radioactive decay of atoms. It causes two types of beta (β) decay $(\beta^- \ and \ \beta^+)$ from radioactive nuclei.

- **Electromagnetic interaction**

This is responsible for the electric force between charged particles (i.e. respulsive or attractive).

- **Gravitational interaction**

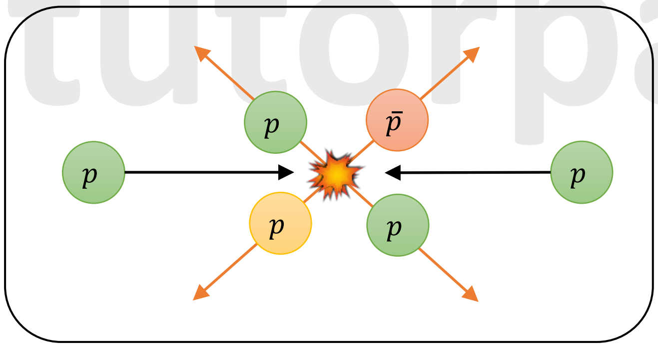
This is the force that governs the motion of planets around stars, moons around planets, and so on...

Pair Production

Energy can transform into mass, and mass can turn into energy, according to one of Einstein's most renowned theories. When energy is transformed to mass, matter and antimatter are produced in equal amounts. This is referred to as pair production.

Pair production only occurs if there is sufficient energy to produce the masses of the particles. It always produces a particle and its corresponding antiparticle because certain quantities must be conserved.

For example, if you fire two protons with a large amount of KE at each other (i.e. they're moving at high speeds), you'll get a lot of energy at the point of impact. Since protons repel each other, causing them to collide takes a lot of energy. When they do collide, the energy supplied is released, hence proton-proton collisions release a lot of energy.



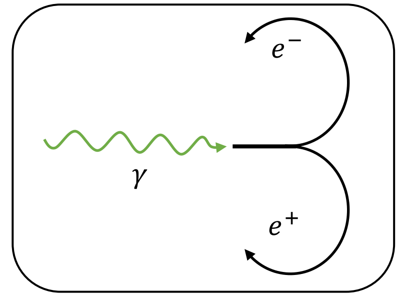
Pair production – two protons colliding and producing a proton-antiproton pair

This energy could be converted to produce more particles. If an extra proton is formed, there will be an antiproton produced too.

Pair Production/Annihilation

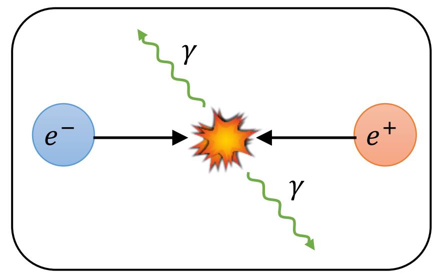
Since electron-positron pairings have a low mass, they are more likely to be formed than any other pair when it comes to pair production.

As there is usually a magnetic field present, the particle trajectories are curved and since the electron and positron have opposite charges, they curve in opposite directions.



Pair production – an electron-positron pair produced from a gamma ray photon

Annihilation is the opposite of pair production. When a particle collides with its antiparticle, annihilation occurs. During annihilation, the particle and antiparticles' entire mass is converted back into energy in the form of two gamma ray photons.



Electron-positron annihilation

To conserve momentum, two gamma ray photons travelling in opposing directions are always produced in annihilation.

The Electronvolt (eV)

When dealing with photons, the energies involved are so little that it makes sense to use a unit other than the Joule, J. When dealing with photon energy, you can use the electronvolt (eV) as a more convenient unit.

1 electronvolt (eV) is the energy transferred by an electron when it moves between two points by a potential difference (p.d.) of 1 Volt.

The kinetic energy (E) gained by an electron (with charge, $Q = e = 1.6 \times 10^{-19} C$) moving through a p.d. of $1\ V$ is given by:

$$E = QV = (1.6 \times 10^{-19}\ C) \times (1\ V)$$

Hence,

$$1\ eV = 1.6 \times 10^{-19}\ J$$

To convert from J to eV: divide by $1.6 \times 10^{-19}\ J$

To convert from eV to J: multiply by $1.6 \times 10^{-19}\ J$

Kinetic Energy and eV

When an electron is accelerated between two electrodes, some electrical potential energy (eV) is converted into kinetic energy (KE).

Consider an electron with a charge (e) and mass (m) that is initially at rest before being accelerated through a p.d. (V) to a final speed (v).

Then:

The KE energy gained by an electron is equal to the work done on it by the accelerating p.d. so:

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

Where:

m = mass of electron measured in kg

v = speed of electron measured in ms^{-1}

e = electron charge measured in C

V = potential difference measured in volts, V

Rearranging the above formula, we get the following equation for electron speed (v):

$$v = \sqrt{\frac{2eV}{m}}$$

Note:

These equations apply to any charged particle.

When the accelerating p.d. is large, the equations are invalid. This is because the charged particles' speeds could approach the speed of light (c), requiring consideration of the relativistic effect of mass increase (i.e. mass is no longer constant).

ΔE=Δmc²

Energy can transform into mass and mass can turn into energy, as shown by Einstein's famous equation $E = mc^2$. This equation indicates that multiplying an object's mass by the square of the speed of light yields its energy equivalent. In processes where energy converts to mass, both matter and antimatter are produced equally, illustrating the constant interchange of matter and energy in the universe.

$$\Delta E = \Delta mc^2$$

When enough energy is present, such as from a gamma ray photon, particles can spontaneously appear, converting the energy into matter. This phenomenon is common in the universe but occurs on a sub-atomic level, requiring advance equipment to detect.

Worked example

A gamma ray photon transforms into an electron and its antimatter counterpart, the positron, both of which have the same mass. Calculate the frequency of the gamma photon.

Solution:

Mass of an electron: $m_e = 9.11 \times 10^{-31}\ kg$.

- Use Einstein's equation to find the energy equivalence of this mass.
$$\Delta E = \Delta mc^2 = (9.11 \times 10^{-31})(3 \times 10^8)^2$$
$$\Delta E = 8.2 \times 10^{-14}\ J$$

- This is the amount of energy needed to produce an electron or a positron. Therefore, to produce both an electron and a positron, the energy of the photon must be double this, totalling: $16.4 \times 10^{-14}\ J$.

Now using $E = hf$, calculate the frequency of the photon:

$$\therefore f = \frac{E}{h} = \frac{16.4 \times 10^{-14}}{6.63 \times 10^{-34}}$$
$$f = 2.47 \times 10^{20}\ Hz$$

Mev/GeV (energy) and MeV/c² and GeV/c²

The electronvolt (eV) is a small unit of energy $(1\ eV = 1.6 \times 10^{-19} J)$. In particle physics, where energies often reach millions or billions of electronvolts, units like MeV (mega-electronvolts) and GeV (giga-electronvolts) are commonly used to describe particle interactions.

Similarly, the atomic mass unit (u), is not an SI unit and is a very small unit of mass widely used in particle physics $(1\ u = 1.67 \times 10^{-27} kg)$.

Energy and mass are linked by the equation $\Delta E = \Delta mc^2$, allowing mass to be expressed in energy units divided by speed of light squared (E/c^2), such as MeV/c^2 and GeV/c^2. $1\ u$ of mass is equivalent to about $931.5\ MeV/c^2$.

Worked example

Calculate the mass in kilograms of $1\ GeV/c^2$.

Solution:

1) Convert GeV to Joules:

$$1\ GeV = 1 \times 10^9 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-10}\ J$$

In SI units, $c = 3 \times 10^8\ ms^{-1}$

2) Use the formula $E = mc^2$ to find the mass equivalent. Rearrange the formula to find m:

$$m = E/c^2 = 1\ GeV/c^2 = \frac{1.6 \times 10^{-10}}{(3 \times 10^8)^2}$$

$$1\ GeV/c^2 = 1.78 \times 10^{-27}\ kg$$

The Quark Model

Quarks are fundamental particles that serve as the foundation for hadrons (such as protons and neutrons).

As part of a hadron categorisation system, the Quark Model was introduced. It was proposed that the properties of hadrons, such as the proton and neutron, might be explained in terms of various combinations of these smaller particles, called Quarks.

Three quarks (and their antiquarks) were proposed in the original model, and they were given the names:

Up (u)	**Down (d)**	**Strange (s)**
Anti-Up $(\bar{u})$	**Anti-Down $(\bar{d})$**	**Anti-Strange $(\bar{s})$**

Later, the particles created by collision experiments became heavier as accelerator technology improved and were capable of delivering high energies. These heavier particles could not be accounted in terms of up, down, and strange.

The following heavier quarks were discovered:

Charm (c)	**Bottom (b)**	**top (t)**
Anti-Charm $(\bar{c})$	**Anti-Bottom $(\bar{b})$**	**Anti-Top $(\bar{t})$**

The later a quark was discovered, the heavier it was.

The bottom quark is sometimes referred to as the beauty, and the top quark is referred to as the truth.

All of the stated quarks have their own properties, which we will discuss later.

The Hadrons

Hadrons aren't fundamental particles. Hadrons are particles which are made up of Quarks. Hadrons are particles that can feel strong nuclear force but not all particles can. Since protons are positively charged, a strong force (strong nuclear force or strong interaction) is required in order to keep them together.

Weak nuclear forces also have an affect on hadrons.

There are two types of Hadrons – BARYONS and MESONS.

Although there are several types of hadrons, only two are found in ordinary matter: protons and neutrons. This is due to the fact that most hadrons are extremely unstable and only live for a short time before decaying into other particles. Free neutrons (neutrons outside the nucleus) decay with a half-life of around 15 minutes, therefore protons are the only stable hadrons.

1) BARYONS

Baryons are made up of 3 quarks while anti-baryons are made up of 3 anti-quarks.

The most common examples of baryons are protons and neutrons.

Protons contain 2 UP quarks and 1 DOWN quark:

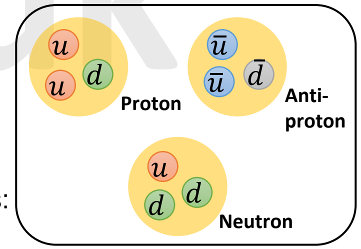
$$p = uud$$

Anti-protons contain 2 anti-up quarks and 1 anti-down quark:

$$\bar{p} = \bar{u}\,\bar{u}\,\bar{d}$$

Neutrons contain 1 UP quark and 2 DOWN quarks:

$$n = udd$$



A Baryon Number (B) is assigned to every baryon. In all particle interactions, a baryon number is a quantum number that must be conserved.

- Protons and neutrons (and all other baryons) each have a baryon number $B = +1$
- Antibaryons have a baryon number of $B = -1$
- Other particles (those that aren't baryons) are assigned a baryon number $B = 0$

The Hadrons

1) Baryons

When particles interact and produce or emit new particles (for example, alpha decay - when a large atom like uranium is too large for the strong nuclear force to keep it stable, it emits an alpha particle from the nucleus to make it more stable), the total baryon number before and after is the same. This fact can be used to predict whether or not a particle interaction will occur: if the total baryon number changes during the interaction, the interaction does not occur.

In any particle interaction, the total baryon number remains constant.

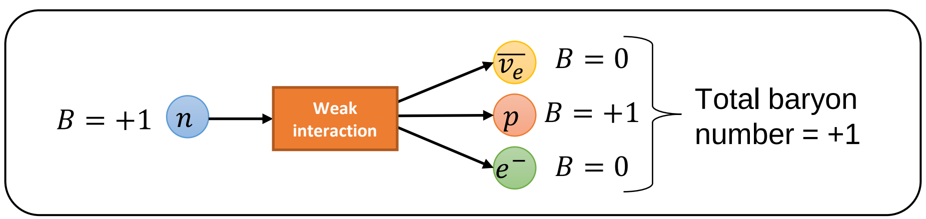
Neutron decay Example

When a neutron decays, a proton, an electron and an antineutrino are produced:

$$n \rightarrow p + e^{-} + \overline{v_e}$$

(This is just the same as β^{-} decay – a neutron decaying into a proton, electron and electron antineutrino).

Since electrons and antineutrinos aren't baryons (they're leptons, as I'll explain later), their baryon number is zero. Protons and neutrons are baryons, so their baryon number is $B = +1$. This means that the total baryon number before and after the interaction is equal $(B = +1)$, indicating that the interaction is possible.



The Hadrons

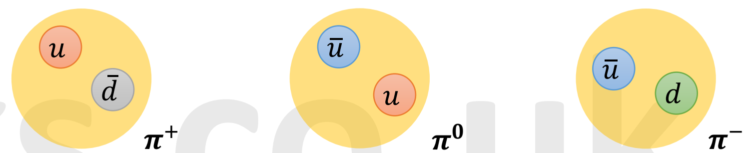
2) Mesons

Mesons interact with baryons through the strong force. All mesons are unstable. Since mesons are not baryons they have a baryon number $B = 0$.

Examples of mesons include:

- **Pions**

Pions (π-mesons) are the lightest mesons. There are three types, each with different electric charges: π^{+}, π^{0} *and* π^{-}. The π^{-} meson is just the antiparticle of the π^{+} mesons. The antiparticle of a π^{0} is itself.

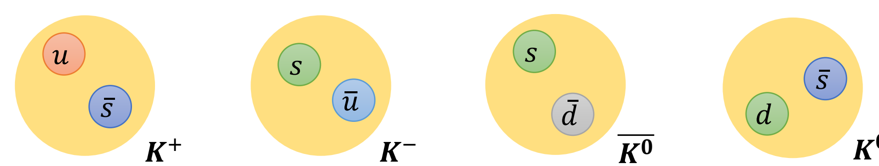


- **Kaons**

Kaons (K-mesons) are more stable and heavier than pions. There are different types of kaons which include: K^{+}, K^{-}, $\overline{K^{0}}$ and K^{0}. Kaons have a very short half-life before decaying into pions.

All mesons are instable and rapidly decay into Leptons and Photons.

Mesons are made up of one Quark and one Anti-Quark.



Leptons

These are Fundamental particles (i.e. particles which are not made up of smaller particles)

Strong nuclear forces do not affect leptons, although they are affected by weak nuclear forces.

Lepton Numbers

There are lepton numbers, just as there are baryon numbers.

- Leptons are assigned a Lepton number (L) of +1
- Anti-Leptons have $L = -1$
- All other particles have $L = 0$

In all reactions, the Lepton Number (L) is conserved.

There are six different types of leptons:

Name	Symbol	Relative Charge	L_e	L_μ	L_τ
Electron	e^-	-1	+1	0	0
Electron – neutrino	v_e	0	+1	0	0
Muon	μ^-	-1	0	+1	0
Muon Neutrino	v_μ	0	0	+1	0
Tau	τ^-	-1	0	0	+1
Tau – neutrino	v_τ	0	0	0	+1

Leptons

Each of these six leptons has an antiparticle with the opposite charge and lepton number:

Name	Symbol	Relative Charge	L_e	L_μ	L_τ
Positron	e^+	+1	-1	0	0
Electron – antineutrino	$\overline{v_e}$	0	-1	0	0
Anti-Muon	μ^+	+1	0	-1	0
Muon – antineutrino	$\overline{v_\mu}$	0	0	-1	0
Anti-Tau	τ^+	+1	0	0	-1
Tau - antineutrino	$\overline{v_\tau}$	0	0	0	-1

- Electrons (e^-) are stable leptons. Muons (μ^-) and tau (τ) are similar to heavy electrons.
- Muons and taus are unstable particles that decay into ordinary electrons over time.
- Each of the three leptons, the electron, muon, and tau, has its own neutrinos $(v_e,\ v_\mu\ and\ v_\tau)$.
- Neutrinos don't do much as they have zero or almost zero mass and zero electric charge.
- Neutrinos only take part in weak interactions. A neutrino can, in fact, pass through the Earth without causing any change.
- Muons and taus are produced in accelerator collision experiments and in the hot cores of stars however they are unstable particles.
- Electron, muon and tau types have to be counted separately.

Quark Properties and Conservation Laws

The charge, baryon number, and strangeness number of the three quarks and their antiquarks are listed in the table below:

Quark	Symbol	Charge (Q)	Baryon Number (B)	Strangeness Number (s)
up	u	+2/3	+1/3	0
down	d	-1/3	+1/3	0
strange	s	-1/3	+1/3	-1
anti-up	$\overline{u}$	-2/3	-1/3	0
anti-down	$\overline{d}$	+1/3	-1/3	0
anti-strange	$\overline{s}$	+1/3	-1/3	+1

Quark Properties and Conservation Laws

Charge

Each quark has a fractional charge, which is added together to form particles with a total relative charge of 0, +1, or -1.

E.g.

- Protons contain 2 UP quarks and 1 DOWN quark:

$$p = uud$$

So the total charge of a proton is:

$$p = +\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

- Neutrons contain 1 UP quark and 2 DOWN quarks:

$$n = udd$$

Therefore the total charge of neutron is:

$$n = +\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

- Pion, π^+ contains 1 UP quark and 1 ANTI-DOWN quark:

$$\pi^+ = u\overline{d}$$

Hence the total charge of pion is:

$$\pi^+ = +\frac{2}{3} + \frac{1}{3} = +1$$

In any particle interaction, charge (Q) is always conserved.

Quark Properties and Conservation Laws

Baryon Number (B)

Each quark also has a fractional Baryon number (B), which is added together to form particles with a total Baryon number (B) of 0, +1, or -1.

All quarks have $B = +1/3$ and all anti-quarks have $B = -1/3$, from which:

- Proton (uud): Total B = +1/3 +1/3 +1/3 = +1
- Neutron (udd): Total B = +1/3 + 1/3 + 1/3 = +1
- Pion, π^+ (u$\bar{d}$): Total B = + 1/3 – 1/3 = 0

In summary:

Particle	Baryon Number
All Baryons	+1
All Anti-Baryons	-1
All mesons and leptons	0

In any particle interaction, Baryon Number (B) is always conserved.

This fact can be used to predict whether or not a particle interaction will occur: if the total baryon number changes during the interaction, it will not.

Quark Properties and Conservation Laws

Strangeness

Hadrons are given the property of strangeness to account for abnormal behaviour (e.g. unusually long half-life).

All particles which contain strange quarks are called strange particles.

Strangeness number, S, like baryon and lepton number, is a quantum number.

The Strangeness number depends on whether the particle contains a strange quark, anti-strange quark, or no strange quarks.

Particles with:	Strangeness Number
Strange quark	-1
Anti-strange quark	+1
No strange quark	0

In hadron interactions, Strangeness number (S) is always conserved.

Only strong interactions conserve Strangeness. The only way to change the type of quark is with the weak interaction, so in strong interactions there must be the same number of strange quarks at the start as there are at the end.

Strangeness is conserved in some weak interactions, such as beta-decay, but not always in other weak interactions.

Quark Properties and Conservation Laws

Example:

The following equation shows the decay of a strange particle, the K^- kaon:

$$anti\ kaon \rightarrow muon + muon\ antineutrino$$
$$K^- \rightarrow \mu^- + \overline{v_\mu}$$

Quark equation: $s\bar{u} \rightarrow \mu^- + \overline{v_\mu}$

Charge (Q): $\left(-\frac{1}{3} - \frac{2}{3}\right) \rightarrow (-1) + (0)$

Baryon number (B): $0 = 0 + 0$

Muon lepton number (L_μ): $0 = +1 + -1$

Strangeness (S): $-1 \neq 0 + 0$

In this interaction, the charge, baryon number and lepton number is conserved. Strangeness is not conserved, as it is the decay of a strange particle, which must happen via this weak interaction.

The interaction is impossible if any of these properties (aside from strangeness) are not conserved on both sides of an equation.

Quark Properties and Conservation Laws

Continue to the next page.

Beta (β) decay

Strong interaction only acts between hadrons and not between leptons, and so some particle behaviour cannot be explained by the strong interaction alone. For example, we need a force to explain Beta decay.

The weak interaction force acts on both hadrons and leptons. While other forces/interactions keep things together, the weak interaction causes things to fall apart or decay. (If you want to learn more about Weak Interaction please see pack 20.5 Particle Interactions (AQA Only)).

BETA (β) decay is caused by the weak interaction between quarks, and many unstable particles, such as free neutrons, decay as a result of weak interaction.

There are two types of beta (β) decay:

1) β^- decay in which electrons are emitted.

2) β^+ decay in which positrons (electron anti-particle) are emitted.

A weak interaction between the quarks of the neutrons and protons causes both types of β-decay.

β^-- decay

In the radioactive decay of an unstable nucleus, electrons (β^-, e^-) can be emitted.

e.g.: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta^- + {}^{0}_{0}\overline{v_e}$

A neutron in the carbon-14 nucleus decays into a proton plus an electron and an electron anti-neutrino, both of which are released in this decay.

- Particle equation: $n^0 \rightarrow p^+ + e^- + \overline{v_e}$
- Quark equation: $udd \rightarrow uud + e^- + \overline{v_e}$

Which simplifies to: $d \rightarrow u + e^- + \overline{v_e}$

Beta (β) decay

β^-- decay

Applying conservation laws:

Simplified quark equation for β^- - decay: $\boldsymbol{d \rightarrow u + e^- + \overline{v_e}}$

- The kinetic energy of the released particles ensures mass/energy and momentum conservation.
- Conservation of charge (Q): $\left(-\frac{1}{3}\right) = \left(+\frac{2}{3}\right) \ + (-1) \ + \ 0$
- Conservation of baryon number (B): $\left(+\frac{1}{3}\right) = \left(+\frac{1}{3}\right) + 0 + 0$
- Conservation of lepton number (L): $0 = 0 + (+1) \ + (-1)$

Since the charge, baryon number, and lepton number are conserved on both sides of the equation, this interaction is possible.

Beta (β) decay

β^+-decay

During the radioactive decay of an unstable nucleus, positrons (β^+, e^+) can be emitted .

e.g.: ${}^{30}_{15}Po \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}\beta^+ + {}^{0}_{0}v_e$

A proton in the polonium-15 nucleus decays into a neutron plus a positron and an electron neutrino, which are both released in this decay.

- Particle equation: $p^+ \rightarrow n^0 + e^+ + v_e$
- Quark equation: $uud \rightarrow udd + e^+ + v_e$

Which simplifies to: $\mathrm{u} \rightarrow d + e^+ + v_e$

Applying conservation laws:

Simplified quark equation for β^+ - decay: $\boldsymbol{u \rightarrow d + e^+ + v_e}$

- The kinetic energy of the released particles ensures mass/energy and momentum conservation.
- Conservation of charge (Q): $\frac{2}{3} \rightarrow -\frac{1}{3} \ + \ +1 \ + \ \ 0$
- Conservation of baryon number (B): $+\frac{1}{3} \rightarrow +\frac{1}{3} + 0 + 0$
- Conservation of lepton number (L): $0 \rightarrow 0 + \ \ -1 \ + \ +1$

Since the charge, baryon number, and lepton number are conserved on both sides of the equation, this interaction is possible.

Relativistic Lifetimes (Edexcel Only)

Nothing can accelerate faster than the speed of light, according to Einstein's theory of special relativity. An experiment was carried out that showed the kinetic energy and momentum of particles can continue to increase indefinitely, but their speed does not. This only happens if the particle's mass increases with its speed. This apparent mass increase becomes significant at speeds approaching light speed – know as 'relativistic speeds'.

Einstein also predicted that time slows down for objects moving at the speed of light when compared to the time of a stationary external observer.

As a result, a particle moving at relativistic speeds would have a longer lifetime recorded by a stationary observer than the actual time (suggested by predictions).

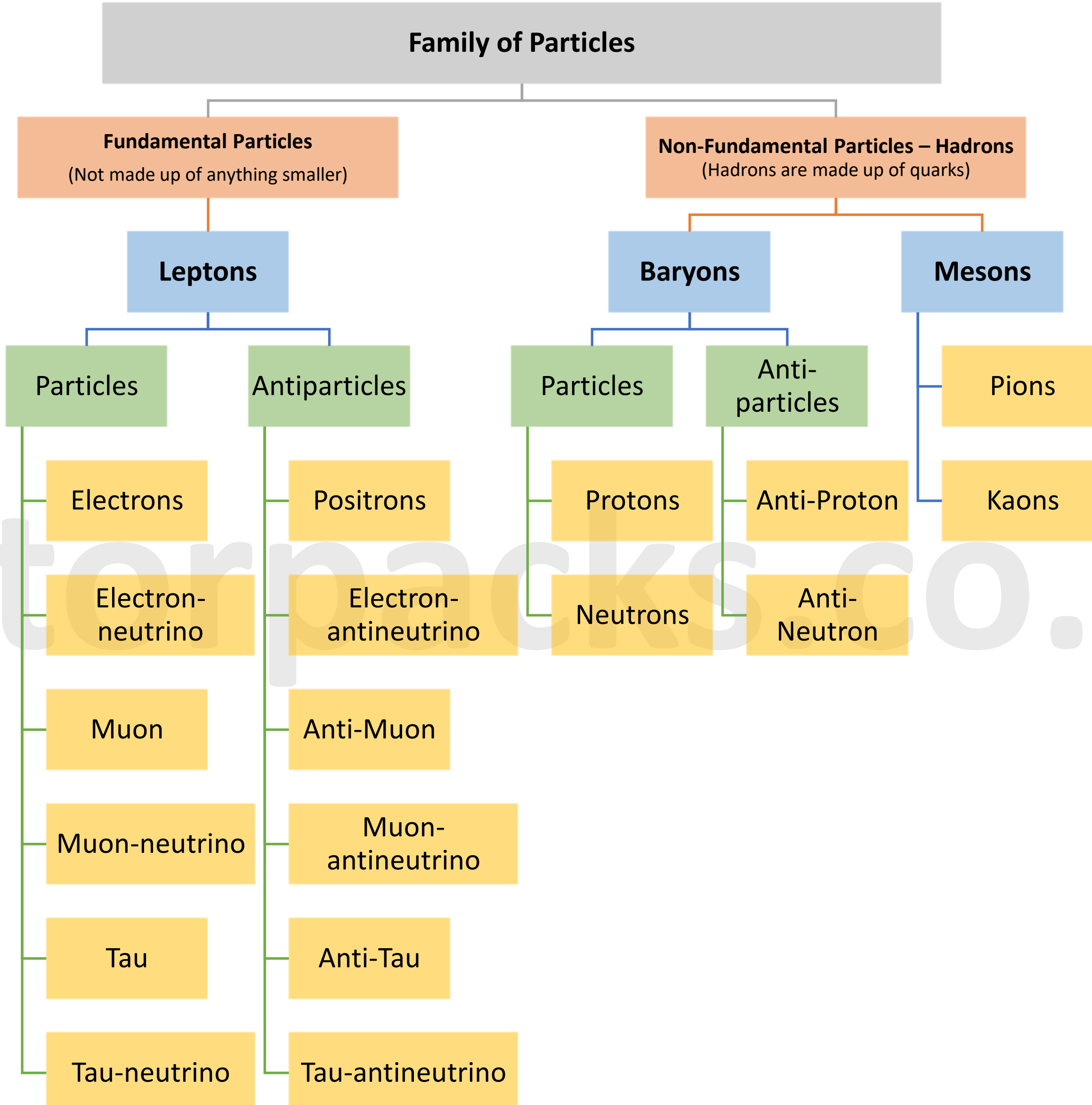
The finding of muons at sea level was one of the first pieces of evidence of these extended particle lifetimes. Muons are created when high-energy cosmic rays interact with the nuclei of atoms high in the atmosphere, and they have a lifetime of around $2\ \mu s$.

These should all decay in a fraction of the time it takes for them to reach the Earth's surface, and we should not be able to detect any at sea level. Even after $2\ \mu s$ seconds have passed, most muons are still present when they reach sea level, and they are detected in significant numbers at low altitudes.

The reason for this is that they are moving extremely fast. The muons still decay in the same short time, but their time moves slowly enough for them to travel tens of kilometres to our equipment on the ground.

The particle interactions seen in accelerator collision experiments are likewise affected by this concept. Since the particles are travelling so quickly, they live longer and travel further than we might anticipate. This allows for several other new interactions to take place when they come into contact with particles they would not have had chance to encounter otherwise.

Particles Chart



Please see '8.2.2 Fundamental Particles worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.