AS Physics Unit 1
Resources

KS5 AS PHYSICS AQA 2450

Mr D Powell
Particle interactions
Concept of exchange particles to explain forces between elementary particles. The electromagnetic force; virtual photons as the exchange particle. The weak interaction limited β-, β+ decay, electron capture and electron-proton collisions; \( W^+ \) and \( W^- \) as the exchange particles. Simple Feynman diagrams to represent the above reactions or interactions in terms of particles going in and out and exchange particles.

Classification of particles
Hadrons: baryons (proton, neutron) and antibaryons (antiproton and antineutron) and mesons (pion, kaon). Hadrons are subject to the strong nuclear force. Candidates should know that the proton is the only stable baryon into which other baryons eventually decay; in particular, the decay of the neutron should be known. Leptons: electron, muon, neutrino (electron and muon types). Leptons are subject to the weak interaction. Know the baryon numbers for the hadrons. Lepton numbers for the leptons will be given in the data booklet

Quarks and antiquarks
Up (u), down (d) and strange (s) quarks only. Properties of quarks: charge, baryon number and strangeness. Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon) only. Change of quark character in β- and β+ decay.
What is the link word?
### 2.1 Particle Zoo p18

| K   | How can we find out about new particles.  
|     | What are k-mesons or Kaons.  
|     | What are muons.  
|     | What are $\pi$-mesons or Pions.  

| S   | Using particle accelerators to investigate particle properties.  
|     | Be able to compare Pions, Kaons and Mesons.  

| U   | The context of Particle Accelerators in terms of the CERN complex.  

Yukawa & the False Meson!

In 1934 Hideki Yukawa predicted the existence and the approximate mass of a particle call the "meson" as the carrier of the strong force that holds the atom together.

Yukawa called his carrier particle the meson, from *mesos*, the Greek word for *intermediate*, because its predicted mass was between that of the *electron* and that of the *proton*, which has about 1,836 times the mass of the electron.

Carl Anderson found the "mu meson" (or muon) in 1936 with other *decay products* of cosmic ray interactions. The mu meson had about the right mass to be Yukawa's carrier of the strong nuclear force, but over the course of the next decade, it became evident that it was not the right particle.

It was eventually found that the mu meson did not participate in the strong nuclear interaction at all, but rather behaved like a heavy version of the *electron*, and is in fact a *lepton* rather than a meson. They had found the *muon*!
Muons

The muon (\( \mu \)) is an elementary particle similar to the electron, with a \(-1.6 \times 10^{-19}\)C negative charge and mass 200x that of the electron.

Together with the electron, the tau, and the three neutrinos, it is classified as a lepton.

As is the case with other leptons, the muon is a fundamental particle.

The muon is unstable with a mean lifetime of 2.2 \( \mu s \). This comparatively long decay life time (the second longest known) is due to being mediated by the weak interaction.

All muons decay to three particles (an electron plus two neutrinos of different types), but the daughter particles are believed to originate newly in the decay.
Pions

In particle physics, pion (short for pi meson) is the collective name for three subatomic particles: $\pi^0$, $\pi^+$ and $\pi^-$. Pions are the lightest mesons and play an important role in explaining low-energy properties of the strong nuclear force.

<table>
<thead>
<tr>
<th>Anti-particle</th>
<th>Quark</th>
<th>Rest mass MeV/c²</th>
<th>S</th>
<th>Decays to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Pion</td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
<td>$u\bar{d} / \bar{u}d$</td>
<td>139.6</td>
</tr>
<tr>
<td>Neutral Pion</td>
<td>$\pi^0$</td>
<td>$\pi^0$</td>
<td>?</td>
<td>135.0</td>
</tr>
</tbody>
</table>

Pion decay via weak interaction
Kaons

In particle physics, a kaon also called K-meson is any one of a group of four mesons distinguished by the fact that they carry a quantum number called strangeness.

In the quark model they are understood to contain a single strange quark (or antiquark).

<table>
<thead>
<tr>
<th></th>
<th>Anti-particle</th>
<th>Quark</th>
<th>Rest mass MeV/c²</th>
<th>S</th>
<th>Decays to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Kaon</td>
<td>K⁺</td>
<td>K⁻</td>
<td>494</td>
<td>+1</td>
<td>μ⁺ + νμ or π⁺ + π⁰</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral Kaon</td>
<td>K⁰</td>
<td>K⁰</td>
<td>498</td>
<td>+1</td>
<td></td>
</tr>
</tbody>
</table>
Why are they Strange?

Strangeness was introduced by Murray Gell-Mann and Kazuhiko Nishijima to explain the fact that certain particles, such as the kaons were created easily in particle collisions, yet decayed much more slowly than expected for their large masses.

Noting the collisions it was postulated that a new conserved quantity, dubbed "strangeness", was preserved during their creation, but not conserved in their decay.

In our modern understanding, strangeness is conserved during the strong (collisions) and the electromagnetic interactions, but not during the weak interactions.
Strangeness Quick Flow

Strangeness was introduced by Murray Gell-Mann and Kazuhiko Nishijima to explain the fact that certain particles, such as the kaons were created **easily in particle collisions**, yet **decayed much more slowly** than expected for their **large masses**.

Noting the collisions it was postulated that a new conserved quantity, dubbed "**strangeness**", was preserved during their creation, but *not* conserved in their decay.

In our modern understanding, strangeness is conserved during the **strong** and the **electromagnetic interactions**, but **not during the weak interactions**.

The reactions below happen $10^{-8}$s and lose their strange quark. Meaning that they cannot occur by strong or EM interaction.

\[ K^+ \rightarrow \mu^+ + \nu_\mu \ , \ K^+ \rightarrow \pi^+ + \pi^0 \ , \ K^- \rightarrow \mu^- + \bar{\nu}_\mu \ , \ K^- \rightarrow \pi^- + \pi^0 \]
Accelerators

The Stanford linear accelerator in California is capable of accelerating electrons to 50 GeV. Synchrotron radiation is not produced by electrons in a linear accelerator since they move in a straight line. The principle of operation of a linear accelerator is that charged particles are accelerated by an alternating pd applied to a series of electrodes. Radio-frequencies are essential to accelerate electrons or protons and a large number of power sources are needed to supply all the electrodes. The length of each electrode is determined by its position in the accelerator tube. The further down the tube an electrode is positioned, the longer it must be. This is necessary to ensure that each particle passes through an electrode in exactly half a cycle of the alternating pd.

\[\text{Source} \rightarrow \text{Evacuated tube} \rightarrow \text{Beam}\]

NB: Synchrotron Radiation – bright light produced when electrons move in circles.
Synchrotron

The CERN Super Proton Synchrotron started operating in 1976, initially to create collisions between high energy protons and a stationary target. Protons from a 50 MeV linear accelerator are boosted to 10 GeV in a smaller proton synchrotron before being injected into the 2.2 km diameter main ring of the SPS. The beam is maintained on its circular path by over 700 bending magnets, capable of producing a peak field of 1.8 T. Over 200 focusing magnets are installed along the beam path and two 500 kW radio-frequency cavities are used to accelerate the beam. Beam pulses of $2 \times 10^{13}$ protons per pulse can be produced, lasting from a few microseconds to a few seconds.

With a fixed target, conservation of momentum means that not all the kinetic energy acquired by a particle is available to create new particles.

- At non-relativistic energies (i.e. $v << c$), the maximum available energy from a collision between a moving particle and an identical stationary particle is 50% of the initial kinetic energy. In comparison, for two identical particles with equal kinetic energies which collide head-on, all the initial kinetic energy is available to create new particles since the total initial momentum is zero.

- At relativistic energies, the maximum available energy from a head-on collision between two identical particles with equal kinetic energies is also equal to the total initial energy. The proportion of the maximum available energy in a relativistic fixed-target experiment decreases as the particle energy increases. For example, no more than about 30 GeV is available when 450 GeV protons collide with stationary protons.
Modern Detectors...

Modern detectors consist of many different pieces of equipment which test for different aspects of an event.

These many components are arranged in such a way that physicists can obtain the most data about the particles spawned by an event.

This is a schematic design of a typical modern detector.
Modern Detectors 2 (extension)

The reason that detectors are divided into many components is that each component tests for a special set of particle properties.

These components are stacked so that all particles will go through the different layers sequentially. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.
What am I thinking of?
### 2.2 Particle Sorting p20

| K | Matter is split into two types Hadrons & Leptons  
|   | Hadrons have the subgroups of Baryons and Mesons  
|   | What do we mean by conservation of energy. |

| S | Recall of symbols, charge, mass, rest energy, interactions for each particle. |

| U | Why are they split like this? |
Hadrons

- Hadrons are unstable with the exception being the proton—the only stable Hadron.
- Hadrons are composed of smaller fundamental particles called Quarks.
- Meson have 2 Quarks and Baryons 3. Hence mesons don’t decay to protons or neutrons.
- They all have masses much larger than that of leptons.
- Some carry charge i.e. (p, K^-, K^+)
- Some have no charge i.e. (n, K^0)
Copy out this flow chart on A3 paper and add any information you can to the bubbles explained why they are separated as such....

**Particles**

- **Leptons:** fundamental particles e.g. electron, neutrino
- **Hadrons:** not fundamental, made from quarks
- **Gauge Bosons:** fundamental particles, force carriers e.g. photon
- **Baryons:** made up of three quarks
- **Mesons:** made up of two quarks
The gauge bosons for electromagnetic forces and gravity are without mass. These forces have infinite range.

The gauge bosons for the strong and weak interactions have mass. These forces are short range.

The strong interaction only acts between hadrons (particles made of quarks)

The weak interaction acts on all particles.
# Particles & Properties

<table>
<thead>
<tr>
<th>particle and symbol</th>
<th>charge / proton charge</th>
<th>antiparticle and symbol</th>
<th>charge / proton charge</th>
<th>rest energy / MeV</th>
<th>interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton ( p )</td>
<td>+1</td>
<td>antiproton ( \bar{p} )</td>
<td>−1</td>
<td>938</td>
<td>strong, Weak decay electromagnetic</td>
</tr>
<tr>
<td>neutron ( n )</td>
<td>0</td>
<td>antineutron ( \bar{n} )</td>
<td>0</td>
<td>939</td>
<td>strong, Weak decay</td>
</tr>
<tr>
<td>electron ( e^- )</td>
<td>−1</td>
<td>positron ( e^+ )</td>
<td>+1</td>
<td>0.511</td>
<td>weak, electromagnetic</td>
</tr>
<tr>
<td>neutrino ( \nu )</td>
<td>0</td>
<td>antineutrino ( \bar{\nu} )</td>
<td>0</td>
<td>0</td>
<td>weak</td>
</tr>
<tr>
<td>muon ( \mu^- )</td>
<td>−1</td>
<td>antimuon ( \mu^+ )</td>
<td>+1</td>
<td>106</td>
<td>weak, electromagnetic</td>
</tr>
<tr>
<td>( \pi ) meson ( \pi^+, \pi^0, \pi^- )</td>
<td>+1,0,−1</td>
<td>( \pi^+ ) for a ( \pi^- ) ( \pi^- ) for a ( \pi^+ ) ( \pi^0 ) for a ( \pi^0 )</td>
<td>−1,0,+1</td>
<td>140; 135; 140</td>
<td>strong, electromagnetic (( \pi^+, \pi^- ))</td>
</tr>
<tr>
<td>K meson ( K^+, K^0, K^- )</td>
<td>+1,0,−1</td>
<td>See Topic 2.4</td>
<td>−1,0,+1</td>
<td>494; 498; 494</td>
<td>strong electromagnetic (( K^+, K^- ))</td>
</tr>
</tbody>
</table>
Conservation of Energy

- Here is an example using a proton and antiproton collisions which have rest energy of about 1GeV each.

- A number of other particles could be produced totalling 6Gev in total energy in this case another proton and antiproton.

\[
\text{Total Energy Before} = \text{Rest energy of the products} + \text{Kinetic Energy Of Products}
\]

\[
6\text{GeV} = 1\text{GeV} \times 2 + 2\text{Gev} \times 2
\]
Quick Questions...

- Give an example of each on your whiteboard?
<table>
<thead>
<tr>
<th>K</th>
<th>Leptons are elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Explaining why there are different types of neutrino</td>
</tr>
<tr>
<td></td>
<td>How are neutrinos detected</td>
</tr>
<tr>
<td>U</td>
<td>Conservation of lepton number dictates allowed interactions.</td>
</tr>
</tbody>
</table>
Leptons

- The Lepton family of particles consist of the electron, muon and the neutrinos. They have a lepton number of +1 (antileptons are -1)
- They are fundamental particles, with no internal structure (i.e. Quarks)
- Do not interact via strong force
- Each of the charged leptons has an antiparticle with identical mass but whose other properties are opposite.
- Each lepton has an associated neutrino, and antineutrino

<table>
<thead>
<tr>
<th></th>
<th>Symbol</th>
<th>Q</th>
<th>Mass (in terms of electron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e^−</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Electron-Neutrino</td>
<td>ν_e</td>
<td>0</td>
<td>≈0</td>
</tr>
<tr>
<td>Muon</td>
<td>μ^-</td>
<td>-1</td>
<td>207</td>
</tr>
<tr>
<td>Muon-Neutrino</td>
<td>ν_μ</td>
<td>0</td>
<td>≈0</td>
</tr>
</tbody>
</table>
Neutrino

Neutrinos are elementary particles that travel close to the speed of light, lack an electric charge, are able to pass through ordinary matter almost undisturbed and are thus extremely difficult to detect. Neutrinos have a minuscule, but nonzero mass. They are usually denoted by the Greek letter (nu) ν

Created as a result of certain types of radioactive decay or nuclear reactions such as those that take place in the Sun, in nuclear reactors, or when cosmic rays hit atoms.

There are three types, or "flavors", of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos (not needed for AQA; each type also has an antimatter partner, called an antineutrino.

Are generated whenever neutrons change into protons or vice versa, the two forms of beta decay. Interactions involving neutrinos are generally mediated by the weak force (rad decay)
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Lepton Conservation

We use the terms "electron number” and "muon number“ to refer to the lepton family of a particle. Electrons and their neutrinos have electron number +1, positrons and their antineutrinos have electron number -1, and all other particles have electron number 0.

Muon number operates with is own family in a similar way to lepton number and both are always conserved when a massive lepton decays into smaller ones.

equation: \[ \mu \rightarrow \nu_\mu + e^- + \bar{\nu}_e \]

electron number: \[ 0 = 0 + 1 + -1 \]

muon number: \[ 1 = 1 + 0 + 0 \]
Lepton Conservation can it happen?

An electron decays into a muon, a muon antineutrino, and an electron neutrino;

$e^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_e$

$1 = 0 + 0 + 1$

$0 = 1 - 1 + 0$

No it cannot....

Although electron and muon numbers are both conserved, energy is not conserved.

A muon has a lot more rest energy than an electron, and a lepton cannot decay into something more massive than it started out due to conservation of energy!
Name me.....
### 2.4 Quarks & Antiquarks p24

| K | Of the Up (u), down (d) and strange (s) quarks only.  
Learn combinations of quarks and antiquarks required;  
- for baryons (proton and neutron only),  
- antibaryons (antiproton and antineutron only)  
- mesons (pion and kaon) |
| S | Compare the properties of quarks; charge, baryon number and strangeness. |
| U | Change of quark character in β- and β+ decay. |
Quarks....

Like teen-age girls, quarks travel in packs, wiggling constantly, kept close together by a force stronger than peer pressure or even gossip. They have different personalities, or "flavors" — sometimes they're up, sometimes down, sometimes they're charming. They wear bizarre tops and bottoms, and sometimes they're flat-out strange.

A.J. Hostetler, Richmond Times-Dispatch

Illustration by Lori Powell, Jefferson Leb
Scale of Quarks

While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that.

We don't know exactly how small quarks and electrons are; they are definitely smaller than $10^{-18}$ meters, and they might literally be points, but we do not know.
Quarks close up...

There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom.

(Also, for each of these quarks, there is a corresponding antiquark.)

Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively.

Quarks also carry another type of charge called color charge. (Not required)

The most elusive quark, the top quark, was discovered in 1995 after its existence had been theorised for 20 years.
Naming of Quarks..

There are six flavours of quarks. "Flavours" just means different kinds. The two lightest are called up and down.

The third quark is called strange. It was named after the "strangely" long lifetime of the K particle, the first composite particle found to contain this quark.

The fourth quark type, the charm quark, was named on a whim. It was discovered in 1974 almost simultaneously at both the Stanford Linear Accelerator Centre (SLAC) and at Brookhaven National Laboratory.

The bottom quark was first discovered at Fermi National Lab (Fermilab) in 1977, in a composite particle called Upsilon.

The top quark was discovered last, also at Fermilab, in 1995. It is the most massive quark. It had been predicted for a long time but had never been observed successfully until then.
Four main quark configurations

The Proton
Made up of two ‘up’ quarks and a ‘down’ quark.

The Pion (π+)
Made up of an ‘up’ quark and an ‘anti-down’ quark.

The Neutron
Made up of 2 ‘down’ quarks and an ‘up’ quark.

The Kaon (K+)
Made up of an ‘up’ quark and an ‘anti-strange’ quark.
Extension on Quarks (not required AS)

- In fact the model predicted all sorts of strange particles, some have been discovered and some have not!
Strangeness Quick Flow

Strangeness was introduced by Murray Gell-Mann and Kazuhiko Nishijima to explain the fact that certain particles, such as the kaons were created easily in particle collisions, yet decayed much more slowly than expected for their large masses.

Noting that collisions it was postulated that a new conserved quantity, dubbed "strangeness", was preserved during their creation, but not conserved in their decay.

In our modern understanding, strangeness is conserved during the strong and the electromagnetic interactions, but not during the weak interactions.

The reactions below happen $10^{-8}$s and lose their strange quark. Meaning that they cannot occur by strong or EM interaction.

\[ K^+ \rightarrow \mu^+ + \nu_\mu, \quad K^+ \rightarrow \pi^+ + \pi^0 \quad K^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad K^- \rightarrow \pi^- + \pi^0 \]
**Strangeness...**

π meson (green) collides with a proton (red)

Quark properties

<table>
<thead>
<tr>
<th></th>
<th>up (u)</th>
<th>down (d)</th>
<th>strange (s)</th>
<th>up (u)</th>
<th>down (d)</th>
<th>strange (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>charge Q</strong></td>
<td>$+\frac{2}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{2}{3}$</td>
<td>$+\frac{1}{3}$</td>
<td>$+\frac{1}{3}$</td>
</tr>
<tr>
<td><strong>strangeness S</strong></td>
<td>0</td>
<td>0</td>
<td>$-1$</td>
<td>0</td>
<td>0</td>
<td>$+1$</td>
</tr>
</tbody>
</table>

**NB:** Strangeness is always conserved in a strong interaction – when things hit each other!
1. On a sheet of A4 paper convert this information into a Venn diagram similar to this...

The Wheel of Mesons....
Quark Properties - Summary

A proton is composed of two up quarks and a down quark

<table>
<thead>
<tr>
<th>Property</th>
<th>Up, u</th>
<th>Up, u</th>
<th>Down, d</th>
<th>Proton, p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge, Q</td>
<td>2/3</td>
<td>2/3</td>
<td>−1/3</td>
<td>1</td>
</tr>
<tr>
<td>Baryon number, B</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
</tr>
<tr>
<td>Strangeness, S</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Antiproton: \( \bar{p} = \bar{u} + \bar{u} + \bar{d} \)

<table>
<thead>
<tr>
<th>Property</th>
<th>( \bar{u} )</th>
<th>( \bar{u} )</th>
<th>( \bar{d} )</th>
<th>Antiproton, ( \bar{p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge, Q</td>
<td>−2/3</td>
<td>−2/3</td>
<td>1/3</td>
<td>−1</td>
</tr>
<tr>
<td>Baryon number, B</td>
<td>−1/3</td>
<td>−1/3</td>
<td>−1/3</td>
<td>−1</td>
</tr>
<tr>
<td>Strangeness, S</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quark Type</th>
<th>Charge ( Q )</th>
<th>Baryon number ( B )</th>
<th>Strangeness ( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>+ 2/3</td>
<td>1/3</td>
<td>0</td>
</tr>
<tr>
<td>d</td>
<td>−1/3</td>
<td>1/3</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>+ 2/3</td>
<td>1/3</td>
<td>0</td>
</tr>
<tr>
<td>s</td>
<td>−1/3</td>
<td>1/3</td>
<td>−1</td>
</tr>
<tr>
<td>t</td>
<td>+2/3</td>
<td>1/3</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>−1/3</td>
<td>1/3</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charm ( C )</th>
<th>Bottomness ( B )</th>
<th>Topness ( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>−1</td>
<td>0</td>
</tr>
</tbody>
</table>
Beta Decay – Reminder!

- So now we have looked at quarks depth you will appreciate what is happening in reality during both forms of beta decay.

- In this case a neutron turns into a proton as a quark has a change of flavour.

- The exchange particle is a $W^-$ boson and results in an electron antineutrino and electron.

- Beta plus decay is the total opposite in every way!
Quick Test?

Using only the ideas of quark charge for uds can you work out the quark composition of each of these particles....

1. for baryons (proton and neutron),

2. antibaryons (antiproton and antineutron )

3. mesons (pion and kaon)
### 2.5 Conservation Rules p26

<table>
<thead>
<tr>
<th>K</th>
<th>Application of the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>How to add up the numbers for each side of the equation for Q, B, S, and ( L_e ) &amp; ( L_\mu ).</td>
</tr>
<tr>
<td>U</td>
<td>Which apply and when i.e. charge, energy, baryon number, lepton number and strangeness to particle interactions.</td>
</tr>
</tbody>
</table>
Rules Summary.....

The laws that are described on this page determine whether any particle interaction can take place, as for them to do so each of the relevant characteristics of the fundamental particles must be conserved.

Conservation of Charge

Any particle interaction must conserve charge (values for the various quarks have been outlined on a previous slide)

Conservation of Baryon Number

This must also be conserved with interactions between Baryons (as anything that is not a Baryon has a Baryon Number = 0. All Baryons have a B Number = 1 and all Anti-baryons have a B Number = -1).

Conservation of Strangeness

Any Hadron that is made up a Strange quark has a Strangeness = -1. Any made up an Anti-strange quark has S = 1. Therefore anything that is not a Hadron has a S = 0.

The Lepton Number

There are however two types of Lepton Number each associated with the Electron and Muon. Any Electron or Electron-neutrino has an L_e Number = 1 with their anti-particles having -1. This pattern also continues with the Lepton-muon number (L_µ) and the Lepton-tau number (L_τ). (tau not required at AS)
Conservation Laws...

- Copy out this flow chart on A4 paper and add any information you can to the picture to explain if this can happen according to conservation laws...
## Conservation of Q/ B/ S

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Rest mass GeV/C²</th>
<th>Q</th>
<th>B</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>K minus</td>
<td>$K^-$</td>
<td>0.4937</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>K plus</td>
<td>$K^+$</td>
<td>0.4937</td>
<td>+1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>K zero</td>
<td>$K^0$</td>
<td>0.4977</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>K zero bar</td>
<td>$\bar{K}^0$</td>
<td>0.4977</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Neutron</td>
<td>n</td>
<td>0.9396</td>
<td>0</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>Proton</td>
<td>p</td>
<td>0.9383</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>$\pi$ minus</td>
<td>$\pi^-$</td>
<td>0.1396</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\pi$ plus</td>
<td>$\pi^+$</td>
<td>0.1396</td>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Spin Extension Materials...

the electron is a spin $\frac{1}{2}$ particle and that electrons in the atom are either spin ‘up’ or spin ‘down’. Quarks are also spin $+\frac{1}{2}$ particles. Thus mesons can possess zero spin because a meson is a quark and antiquark. Long lived baryons are spin $+\frac{1}{2}$ particles, corresponding to two quarks with spin $+\frac{1}{2}$ and one quark with spin $-\frac{1}{2}$. Short-lived baryons are spin $+\frac{3}{2}$ particles, corresponding to three quarks with parallel spins.

The fact that three of the short-lived baryons are composed of identical quarks with identical spins led to the concept of ‘colour charge’ to distinguish between otherwise identical quarks in a baryon. Just as electric charge is either + or -, the 'colour charge' of a quark is either red or blue or green. Only colourless (i.e. white) combinations exist. A baryon is colourless because it contains a quark of each colour. A meson is colourless because it contains a quark of a certain colour and an antiquark of the same anticolour (e.g. a red quark and an antired antiquark).

Not needed for AS – just to prevent confusion if you see it on the web!

**Spin:** If you want the simple explanation spin is angular momentum i.e. particles are “spinning”. It can take various values in quantum mechanics – a concept for university!
Formation of the Universe

http://abyss.uoregon.edu/~js/ast123/lectures/lec17.html
Exam Questions
Quick Questions…

- Give an example of each on your whiteboard?
Exam Question 1

(a) K mesons were originally called ‘strange’ because they are produced in one type of interaction and they decay through a different type of interaction.

(i) In which type of interaction are they produced?
(ii) Which type of interaction causes them to decay?
(iii) In which type of interaction is strangeness always conserved?

(b) (i) Describe the 3-quark model of hadrons.
(ii) The 3-quark model originated from a theory that explained the properties of baryons and mesons. Show that the 3-quark model explains why there are just 4 charged mesons.

A) i) Strong interaction (i.e. Particle collision
   ii) Weak
   iii) Weak   (See p26 for example)
Exam Question 1

(a) K mesons were originally called ‘strange’ because they are produced in one type of interaction and they decay through a different type of interaction.

(i) In which type of interaction are they produced?
(ii) Which type of interaction causes them to decay?
(iii) In which type of interaction is strangeness always conserved?

(b) (i) Describe the 3-quark model of hadrons.
(ii) The 3-quark model originated from a theory that explained the properties of baryons and mesons. Show that the 3-quark model explains why there are just 4 charged mesons.

B) the idea is that all hadrons are made up of 3 quarks which can never be isolated. They each contribute charge and mass to the hadron. Each quark also has an antiquark with opposite charge and bayron number. u = up Q = 2/3, d = down Q = 1/3, s = strange Q = -1/3.

ii) If we look at uds, their are only 4 combinations of quark pairs;
Pi + = u + anit(d) = 2/3 + 1/3 = +1
Pi - = d + anit(u) = -1/3 + (-2/3) = – 1
K(-) = s + anti(u) = -1/3 + (-2/3) = -1
K(+) = u anti(s) = 2/3 + 1/3 = +1
Exam Question 2

From the following list of particles,

\[ p \quad \bar{n} \quad \nu_e \quad e^+ \quad \mu^- \quad \pi^0 \]

identify all the examples of

(i) hadrons, .................................................. \[ p\bar{n}\pi^0 \checkmark \]

(ii) leptons, .................................................. \[ \nu_e e^+ \mu^- \checkmark \]

(iii) antiparticles, ......................................... \[ \bar{n}e^+ \checkmark \]

(iv) charged particles. ..................................... \[ pe^+ \mu^- \checkmark \]

(4 marks)
Exam Question 3

(a) (i) Underline the particles in the following list that may be affected by the weak interaction.

- positron
- neutron
- photon
- neutrino
- positive pion

(ii) Underline the particles in the following list that may be affected by the electromagnetic force.

- electron
- antineutrino
- proton
- neutral pion
- negative muon

(b) A positive muon may decay in the following way,

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$ 

(i) Exchange each particle for its corresponding antiparticle and complete the equation to show how a negative muon may decay.

$$(\mu^-) \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

(ii) Give one difference and one similarity between a negative muon and an electron.

**difference:** mass or half-life or generation of lepton

**similarity:** both leptons or both negatively charged
Exam Question 4

(a) State the quark substructure of a neutron.
(b) Which of the following terms can be used to describe a neutron?
   antiparticle  baryon  fundamental particle  hadron  lepton  meson

(2 marks)  (2 marks)

AQA, 2004

The Neutron
Made up of 2 ‘down’ quarks and an ‘up’ quark.

b) Hadron or baryon
Exam Question 5

(a) A particle is made up from an up antiquark and a down quark.
(i) Name the classification of particles that has this type of structure.
(ii) Find the charge on the particle.
(iii) State the baryon number of the particle.

(b) A suggested decay for the positive muon ($\mu^+$) is

$$\mu^+ \rightarrow e^+ + \nu_e$$

Showing your reasoning clearly, deduce whether this decay satisfies the conservation rules that relate to baryon number, lepton number and charge.

(i) Meson
(ii) Anti $u = -2/3$  $d = -1/3$  so total is -1  pi(minus)
(iii) $B = 0$  (as it is a meson, $u = -B/3$  $d = +B/3$

b)

$B \rightarrow 0 = 0 + 0$

$L \rightarrow 0 = -1 + 1$

$Q \rightarrow +1 = +1 + 0$

NB Muon number is not as you are missing the anti muon neutrino product
Exam Question 6

A sigma plus particle, $\Sigma^+$, is a baryon.

(i) How many quarks does the $\Sigma^+$ contain?

3 Quarks

(ii) If one of these quarks is an s quark, by what interaction will it decay?

Weak (nuclear)

(iii) Which baryon will the $\Sigma^+$ eventually decay into?

Proton, as all baryons eventually decay into protons.

(3 marks)
Exam Question 7

Some subatomic particles are classified as *hadrons*.

(a) What distinguishes a hadron from other subatomic particles?  

(b) Hadrons fall into two subgroups. Name each subgroup and describe the general structure of each.  

(c) The following equation represents an event in which a positive muon collides with a neutron to produce a proton and an antineutrino.

\[ n + \mu^+ \longrightarrow p + \bar{\nu}_\mu \]

Show that this equation obeys the conservation laws of charge, lepton number and baryon number.

(a) hadrons are subject to the strong nuclear force [or hadrons consist of quarks (or antiquarks)]  

(b) baryons and mesons  

baryons consist of three quarks  
antibaryons consist of three antiquarks  
mesons consist of a quark and an antiquark  
(any two)  

(c) Q: 0 + 1 = 1 + 0  
L: 0 − 1 = 0 − 1  
B: 1 + 0 = 1 + 0  

AQA, 2004
Exam Question 8

A negative pion ($\pi$) is a meson with a charge of $-1e$. State and explain the structure of the $\pi^-$ in terms of the up and down quarks.

- The pi (minus) consists of;
  - a single $d$ quark ($Q = -1/3$)
  - a single anti $u$ quark ($Q = -2/3$)
- Total charge is thus $-1$
- Obviously it is made of only 2 quarks as it is a **meson**
Exam Question 9

The following is an incomplete equation for the decay of a free neutron.

\[ _0^1n \rightarrow _1^1p + _0^0e + \ldots \]

(a) Complete the equation by writing down the symbol for the missing particle. (2 marks)

(b) Use the principles of conservation of charge, baryon number and lepton number to demonstrate that decay is possible. (3 marks)

(c) The following reaction can take place when two protons meet head on, provided the two colliding protons have sufficient kinetic energy:

\[ p + p \rightarrow p + p + \bar{p} + p \]

If the two colliding protons each have the same amount of energy, calculate the minimum kinetic energy, in MeV, each must have for the reaction to proceed. (2 marks)

\[ 2 \times 938\text{Mev} \rightarrow 4 \times 938 \text{ Mev} \]

Each initial proton collided must have at least 938MeV of kinetic energy alone to make the reaction proceed. Otherwise there is not enough energy to form the 3 protons and antiprotons. So in total there must be 1876MeV of KE shared between both protons.
Exam Question 10

(a) (i) What class of particle is represented by the combination of three antiquarks, \( \bar{q} \bar{q} \bar{q} \)?

(ii) Name a hadron that has an antiparticle identical to itself.

(b) The kaon \( K^+ \) has a strangeness of +1.

(i) Give its quark composition

(ii) The \( K^+ \) may decay via the process

\[
K^+ \rightarrow \pi^+ + \pi^0
\]

State the interaction responsible for this decay.

(iii) The \( K^+ \) may also decay via the process

\[
K^+ \rightarrow \mu^+ + \nu_\mu
\]

Change each particle of this equation to its corresponding antiparticle in order to complete an allowed decay process for the negative kaon \( K^- \).

\[
K^- \rightarrow
\]

(iv) Into what class of particle can both the \( \mu^+ \) and the \( \nu_\mu \) be placed?

(v) State one difference between a positive muon and a positron, \( e^+ \).
Ans Q10

(a) (i) What class of particle is represented by the combination of three antiquarks, \( \bar{u} \bar{d} \bar{d} \)?

Baryon & antibaryon (hadrons for 1 mark)

(ii) Name a hadron that has an antiparticle identical to itself.

\[ \pi^0 \hspace{1cm} \text{neutron} \]

(3 marks)
Ans Q10

(b) The kaon $K^+$ has a strangeness of +1.

(i) Give its quark composition.

\[ u \bar{s} \]

(ii) The $K^+$ may decay via the process

\[ K^+ \rightarrow \pi^+ + \pi^0. \]

State the interaction responsible for this decay.

weak (interaction)

(iii) The $K^+$ may also decay via the process

\[ K^+ \rightarrow \mu^+ + \nu_\mu. \]

Change each particle in this equation to its corresponding antiparticle in order to complete an allowed decay process for the negative kaon $K^-.$

\[ K^- \rightarrow \mu^- + \bar{\nu}_\mu. \]

(iv) Into what class of particle can both the $\mu^+$ and the $\nu_\mu$ be placed?

lepton

(v) State one difference between a positive muon, $\mu^+$, and a positron, $e^+.$

mass (or its generation or rest energy or stability)
Exam Question 11

The equation represents the collision of a neutral kaon with a proton, resulting in the production of a neutron and a positive pion.

\[ K^0 + p \rightarrow n + \pi^+ \]

(a) Show that this collision obeys three conservation laws in addition to energy and momentum.

- **baryon number**: \(0 + 1 = 1 + 0\)
- **lepton number**: \(0 + 0 = 0 + 0\)
- **charge**: \(0 + 1 = 0 + 1\)

The neutral kaon has a strangeness of +1.

Write down the quark structure of the following particles.

\[ K^0 \] \(\bar{u}\bar{d}\) \(\checkmark\)

\[ \pi^- \] \(u\bar{d}\) \(\checkmark\)

\[ p \] \(u\bar{d}\bar{u}\) \(\checkmark\)

Number of quarks and antiquarks in each \(\checkmark\)

(3 marks)