Feynman diagrams

Feynman diagrams are pictorial ways of representing the interactions of quantum particles. They were first introduced by Richard Feynman in 1948. Feynman realised that the interactions of particles on the quantum scale could be represented on paper by a series of arrows and wavy lines, following a set of simple rules. As an example, Figure 2.9 shows the standard Feynman diagram illustrating β^- radioactive decay.

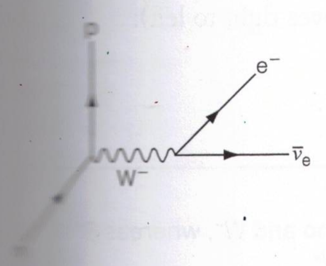

Figure 2.9 Feynman diagram illustrating β^- decay.

Feynman diagrams are generally read from left to right. Figure 2.9 shows a neutron decaying into a proton and a W^- exchange particle, which subsequently decays into an electron and an electron antineutrino. This is an example of the **weak** interaction and can be written as an equation:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}_e$$

You can see immediately the advantage of the Feynman diagram over the symbol equation. The Feynman diagram summarises all the parts of the interaction, whereas the equation only tells us what goes into the interaction and what comes out. It tells us nothing about what goes on during the interaction.

Feynman diagram rules

- Particles are represented by straight lines with arrow heads drawn on them.
- Exchange particles are represented by wavy lines.
- Time generally moves on the *x*-axis from left to right (although this is not a hard and fast rule, and many Feynman diagrams have time running vertically).
- Particles are created and annihilated at the vertices between the lines.
- Particles made up of quarks have the quark lines draw parallel and next to each other.
- Exchange particles generally transfer from left to right unless indicated by an arrow above the wavy line.

Feynman diagram examples

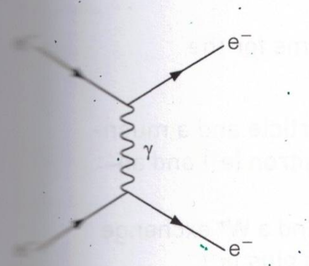

Figure 2.10 Feynman diagram illustrating two electrons meeting.

Two electrons scattering off each other (Figure 2.10)

Two electrons meet, exchange photons and scatter away from each other. The photon symbol γ indicates that this is an example of an **electromagnetic** interaction.

β^+ (positron) radioactive decay (Figure 2.11)

In this case, a proton decays into a neutron and a W^+ exchange particle, which subsequently decays into a positron and an electron neutrino. This is another example of the **weak** interaction, (like β^- decay), and is summarised by the equation:

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu_e$$

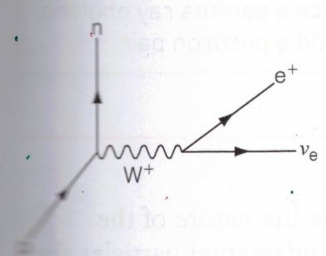

Figure 2.11 Feynman diagram illustrating β^+ (positron) radioactive decay.

Electron capture (Figure 2.12)

Electron capture is another example of the **weak** interaction. An electron is absorbed by a proton within a nucleus. The proton decays into a neutron and a W^+ exchange particle, which interacts with the electron forming an

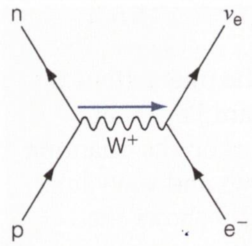

Figure 2.12 Feynman diagram illustrating electron capture.

electron neutrino (as the proton acts on the electron the arrow above the exchange particle moves left to right):

$${}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + \nu_e$$

Electron–proton collision (Figure 2.13)

An electron and a proton collide transferring a W^- exchange particle, indicating the **weak** interaction; the proton decays into a neutron and the electron decays into an electron neutrino (as the electron collides with the proton the arrow above the exchange particle moves right to left):

$${}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + \nu_e$$

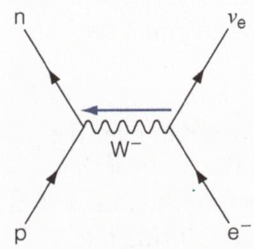

Figure 2.13 Feynman diagram illustrating electron–proton collision.

TIP

β^- decay is negative so involves e^-, an antineutrino and W^-, whereas β^+ decay is positive so involves e^+, a neutrino and W^+.

Proton–neutron bound by a gluon (Figure 2.14)

A **gluon** is exchanged between a neutron and a proton binding the two particles together (the process repeats over and over again). Notice that the Feynman diagram symbol for a gluon is a different wavy line from that of the photon or the $W^{\pm}/Z$ exchange particles. This is an example of the **stron** interaction.

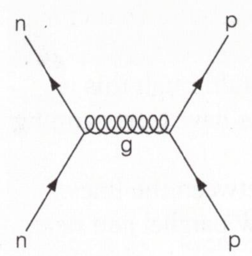

Figure 2.14 Feynman diagram illustrating proton–neutron binding via gluon exchange.

ACTIVITY

Drawing Feynman diagrams

Write decay equations and draw Feynman diagrams for the following decays.

1 A muon plus (μ^+) decays into a W^+ exchange particle and a muon-antineutrino ($\bar{\nu}_\mu$). The W^+ then decays into a positron (e^+) and an electron neutrino (ν_e).
2 A kaon zero (K^0) decays into a pion minus (π^-) and a W^+ exchange particle, which subsequently decays into a pion plus (π^+).
3 An electron neutrino and an electron antineutrino annihilate into a gamma ray photon.
4 An electron neutrino decays into an electron and a W^+ exchange particle, which subsequently collides with a neutron producing a proton.
5 An electron and a positron annihilate to produce a gamma ray photons, one of which then pair produces an electron and a positron pair.

Classification of particles

Although the Standard Model is used to describe the nature of the matter in the observed Universe, many of the fundamental particles tha are part of the model are rarely observed on their own and, even when they are, it is only at extremely high energy. Most of the fundamental particles are seen in combination with others, forming particles that car exist on their own at lower energies. Most of these composite particles were 'discovered' before their constituent fundamental particles and, in the years after the Second World War, names were given to these composite particles and the groups that they seemed to belong to. The particles were arranged into three groups: hadrons, leptons and exchange particles.

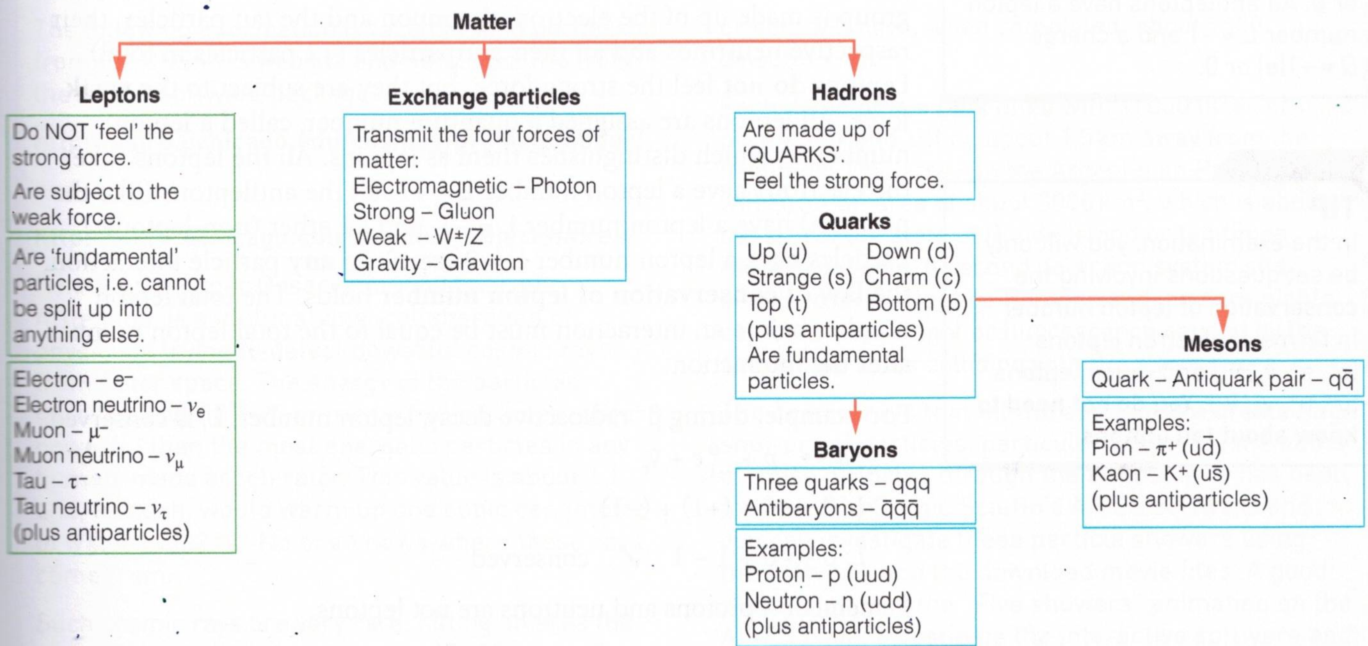

Figure 2.15 The particle garden.

TIP

All the leptons, exchange particles and quarks make up the particles of the Standard Model. However, the tau and tau-neutrino leptons and the charm, top and bottom quarks are not part of the examination specification. Any questions set on the examination papers involving these particles would give you all the information that you need to answer the question.

TEST YOURSELF

18 Use the following list to answer parts (a) to (e).
proton pion muon photon neutron
- **a)** Which particle is a lepton?
- **b)** Which particles are hadrons?
- **c)** Which particles are fundamental particles?
- **d)** Which particle is a meson?
- **e)** Which particle is an exchange particle?

19 State the difference between a baryon and a meson.

20 Which particles feel the weak interaction?

21 Use the following list of particle groups to answer parts (a) to (d).
lepton hadron meson baryon exchange particle.

Which group(s) do the following particles belong to?
- **a)** neutron
- **b)** kaon minus
- **c)** W^+
- **d)** electron antineutrino

> **TIP**
> All leptons have a lepton number L = +1, but a charge $Q = -1(e)$ or 0. All antileptons have a lepton number L = −1 and a charge $Q = +1(e)$ or 0.

> **TIP**
> In the examination, you will only be set questions involving the conservation of lepton number in terms of electron leptons (e^-, e^+, ν_e, $\bar{\nu}_e$) and muon leptons (μ^-, μ^+, ν_μ, $\bar{\nu}_\mu$). **You do not need to know about tau leptons.**

Leptons

Exchange particles aside, matter is arranged into two broad groups with very different properties: leptons and hadrons. **Leptons** are fundamental particles (and are described as part of the Standard Model). The lepton group is made up of the electron, the muon and the tau particles, their respective neutrinos and all their antiparticles (12 particles in total). Leptons **do not** feel the strong force, but they are subject to the **weak** force. All leptons are assigned a quantum number, called a lepton number, L, which distinguishes them as leptons. All the leptons (like the electron) have a lepton number L = +1, all the antileptons (like the positron) have a lepton number L = −1, and all other (non-leptonic) particles have a lepton number L = 0 (zero). In **any** particle interaction, the **law of conservation of lepton number** holds. The total lepton number before an interaction must be equal to the total lepton number after the interaction.

For example, during β^- radioactive decay, lepton number, L, is conserved.

$$^1_1n \rightarrow {}^1_1p + {}^{0}_{-1}e + \bar{\nu}_e$$

$$L: 0 \rightarrow 0 + (+1) + (-1)$$

$$L: 0 \rightarrow 0 + 1 - 1 \quad \checkmark \quad \text{conserved}$$

Remember – protons and neutrons are not leptons.

Particle **lifetime** is the average time that a particle exists from its creation to its decay. Table 2.2 shows some examples.

Muon decay

Muons are unstable particles with a mass of about 200 times the mass of an electron. Muons have unusually long **lifetimes**, of the order of 2.2 μs and only the neutron, proton and atomic nuclei have higher lifetimes. All muons decay via the weak interaction into three particles, one of which has to be an electron (or a positron) and the other two particles are neutrinos. The decay equations for the muon and the antimuon are:

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

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

Table 2.2 Mean lifetimes for some particles.

Particle	Mean lifetime
proton	$>1 \times 10^{29}$ years.
electron	$>4.6 \times 10^{26}$ years
(free) neutron	885.7 seconds
muon	2.2×10^{-6} seconds
π^0	8.4×10^{-17} seconds
π^+	2.6×10^{-8} seconds
W^+	1×10^{-25} seconds

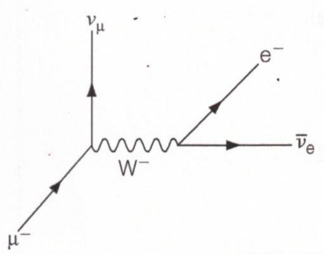

Figure 2.16 Feynman diagram showing muon decay.

The Feynman diagram for the decay of the muon is given in Figure 2.16.

ACTIVITY

The Pierre Auger Observatory and Project AIRES Cosmic Ray Shower Simulations

The following information is taken by kind permission from the COSMUS website and Sergio Sciutto from the AIRES software package:

http://astro.uchicago.edu/cosmus/projects/auger/

and

http://astro.uchicago.edu/cosmus/projects/aires/

'The Pierre Auger Observatory in Malargue, Argentina, is a multinational collaboration of physicists trying to detect powerful cosmic rays from outer space. The energy of the particles here is above 10^{19} eV, or over a million times more powerful than the most energetic particles in any human-made accelerator. This value is about 1 J and, as such, would warm up one cubic centimetre of water by 0.2 °C. No one knows where these rays come from.

Such cosmic rays are very rare, hitting an area the size of a football pitch once every 10 000 years. This means you need an enormous "net" to catch these mysterious ultra high energy particles. The Auger project will have, when completed, about 1600 detectors.

Each detector is a tank filled with 11 000 litres of pure water and sitting about 1.5 km away from the next tank. This array on the Argentinian Pampas will cover an area of about 3000 km^2, which is about the size of the state of Rhode Island or ten times the size of Paris. A second detection system sits on hills overlooking the Pampas and, on dark nights, captures a faint light or fluorescence caused by the shower particles colliding with the atmosphere'.

The cosmic rays that hit the atmosphere create huge showers of particles, particularly leptons; the paths of these particles through the atmosphere has been modelled by Sergio Sciutto's AIRES software and you can investigate these particle showers using the software and the download movie files. A good place to start is the "Five showers" animation on the AIRES page. Investigate the interactive software and the movie files to find out more about how cosmic rays produce particle interactions in the upper atmosphere.

TEST YOURSELF

22 What is the law of conservation of lepton number?

23 The rest-mass of an electron is 9.11×10^{-31} kg. Use this value to estimate the rest-mass of a muon.

24 Use the law of conservation of lepton number to explain why an interaction involving an electron and a positron annihilating and producing two muons **is not** possible.

25 Explain why an electron antineutrino is always produced during β^- emission.

TIP

Remember – you need to know about the following quarks:

up (u) charge, $+\frac{2}{3}e$

down (d) charge, $-\frac{1}{3}e$

strange (s) charge, $-\frac{1}{3}e$

(and their antiquarks, with opposite signs of charge).

Hadrons

Hadrons are particles that are made up of quarks and are therefore subject to the **strong** nuclear interaction. There are two sub-classes of hadrons.

Baryons, such as the proton and the neutron (and their antiparticles), are made up of three quarks (or three antiquarks). The proton comprises uud, with a total charge of +1e and the antiproton comprises $\overline{u}\overline{u}\overline{d}$, with a total charge of −1e.

Mesons, such as the pion and the kaon (and their antiparticles), are made up of a quark–antiquark pair.

TIP

Make sure you know the quark structure of the following particles:

- Proton, p, uud (and antiproton, $\overline{u}\overline{u}\overline{d}$)
- Neutron, n, udd (and antineutron, $\overline{u}\overline{d}\overline{d}$)
- Pion⁺, π^+, $u\overline{d}$
- Pion⁻, π^-, $d\overline{u}$,
- Pion⁰, π^0, $u\overline{u}$ or $d\overline{d}$

(The π^+ and π^- are antiparticles of each other, π^0 is its own antiparticle.)

- Kaon⁺, K^+, $u\overline{s}$
- Kaon⁻, K^-, $s\overline{u}$
- Kaon⁰, K^0, $d\overline{s}$ (and antiparticle, $\overline{K^0}$, $s\overline{d}$)

(The K^+ and K^- are antiparticles of each other.)

Baryons

As baryons are made up of three quarks, and there are six flavours of quark, there are many different possible baryons. Two of these baryons, the proton and the neutron, are well known and make up most of the mass of the Universe. The other baryons, containing the more massive quarks, are more exotic and are only observed at high energy inside particle detectors such as the LHC, or high up in the atmosphere as the result of interactions of cosmic rays with particles in the upper atmosphere. Each baryon has its own antibaryon – which is made up of the corresponding antiquarks. For example, the sigma baryon, Σ^+, is made up of two up quarks and a strange quark, uus, and the anti-sigma baryon, $\overline{\Sigma}^+$, is made up of two anti-up quarks and an anti-strange quark, $\overline{u}\overline{u}\overline{s}$.

The proton is the most stable and abundant baryon. Spontaneous free proton decay has never been observed and, although some non-Standard Model theories predict that it can happen, the predicted lifetime of the proton is of the order of 10^{34} years. The current measurement of the age of the Universe is only 13.8 billion years (13.8×10^9 years). As the Standard Model has proved to be remarkably robust, then it seems that free protons are stable, and all other baryons will eventually decay into protons. Neutrons also appear to be stable within most nuclei (unless they are β^- radioactive decay emitters), but when they are isolated on their own (free) they have a mean lifetime of 882 seconds (about 15 minutes). The vast majority of all the other baryons have vanishingly short lifetimes, between 10^{-10} and 10^{-24} seconds.

All baryons are assigned a **baryon** quantum **number**, B. All baryons have baryon number B = +1, all anti-baryons have a baryon number B = −1 and all non-baryons have B = 0. Like lepton number, baryon number is also conserved in particle interactions. The total baryon number of all particles before an interaction must equal the total baryon number after the interaction.

As baryons have integer values of baryon number, quarks must have a baryon number of $+\frac{1}{3}$ and antiquarks have a baryon number of $-\frac{1}{3}$. Protons are baryons with a quark structure of uud, so they must have a baryon number of $+\frac{1}{3}+\frac{1}{3}+\frac{1}{3} = +1$, and antiprotons with a quark structure of $\overline{u}\overline{u}\overline{d}$ must have a baryon number of $-\frac{1}{3}-\frac{1}{3}-\frac{1}{3} = -1$.

Feynman diagrams can be drawn involving composite particles such as the proton and the neutron (containing quarks), and they also show how the

TIP

Remember charge is also a quantum number like baryon number and is also conserved in particle interactions.

For example, during electron capture a proton inside a nucleus can interact with one of the electrons surrounding the nucleus and it can decay into a neutron and W^+ exchange particle, which then interacts with the electron producing an electron neutrino:

$${}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + \nu_e$$

B: + 1 + 0 → + 1 + 0 ✓ conserved

Q: + 1 + (−1) → + 0 + 0 ✓ conserved

quarks change during an interaction. The quarks making up the composite particle are shown by arrowed lines drawn parallel and next to each other. The Feynman diagram for β^- decay then becomes:

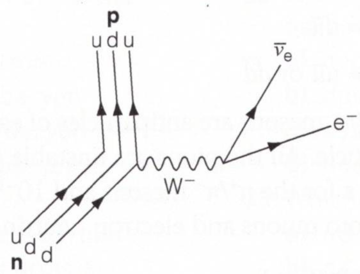

Figure 2.17 Feynman diagram for β^- decay.

In this example, the down quark decays into the W^- exchange particle and an up quark.

The Feynman diagrams for positron emission by protons in terms of quarks is also shown below:

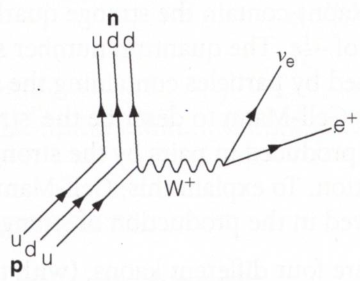

Figure 2.18 Feynman diagram illustrating β^+ (positron) radioactive decay involving quarks.

TEST YOURSELF

26 Explain why a proton can be a hadron and a baryon.

27 What is the quark structure of a neutron?

28 During positron emission, the quark structure of a proton changes. Describe this change.

29 Write a nuclear reaction equation for positron emission and use the equation to show that baryon number is conserved.

Mesons

Meson particles were first proposed by the Japanese physicist Hideki Yukawa in 1934 as a way of explaining the strong force holding protons and neutrons together to make nuclei. Yukawa suggested that the strong force was due to the proton and the neutron exchanging mesons. We now know that pions (pi-mesons) are exchanged between protons and neutrons, but that the strong interaction is actually due to the interaction between quarks that make up the protons and neutrons. Pions, being made up of quarks, also feel the strong force and are able to exist outside nucleons and so the strong interaction between the proton and the neutron is due to the pion exchange with the pions acting as a 'force carrier'.

Mesons are hadron particles made up of a quark–antiquark pair.

Mesons are made up of quark–antiquark pairs, $q\bar{q}$, and as with baryons, because there are six quarks and six antiquarks, there are many different possible mesons. Most mesons are high-energy particles and are only seen to exist inside the detectors of particle accelerators, but the pion and the kaon are produced when high-energy cosmic rays interact with the upper atmosphere and can be observed by high-altitude particle detectors. Mesons have a lepton number, L = 0 (they are not leptons) and a baryon number, B = 0 (they are not baryons).

TIP

Although mesons are hadrons, they are not baryons and hence their baryon number is 0.

Pions are combinations of the up, u, and down, d, quarks and their antiparticles. There are three types of pion:

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

$$\pi^- = d\bar{u}$$

$$\pi^0 = u\bar{u} \text{ or } d\bar{d}$$

The π^+/π^- mesons are antiparticles of each other and the π^0 is its own antiparticle. All the pions are unstable and decay with lifetimes of the order of 10^{-8} s for the π^+/π^- mesons and 10^{-16} s for the π^0 meson. The π^+/π^- mesons decay into muons and electron neutrinos via the weak interaction:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

The Feynman diagram for π^- decay is shown in Figure 2.19.

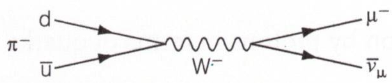

Figure 2.19 Feynman diagram showing pion minus decay.

The π^0 meson decays into two gamma rays.

The other common meson produced by cosmic ray interactions is the kaon. Kaons contain the strange quark (or antiquark), s, which has a charge of $-\frac{1}{3}$e. The quantum number **strangeness**, symbol S, is a property possessed by particles containing the strange quark and was coined by Murray Gell-Mann to describe the 'strange' behaviour of particles that are always produced in pairs by the strong interaction but decay via the weak interaction. To explain this, Gell-Mann suggested that strangeness was conserved in the production of strange particles, but not in their decay.

There are four different kaons, (with their strangeness values, S):

$$K^+ = u\bar{s} \ (S = +1)$$

$$K^- = s\bar{u} \ (S = -1)$$

$$K^0 = d\bar{s} \ (S = +1) \text{ and } \overline{K}^0 = s\bar{d} \ (S = -1)$$

TIP

The K⁺ particle has a charge of +1 because of the addition of the charges on the u and $\bar{s}$ quarks, $+\frac{2}{3}e + \left(+\frac{1}{3}e\right) = +1e$. The same is true for the charge on the K⁻ particle, $-\frac{2}{3}e + \left(-\frac{1}{3}e\right) = -1e$.

Kaon pair production occurs via the strong interaction (where strangeness is conserved).

For example, during the high-energy collision of two protons, a K⁺/K⁻ pair is produced:

$$p + p \rightarrow p + p + K^+ + K^-$$

Strangeness check:

$$0 + 0 = 0 + 0 + (+1) + (-1) = 0 \ ✓ \quad \text{conserved}$$

TIP

The strange quark has strangeness −1. The anti-strange quark has strangeness +1.

Kaons are unstable, decaying via the weak interaction with lifetimes of about 10^{-8} s to 10^{-10} s. There are several processes by which the charged kaons can decay:

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

$$K^+ \rightarrow \pi^+ + \pi^0$$

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

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

$$K^- \rightarrow \pi^- + \pi^0$$

$$K^- \rightarrow \pi^0 + \mu^- + \bar{\nu}_\mu$$

None of the decay products of these decays contain a strange quark, so strangeness is not conserved.

TEST YOURSELF

30 What is the charge and baryon number of the following particles:

a) proton
b) antiproton
c) neutron
d) electron
e) antineutron
f) positron
g) uds baryon
h) $\bar{u}\bar{u}\bar{s}$ baryon
i) dss baryon

31 The Standard Model and the particle garden arranges matter into the following groups:

A leptons
B quarks
C exchange particles
D baryons
E mesons

Which groups do the following particles (represented by their symbols only) belong to?

a) p
b) n
c) e^-
d) γ
e) μ^+
f) π^-
g) *u*
h) *uds*

32 Which of the following particles are **possible** baryons?

a) $\bar{d}uu$
b) duu
c) sss
d) dud
e) $\bar{d}\bar{u}\bar{s}$
f) sdu
g) ddd
h) $\bar{u}\bar{s}d$

33 Which of the following are **impossible** mesons?

a) ud
b) $d\bar{s}$
c) $u\bar{u}$
d) sd
e) dd
f) $d\bar{d}$

34 What is the baryon and lepton structure of the following atoms?

a) ${}^{2}_{1}H$
b) ${}^{4}_{2}He$
c) ${}^{14}_{6}C$
d) ${}^{23}_{11}Na$
e) ${}^{238}_{92}U$
f) ${}^{294}_{118}Uuo$

ACTIVITY

The Lancaster Particle Physics Package (LPPP)

The LPPP is an online resource for studying the interactions of particles. The package consists of a series of guided computer simulations that take you through the way that particle physicists study particle interactions experimentally. The computer simulations are backed up with basic physics explanations of what is going on inside each simulation. The package contains some material studied in other chapters of this book and at A level. The package can be accessed by using the following link:

www.lppp.lancs.ac.uk

Work your way through the package; you can dip in and out of it throughout the whole of the A level course.

TIP

Remember – Einstein's energy-mass equation, $E = mc^2$, shows that, on the quantum scale, mass and energy are interchangeable – mass can convert to energy and energy can convert back to mass. It is better to talk about mass-energy being conserved on a quantum scale rather than the conservation of mass and the conservation of energy.

Conservation laws

Throughout this chapter you have met several different quantum number conservation laws – properties or physical quantities that are the same after an interaction as they are before the interaction. Three further quantities are also always conserved in any interaction, these are:

- charge, Q
- momentum, p
- mass-energy, $E = mc^2$.

To these we add the quantum number conservation laws:

- lepton number, L
- baryon number, B
- strangeness, S.

With the exception of strangeness, all the other quantities are **always** conserved in **any** interaction. Strangeness is conserved in strong interactions but not in weak interactions (as the strange quark changes flavour).

Some examination questions ask you to decide if a given particle interaction, usually given to you in equation form, can happen or not. Momentum and mass-energy will always be conserved, so all you have to do is to determine if charge, Q; lepton number, L; baryon number, B; and strangeness, S, are conserved. (If strangeness is not conserved this could indicate that the interaction is a weak interaction). Consider the examples shown below.

EXAMPLE

Is this particle interaction possible?

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

Answer

A great way to do this is to construct a table similar to the one below:

Table 2.3

Conservation quantity	Before interaction			After interaction			Quantity conserved?
	p	$\bar{\nu}_e$	Total	e+	n	Total	
Q	+1	0	+1	+1	0	+1	✓
B	+1	0	+1	0	+1	+1	✓
L	0	−1	−1	−1	0	−1	✓
S	0	0	0	0	0	0	✓

In this example all the quantities are conserved, so the interaction is possible.

EXAMPLE

Is this interaction possible?

$$p + e^+ \rightarrow e^- + \Sigma^0 + K^+$$

Answer

The Σ^0 baryon has the following properties: Q = 0; B = +1; L = 0 and S = −1. Using the same table as in the previous example, but adding an extra product column:

Table 2.4

Conservation quantity	Before interaction			After interaction				Quantity conserved?
	p	e^+	Total	e^-	Σ^0	K^+	Total	
Q	+1	+1	+2	−1	0	+1	0	✗
B	+1	0	+1	0	+1	0	+1	✓
L	0	−1	−1	+1	0	0	+1	✗
S	0	0	0	0	−1	+1	0	✓

In this case charge, Q, and lepton number, L, are not conserved, so this interaction is not possible.

> **TIP**
> The format of the table can be modified depending on the number of particles involved – you can add extra columns or take them away.

ACTIVITY

Use the conservation laws to decide if the following particle interactions can occur. A table of properties of particles is also shown.

Table 2.5

Particle	Charge, Q	Baryon number, B	Lepton number, L	Strangeness, S
p	+1	+1	0	0
n	0	+1	0	0
e^-	−1	0	+1	0
e^+	+1	0	−1	0
ν_e	0	0	+1	0
$\bar{\nu}_e$	0	0	−1	0
Σ^0	0	+1	0	−1
Σ^-	−1	+1	0	−1
K^+	+1	0	0	+1

1. $p + \pi^- \rightarrow \Sigma^- + K^+$
2. $p + \bar{\nu}_e \rightarrow e^+ + \Sigma^0$
3. $n \rightarrow p + e^+ + \nu_e$
4. $p + e^+ \rightarrow e^- + \Sigma^0 + K^+$
5. $n \rightarrow p + e^- + \bar{\nu}_e$
6. $\pi^- + p \rightarrow n + \pi^0 + \bar{\nu}_e$

What you need to know

- For every type of particle there is a corresponding antiparticle.
- Particles and antiparticles have: rest-mass (in MeV/c^2); charge (in C) and rest-energy (in MeV).
- The positron, the antiproton, the antineutron and the electron antineutrino are the antiparticles of the electron, the proton, the neutron and the electron neutrino respectively.
- The four fundamental interactions are: gravity, electromagnetic, weak and strong. (The strong nuclear force is also known as the strong interaction.)
- Exchange particles are used to explain forces between elementary particles on the quantum scale.
- The virtual photon is the exchange particle for the electromagnetic interaction.
- Examples of the weak interaction are β^- decay, β^+ decay, electron capture and electron–proton collisions.
- The W^+ and W^- are the exchange particles of the weak interaction.
- Feynman diagrams are used to represent reactions or interactions in terms of particles going in and out, and exchange particles.
- Hadrons are particles that are subject to the strong interaction.
- There are two classes of hadrons:
  - baryons (proton, neutron) and antibaryons (antiproton and antineutron)
  - mesons (pion, kaon)
- Baryon number, B, is a quantum number that describes baryons. Baryons have B = +1; antibaryons, B = −1; non-baryons, B = 0.
- Baryon number is always conserved in particle interactions.
- The proton is the only stable baryon and all other baryons will eventually decay into protons.

- Free neutrons are unstable and decay via the weak interaction forming a proton, β^- particle and an electron antineutrino.
- Pions and kaons are examples of mesons. The pion is the exchange particle of the strong nuclear force between baryons. The kaon is a particle that can decay into pions.
- Leptons are particles that are subject to the weak interaction.
- Leptons include: electron, muon, neutrino (electron and muon types) and their antiparticles.
- Lepton number, L, is a quantum number used to describe leptons; leptons have L = +1; antileptons, L = −1; non-leptons, L = 0.
- Lepton number is always conserved in particle interactions.
- Muons are particles that decay into electrons.
- Strange particles are particles that are produced through the strong interaction and decay through the weak interaction (e.g. kaons).
- Strangeness (symbol S) is a quantum number to describe strange particles. Strange particles are always created in pairs by the strong interaction (to conserve strangeness).
- Strangeness is conserved in strong interactions. In weak interactions the strangeness can change by −1, 0 or +1.
- Quarks have: charge $\left(+\frac{1}{3}, -\frac{1}{3}, +\frac{2}{3}, -\frac{2}{3}\right)$, baryon number, $\left(+\frac{1}{3}, -\frac{1}{3}\right)$ and strangeness (+1, 0 or −1).
- Hadrons have the following quark structures:
  - baryons (proton, uud; neutron, udd), antiproton, $\bar{u}\bar{u}\bar{d}$, and antineutron, $\bar{u}\bar{d}\bar{d}$)
  - mesons:
    - pions - Pion⁺, π^+, $u\bar{d}$; Pion⁻, π^-, $d\bar{u}$; Pion⁰, π^0, $u\bar{u}$ or $d\bar{d}$
    - kaons - Kaon⁺, K^+, $u\bar{s}$; Kaon⁻, K^-, $s\bar{u}$; Kaon⁰, K^0, $d\bar{s}$ or $s\bar{d}$.
- During β^- decay a d quark changes into a u quark, and during β^+ decay a u quark changes into a d quark.
- Conservation laws for charge, baryon number, lepton number and strangeness can be applied to particle interactions.

TEST YOURSELF

35 Match the pions to their correct quark structures:

π^0 $\quad$ π^+ $\quad$ π^-

$d\bar{u}$ $\quad$ $u\bar{u}$ $\quad$ ud, $u\bar{d}$

36 Which of the following pion decays is not possible?

a) $\pi^+ \rightarrow e^+ + \nu_e$

b) $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

c) $\pi^0 \rightarrow \gamma + \gamma$

d) $\pi^- \rightarrow \mu^- + \mu^+$

e) $\pi^+ \rightarrow \mu^+ + \nu_\mu$

37 Identify the quark structure of the following strange particles from the quark list below.

P uus
Q uds
R $u\bar{s}$
S $s\bar{u}$
T $d\bar{s}$

a) K^+

b) K^-

c) Λ^0 (lamda⁰) baryon

⇨

38 Strange quarks, responsible for the long half-lives of strange particles during the weak interaction, were first proposed by Murray Gell-Mann and George Zweig in 1964. As baryon number had already been defined as +1 for protons and neutrons the subsequent discovery of quarks required them to have $+\frac{1}{3}$ and $-\frac{1}{3}$ baryon numbers. Table 2.6 compares some of properties of strange and down quarks and their antiquarks:

Table 2.6

Quark	Baryon number	Charge/e	Strangeness
s	$\frac{1}{3}$	$-\frac{1}{3}$	−1
$\bar{s}$	$-\frac{1}{3}$	$+\frac{1}{3}$	+1
d	$\frac{1}{3}$	$-\frac{1}{3}$	0
$\bar{d}$	$-\frac{1}{3}$	$+\frac{1}{3}$	0

a) Quarks and antiquarks can combine to form four possible mesons. Copy and complete the table, calculating the baryon number, charge and strangeness of the four mesons.

Table 2.7

Quark pair	$s\bar{s}$	$s\bar{d}$	$d\bar{s}$	$d\bar{d}$
Name	phi	kaon^0 (anti-symmetric)	kaon^0 (symmetric)	rho^0
Baryon number				
Charge/e				
Strangeness				

b) The phi and rho^0 mesons have the same properties in the table. Suggest a way that these two mesons could be distinguished from each other.

39 The last quark to be identified experimentally was the top, t, quark in 1995, 18 years after it was first added as a concept to the Standard Model.

a) Suggest why physicists were able to predict the existence of the top quark even though it took 18 years to observe it experimentally.

b) The top quark was observed experimentally by the Tevatron particle accelerator at Fermilab in the USA. The tevatron collided protons and antiprotons with an energy of 1.8 TeV (1.8×10^{12} eV). Although the protons and anti-protons have a high momentum, the sum of the momentums of a colliding pair of particles – a proton and an antiproton – is zero, because they are travelling in opposite directions with the same speed. The resulting collisions produced top quark–antitop quark pairs that were then observed in the particle detectors. Explain why top quark–antitop quark pairs move in opposite directions after they are produced by the collision.

c) The top quark (and antiquark) has an extremely short lifetime (5×10^{-25} s) and decays into a bottom quark and a $W^{\pm}$ exchange particle. This is shown in Figure 2.20.

Identify particles X and Y.

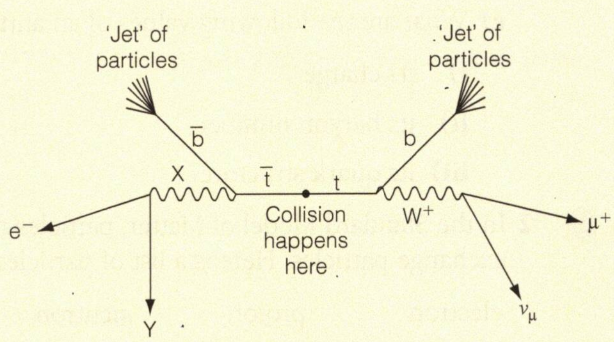

Figure 2.20 Feynman diagram of top–antitop quark pair production.

40 The charm quark was observed experimentally by two particle physics teams at almost the same time in 1974. One team was based at the Brookhaven National Laboratory (BNL) and the other at the Stanford Linear Accelerator (SLAC). Both teams observed a $c\bar{c}$ meson. The BNL team called it the psi (ψ) meson and the SLAC team named it the J meson – since then it has been known as the J/ψ meson. The J/ψ meson has the following properties:

Table 2.8

Charge	Baryon number	Lepton number
0	0	0

The J/ψ meson can decay in many ways; two of these are shown below:

$$J/\psi \rightarrow e^+ + e^-$$

$$J/\psi \rightarrow \mu^+ + \mu^-$$

Explain, using conservation laws, how both of these decay equations are correct. You need to consider:

- energy
- momentum
- charge
- baryon number
- lepton number.