# Teacher Resource Bank

GCE Physics A

Other Guidance:

- Particle Physics

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# AQA Physics Specification A Particle Physics

## Preface

This booklet covers the Particle Physics topics in AS unit 1, PHYA1, of the new GCE Physics Specification A. The booklet aims to provide background material for teachers and offers some guidance as to prerequisites and depth of study. The numbered chapters of the contents list below are directly relevant to the specification. The appendices in the booklet are not part of the specification and are intended to provide further background material to give teachers deeper knowledge of Particle Physics.

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## Introduction

Although this booklet is not intended as a teaching scheme, the following points are provided to assist teachers offering AS specification A. In addition, an outline teaching scheme is suggested and *How Science Works* opportunities in unit 1, Particle Physics, are outlined.

**1** Teachers are advised to cover **3.1.1 Constituents of the atom** and **3.1.1 Stable and unstable nuclei** before commencing the Particle Physics topics in 3.1.1.

**2** The photon model in **3.1.1 Particles, antiparticles and photons** may be covered without first covering **3.1.2 The photoelectric effect**. Students would need to be taught that electromagnetic radiation consists of wavepackets called photons and the energy of each photon is related to the radiation frequency through the photon energy equation $E = hf$.

**3** The specification includes the electromagnetic interaction and the photon as its exchange particle, the weak interaction and the $W^+$ boson and $W^-$ boson as exchange particles and the strong interaction without reference to exchange particles. The idea of the strong nuclear force holding the protons and neutrons together in the nucleus should be covered with reference to its general characteristics and its force – distance curve. The weak nuclear force, also referred to as the weak interaction, may be introduced as being responsible for $\beta$ decay.

**4** Students will be familiar with $\alpha$ and $\beta^-$ decay from their GCSE studies. However, they may not have met the equation for each type of decay and will need to be taken through the nature of

- $\alpha$ decay as a process in which a large unstable nucleus becomes stable or less unstable by emitting two protons and two neutrons as an $\alpha$ particle,
- $\beta^-$ decay as a process in which a neutron in a neutron-rich nucleus changes into a proton, creating and emitting an electron (i.e. $\beta^-$ particle) at the same time.

Discussion of $\beta^-$ decay can then be used to lead on to positron emission by proton-rich nuclei, the existence of antimatter particles and the need on energy grounds for the antineutrino in $\beta^-$ decay and the neutrino in $\beta^+$ decay.

**5** AS unit 1 does not require the **use** of $E = m c^2$ or the atomic mass unit, both of which are in A2 unit 5, section A. However, students should know after studying unit 1 that

- energy and mass are interchangeable on a scale given by $E = m c^2$,
- matter particles and antiparticles gain or lose mass when energy is transferred to or from them respectively,
- when a particle and its antiparticle interact, they annihilate each other and their mass is converted into energy,
- the rest mass of a particle or antiparticle may be considered as 'rest energy' that can only be released in an annihilation event,
- a photon of sufficient energy can create a particle-antiparticle pair; two photons are created when a particle and corresponding antiparticle annihilate each other.

## How Science Works

Particle Physics offers opportunities to develop some of the non-practical strands of *How Science Works*.

**A Use theories, models and ideas to develop and modify scientific explanations**

- the strong nuclear force introduced to explain why most nuclei are stable
- strangeness was introduced to account for 'allowed' particle reactions not observed

**G Appreciate the tentative nature of scientific knowledge**

- antiparticles were predicted before they were discovered
- the antineutrino was introduced to account for conservation of energy in $\beta^-$ decay and discovered later

**I Consider applications and implications of science and appreciate their associated benefits and risks**

- the benefits to a patient of a PET scan need to be considered against the risk of harm due to gamma radiation from positron-electron annihilation events in the patient

**K Appreciate the role of the scientific community in validating new knowledge and ensuring integrity**

- experimental confirmation of the existence of the W boson was validated by other scientists independently

## Possible teaching scheme for AS Specification, Unit 1 Particle Physics

| Part 1 (1½ - 2 weeks) | Notes |
|---|---|
| **What's inside the atom?** | |
| Reminder of the nuclear model of the atom from GCSE – note that Rutherford scattering in now at A2<br>Isotopes; isotope notation; charge/mass | - isotope notation<br>- charge/mass calculations |
| **Why are some nuclei unstable?** | |
| The strong nuclear force and its characteristics | - Geiger counter demonstration |
| Radioactivity; charges in unstable nuclei due to alpha, beta decay and gamma decay<br>The need for the neutrino | - HSW |
| **What are photons?** | |
| Electromagnetic waves from GCSE; $c = f\lambda$<br>Photons $E = hf$; laser light | - calculations using $c = f\lambda$ and $E = hf$ |
| **What is antimatter?** | |
| Positron emission; change in nuclear composition | - PET scanner |
| Discovery of the first antimatter particle; the positron | - HSW |
| Dirac's prediction of antimatter<br>Annihilation and pair production; rest energy and $E – m c^2$ | - use of data book for rest energy values |
| **How do particles interact?** | |
| Force and momentum from GCSE<br>Electromagnetic force and virtual photons; Feynman diagram<br>The weak nuclear force or 'weak interaction'; its role in beta decay | - momentum transfer demonstration e.g. throwing a heavy ball |
| $W^+$ and $W^–$ bosons as the exchange particles in n, $v$, and p, anti-$v$ interactions<br>Feynman diagrams for above interactions and for both types of beta decay<br>Electron capture | - interpret Feynman diagrams |

| Part 2 (2½ - 3 weeks) | Notes |
|---|---|
| **In terms of mass, are there particles between electrons and protons?** | |
| Prediction of 'mesons' as exchange particle of the strong nuclear force | - HSW |
| The discovery of the muon and the $\pi$ meson; the antimuon; muon decay<br>Strange particles; their discovery and production through the strong interaction and decay via the weak interaction<br>K meson less massive than the proton and decaying into $\pi$ mesons<br>Other mesons heavier than the proton decaying into protons and $\pi$ mesons | - 'meson' was a 'middleweight particle' but now a quark – antiquark particle so muon is not a meson |

| **What sorts of particles (and antiparticles) are there?** | |
|---|---|
| Hadrons and leptons<br>Baryons and mesons as the classes of hadrons; ‘quark’ substructure?<br>Collider experiments to make particles and antiparticles – use of conservation of energy | - classify by interaction then hadrons originally by mass but now by quark content - quark model to come<br>- use rest energy values |
| **Are leptons elementary?** | |
| Muons and electrons neutrinos; experimental evidence | - 2 branches needed |
| Leptons number conservation rules | - examples |
| **What are quarks?** | |
| Reactions that obey the rules but don’t happen; strangeness number and conservation | - examples |
| The 3 quark model for baryons, antibaryons and mesons; quark rules | |
| Protons and neutrons in quark terms; all baryons decay to the proton | - quark properties |
| The first experimental evidence for quarks | - HSW |
| **Why are conservation rules important?** | |
| Physical quantities that are the same before and after a change are ‘conserved’<br>Conservation rules enable us to predict change | - meaning of conservation in physics |
| Conservation of energy and charge applies to all changes – conservation of momentum is A2 | - examples of equations that work |
| Particle interactions and decays must obey conservation of energy and of charge and of<br>- baryon number<br>- lepton number for each lepton branch<br>- strangeness but only in the strong interaction | - equations that don’t work |

## Overview

Matter consists of quarks and leptons. Antimatter consists of antiquarks and antileptons.

Quarks combine in threes to form baryons; antiquarks combine in threes to form antibaryons; a meson consists of a quark and an antiquark.

Leptons do not combine with other leptons or antileptons or any other particles.

It isn’t possible to produce/annihilate

- a quark (or antiquark) without producing/annihilating a corresponding antiquark (or quark)
- a lepton (or antilepton) without producing/annihilating an antilepton (or lepton) of the same type

The strange quark (and antiquark) is unstable and decays into an up quark, an electron and an electron antineutrino.

## Chapter 1 Particles, Antiparticles & Photons

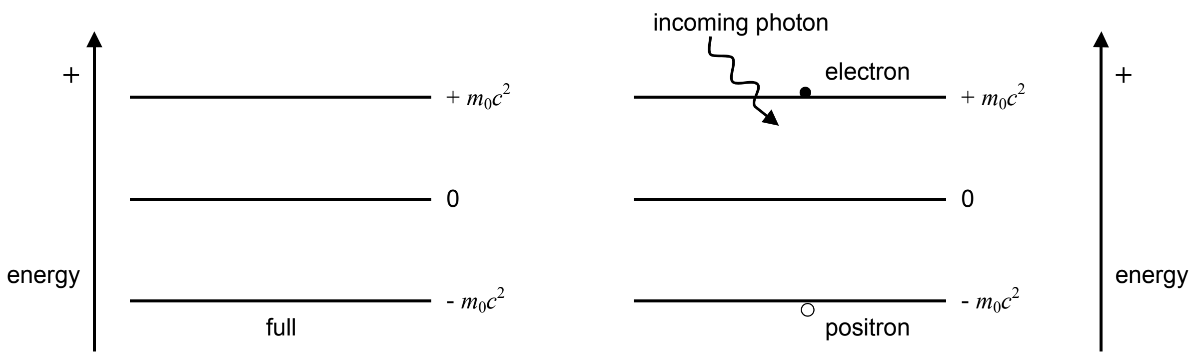
Before starting this section, students should know the structure of the atom and the nature of $\alpha$, $\beta$ and $\gamma$ radiation. In this section they will learn to use the notation for isotopes and the equations for $\alpha$, $\beta^-$ and $\beta^+$ emission. They will also learn that electromagnetic radiation consists of photons of energy $E = hf$ where $f$ is the frequency of the radiation. They will find out that energy can be converted into mass (e.g. a photon of sufficiently high energy can turn into a matter and an antimatter particle) and that mass can be converted to energy (e.g. a matter particle and an antimatter particle can interact and turn into two photons). They will also learn that the rest mass of the particle and antiparticles as 'rest energy' needs to be considered in applying the conservation of energy to a particle reaction. The **use** of $E = mc^2$ is not required in this unit but students should know that the equation gives the scale of conversion (of mass to energy or energy to mass) and they should be familiar with the table of data listing rest energy values in the *Data and Formulae Booklet* for Specification A, for example, to appreciate that pair production of an electron and a positron requires the energy of the photon to be at least 1.02 MeV. References in these notes to rest energy values should not be taken to mean that students have to learn these values.

## Antimatter

### (a) The Positron

The existence of antimatter was first proposed by Paul Dirac in 1928 who put forward a theory combining relativity and quantum mechanics which implied that electrons exist in negative energy states as well as positive energy states. The negative energy states are normally fully occupied by electrons and therefore not normally observable. However, a photon of sufficient energy is capable of exciting an electron from a negative energy state to a positive energy state, thus creating an electron with positive energy and a 'hole' in the negative energy state.
The 'hole' therefore behaves like a positively-charged electron, now referred to as a positron.

**Figure 1**




The positron is an example of antimatter and it is the antiparticle of the electron. Every particle has an antiparticle, except for certain particles like the photon. The antiparticle of any charged particle has opposite charge to that of the particle. Experimental evidence for the positron was first produced by Carl Anderson in 1932 from cloud chamber photographs.

The creation of an electron and a positron from a gamma photon is an example of **pair production**. The minimum photon energy $hf$ to produce an electron and positron is equal to $2m_0c^2$, where $m_0$ is the rest mass of an electron.

**Figure 2**

(a) Evidence for the positron (b) Pair production

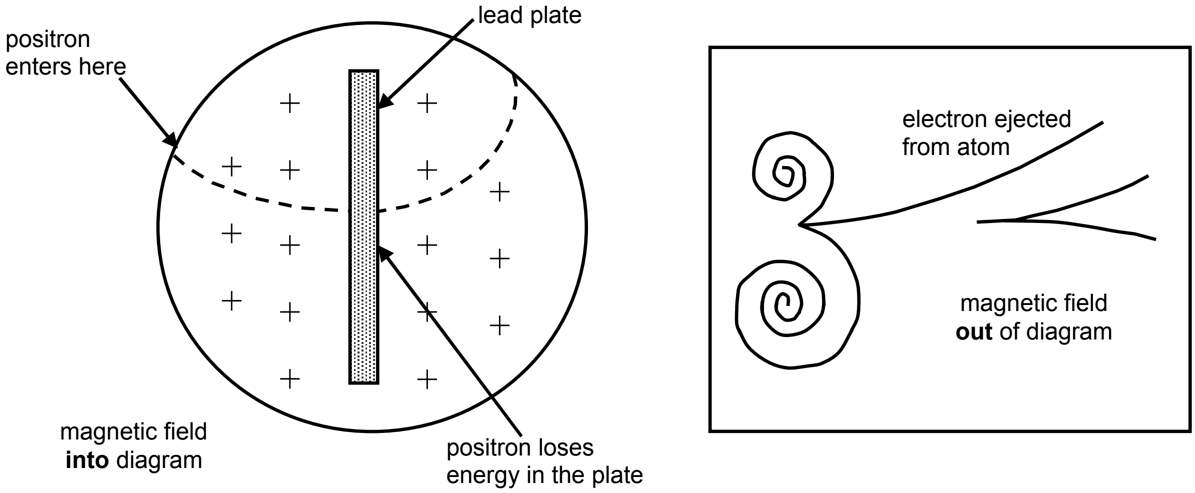



Figure 2 (b) shows a bubble chamber photograph depicting two electron-positron pairs created in a magnetic field. The gamma photon does not leave a track because it is uncharged. Students might like to consider

- why the tracks curve in opposite directions from the point of production
- the significance of the curvature in terms of particle momentum
- the cause of the spirals
- the minimum photon energy needed to cause pair production of an electron and a positron, given the rest energy of an electron is 0.55 MeV.

**(b) The Antiproton** ($\overline{p}$)

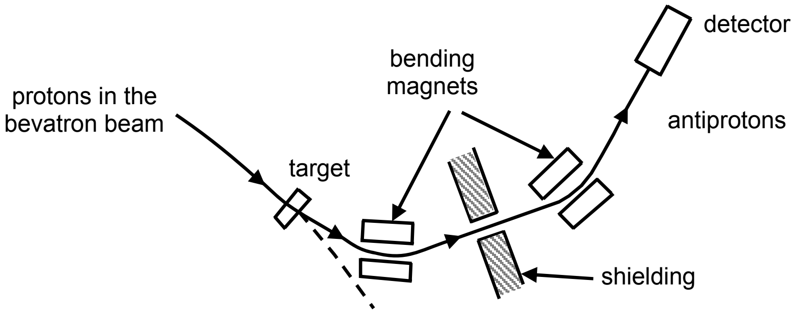
Antiprotons were first created and detected in 1955 when the University of California 6 GeV proton synchrotron known as the 'bevatron' was put into operation. High energy protons were targeted at stationary protons, creating protons and antiprotons as a result.

$$p + p \rightarrow \overline{p} + p + p + p$$

The rest energy of a proton is 0.938 GeV. To create a proton and an antiproton in a colliding beam collision requires minimum kinetic energy equal to 1.87 GeV. However, the bevatron is a fixed-target accelerator and its moving protons need at least 5.6 GeV to create proton-antiproton pairs in a fixed target collision and to conserve momentum.

Antiprotons and other types of particles were created in a proton-proton collision. The antiprotons were negatively charged and therefore could be separated by a magnetic field from the other types of particles and then detected electronically. The mass of the antiproton was measured and found to be equal to the mass of the proton.

**Figure 3**




Accelerators now in operation at much higher energies can produce and 'store' antiprotons in synchrotron rings for use in proton-antiproton colliding experiments.

## Annihilation

An electron and a positron in collision annihilate each other and create two gamma photons carrying total energy equal to the total energy of the electron and positron. Such events can be seen on bubble chamber photographs where the track of a positron abruptly terminates due to a collision with an atomic electron.

Annihilation of electrons and positrons is deliberately caused in high energy accelerators such as CERN's LEP and the Stanford Linear Collider (see page 25). The energy available from the annihilation of a high energy electron and a high energy positron in these accelerators is sufficient to create new particles and antiparticles which are too massive and unstable to occur otherwise.

Any particle and its antiparticle in collision annihilate each other to create radiation. Annihilation can be considered as pair production in reverse. For pair production to occur, the initial energy must be at least equal to $2m_oc^2$, where $m_o$, is the rest mass of the particle being created. When annihilation occurs, the minimum energy released is $2m_oc^2$.

## Chapter 2 Particle Interactions

### Exchange Particles

The concept of exchange particles is difficult to support at A level since experimental evidence remains the province of high energy laboratories. Before introducing the concept, it is essential to have introduced students to photons as wavepackets of electromagnetic waves and it is helpful if students have covered basic ideas of electrostatic force and the strong nuclear force.

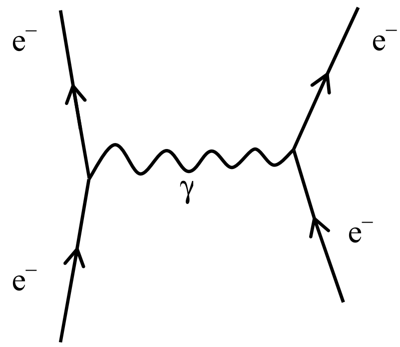
The four fundamental forces (gravitation, electromagnetic, strong nuclear and weak nuclear) are all thought to be caused through exchange of particles, referred to as carriers or exchange particles. For example, two electrons interact with each other through the exchange of one or more *virtual* photons. In the photoelectric effect, an emitted electron absorbs a photon and acquires its energy; in an X-ray tube, X-ray photons are emitted when fast-moving electrons are stopped. The concept of electrons absorbing or emitting photons should not be new to students; here, they are asked to consider two electrons interacting through the exchange of a photon. However, the exchanged photon is undetectable because its detection would prevent the exchange. Hence the exchange is referred to as *virtual.*

The concept of exchange particles as force carriers was devised to explain why the strong nuclear force is limited in range to no more than about 1 fm. No particle can travel this distance in less than about $3 \times 10^{-23}$ s since the speed of light is the maximum possible speed of any particle. According to the Uncertainty Principle, this corresponds to an uncertainty in the rest energy of a nucleon equal to about 200 MeV. Yukawa developed these ideas in detail in 1935 and predicted the existence of exchange particles between nucleons to explain the origin of the strong nuclear force. Experimental evidence for these particles, now referred to as $\pi$ mesons or *pions*, was first obtained in 1947 as a result of studying particle tracks in photographic emulsions exposed to cosmic radiation at high altitudes.

### Feynman Diagrams

Richard Feynman invented the concept of virtual photons as part of his theory of quantum electrodynamics. The mathematics of the theory is very complicated. Fortunately, Feynman depicted the theory using diagrams to represent the interactions.

**Figure 4**
This shows the exchange of a single virtual photon when two electrons interact



## Neutrinos and Antineutrinos

The neutrino is an uncharged particle, which is emitted in radioactive β decay and is thought to have a very small mass (of the order of a millionth of the mass of the electron). The 'weak' nuclear force is responsible for the emission of a β-particle when a proton changes into a neutron or vice versa. The strong nuclear force holds neutrons and protons together in the nucleus. The weak nuclear force allows a proton to change into a neutron or vice versa.
The fact that a neutrino or an antineutrino is also emitted is an important aspect of the section of the syllabus on β-decay but the historical reason for the neutrino hypothesis is not followed up here.

For positron emission,

$$\mathrm{p} \rightarrow \mathrm{n} + \beta^{+} + v$$

where $v$ is a neutrino.

For electron emission,

$$\mathrm{n} \rightarrow + \mathrm{p} + \beta^{-} + \bar{v}$$

where $\bar{v}$ is an antineutrino.

The antineutrino is the antiparticle of the neutrino, differing only in that its spin direction is parallel to its momentum direction, unlike the neutrino which has spin antiparallel to its momentum. Conclusive experimental evidence for neutrinos and antineutrinos was obtained in 1956 when the reactions between antineutrinos from a nuclear reactor and protons were detected and measured.

$$\bar{v} + \mathrm{p} \rightarrow \mathrm{n} + \beta^{+}$$

Scientists were unable to detect reactions between antineutrinos and neutrons and therefore concluded that neutrons only react with neutrinos.

$$v + \mathrm{n} \rightarrow \mathrm{p} + \beta^{-}$$

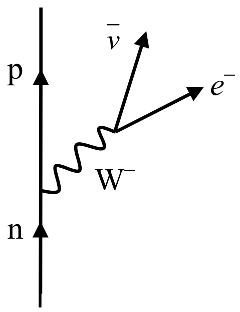
Experimental evidence for the non-zero mass of the neutrino was reported as long ago as 1980 and recent experiments indicate a mass of about 1 eV for the least massive neutrino, the electron neutrino.

## The Weak Nuclear Force

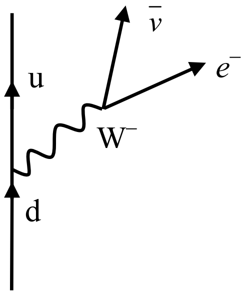
This is responsible for β-decay processes as well as interactions involving electrons or neutrinos with protons or neutrons. The weak nuclear force is carried by exchange particles known as W-bosons. The rest energy of a W-boson is 81 GeV its range is thought to be of the order of $10^{-18}$ m. There are two types, the $W^+$ and the $W^-$, which are represented in Feynman diagrams as illustrated below.

**Figure 5**
Feynman diagrams

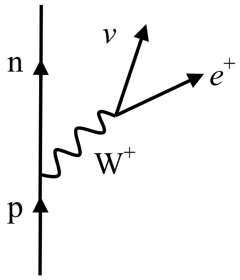
**1** $\beta^-$ decay
Identical representations



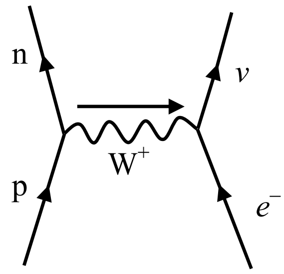

Quark representation



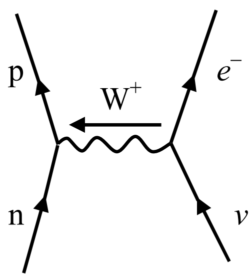

**2** $\beta^+$ decay



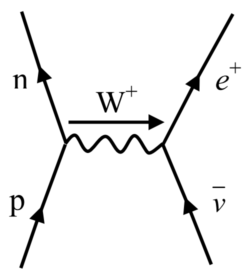

**3** Electron capture



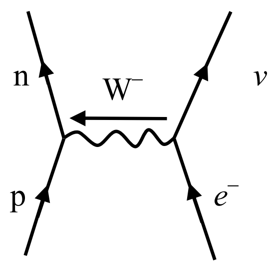

**4** Neutrino-neutron collisions




**5** Antineutrino-proton collisions




**6** Electron-proton collisions




Note, in diagrams 4, 5 and 6, the exchange particle in each case could be the oppositely charged W particle travelling in the opposite direction. In diagram 3, although the interaction is usually represented in the direction, candidates would gain credit as long as they show a W boson in the correct direction according to its charge.

These and similar interactions have been detected and measured. Charge is conserved in all cases. A proton-antiproton collision can also create a W-boson if the energy of the colliding particles is at least 80 GeV. This interaction differs from the others in that protons and antiprotons can also interact through the strong nuclear force and other particles axe created as well as W-bosons. Questions on the weak interaction, in respect of Feynman diagrams, will be limited to changes in which a proton changes to a neutron or vice versa.

## Chapter 3 Classification of Particles

The emphasis in this chapter is on developing general rules and patterns that are explained by the quark model as described in the next section. The rules and patterns have been derived from experiments which are not described here as they are not needed for AS unit 1. Information in the appendices is provided about such experiments as useful background material for teachers. Candidates will not be expected to remember baryon and lepton numbers for individual particles and antiparticles.

### Hadrons

Hadros is Greek for 'massive'. Any particle that experiences the strong nuclear force is a **hadron**. Thus, protons, neutrons and pi-mesons (pions) are hadrons whereas electrons, photons, neutrinos and W-bosons are not. Hadrons are classified as either baryons or mesons. Originally, mesons were classified as particles with masses between that of the electron and the proton. However, this form of classification proved inadequate when accelerator experiments created more and more new particles. High energy collisions between protons and nucleons in accelerator experiments create new particles which usually decay into other particles. The search for order and patterns among the wide range of particles created by accelerator experiments has stretched over half a century.
Many different particles can be created and each particle has been measured to attempt to find a coherent pattern explaining their properties. The end result of these experiments is startling in its simplicity.

A meson is a quark-antiquark combination.
A baryon is a combination of three quarks.

### Baryons

Protons and neutrons are examples of baryons. When high energy protons and antiprotons collide, certain reactions which are permitted by conservation of charge and of energy are never seen.

$p + \overline{p} \rightarrow n + \overline{n}$ is observed

$p + \overline{p} \rightarrow n + n$ is never observed

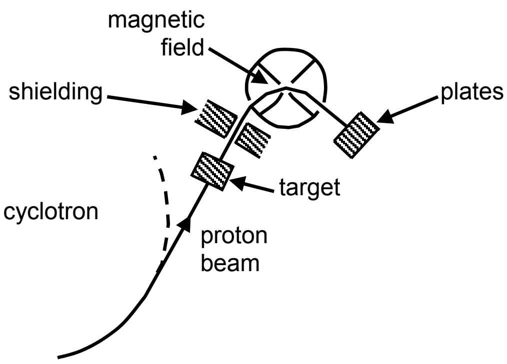
To make sense of the pattern of observed reactions, each particle is assigned a **baryon number** B which is 1 for baryons, -1 for antibaryons and 0 for mesons and leptons. **Thus, in all particle reactions, the total baryon number is conserved.**

### Mesons

**Pi-mesons** (or pions) are the exchange particles of the strong nuclear force. Pion beams can be produced by an accelerator capable of making protons collide at energies in excess of 300 MeV.

Pions were first created artificially when protons from a cyclotron were directed at stationary nucleons. Pions ejected from the stationary target cyclotron were deflected by a magnetic field and then stopped by a bank of photographic plates. The charge and mass of the pions was determined from the magnetic deflection and range in the photographic plates. Positive and negative pions, labelled $\pi^+$ and $\pi^-$ respectively, were identified with identical rest energies at 140 MeV.
Later experiments confirmed the existence of an uncharged pion, $\pi^o$, of rest energy 135 MeV which decays much more rapidly than either charged pion.

**Figure 6**




A large number of other types of mesons and baryons have been discovered from cosmic ray and accelerator experiments. Strangeness as a particle property was established from the pattern of results from these experiments and the quark model was put forward in 1964 to explain these underlying patterns.

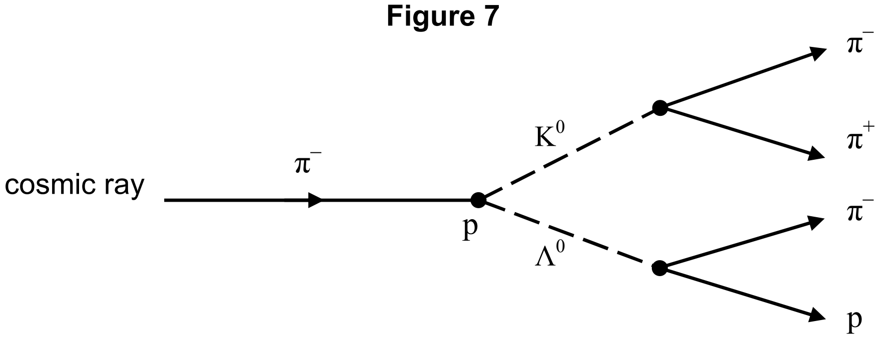
## Strangeness

**K-mesons** (also referred to as kaons) were discovered in 1947 when CD Rochester and CD Butler at the University of Manchester obtained photographs of the effect of cosmic rays on a lead plate in a cloud chamber in a magnetic field. Their photographs clearly showed V-shaped tracks, each formed by two particles created from the decay of a neutral particle. Analysis of their measurements showed that each cosmic ray interaction created two neutral particles with different masses, each of which decayed further into a V-shaped track. In this type of interaction where V-tracks are seen, the particles produced by the cosmic rays are always created in pairs. For this reason, they were referred to as strange particles.

Further experiments showed that the two strange particles created by each cosmic ray particle had distinctive decay products. The two particles were referred to as

**1** the kaon (symbol $K$) which always decayed into pions,
**2** the hyperon (symbol $\Lambda$) which always produced a neutron or a proton in its decay products.

**Figure 7**




The rest energy of the kaon is about 495 MeV and it can be positive, negative or neutral whereas the hyperon (rest energy 1115 MeV) is neutral only. Both types of particles caused tracks up to several centimetres in length and hence lasted for a time of the order of $10^{-10}$ s.

Further investigations of cosmic ray tracks in photographic emulsions led to the discovery of positively and negatively charged hyperons of rest energy about 1200 MeV. These particles are denoted by the symbols $\Sigma^+$ and $\Sigma^-$ respectively. A further particle, $\Sigma^0$, of energy 1193 MeV also discovered with a much shorter lifetime than its charged counterparts.

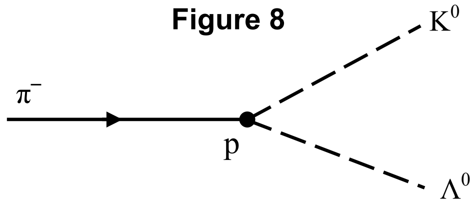
Strange particles were produced artificially for the first time by the Brookhaven accelerator in 1952. The results confirmed the property of these particles that they are always produced in pairs.
For example, a pion in collision with a proton would produce a kaon and a hyperon, as below.

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

**Strangeness** (symbol S) as a quantum number was introduced to explain why strange particles are always created in pairs and why certain reactions are never observed. The determination of the strangeness of a particle is based on the assumption **that strangeness is always conserved when particles interact through the strong nuclear force**. Change of strangeness only takes place when particles interact through the weak nuclear force. Also, the strangeness of a particle is always the opposite to that of its antiparticle. These rules formed an essential step towards our present understanding of sub-nuclear interactions based on the quark model.

The $K^0$-meson was assigned strangeness = +1. The strangeness of $\Lambda^0$ was therefore -1.
The strangeness of other strange particles was worked out from the above starting point and results in S = 1 for the $K^+$ and $K^0$ and S = -1 for the $K^-$, $\Lambda^0$ and the $\Sigma$ hyperons.

**Figure 8**




## Leptons

Leptos is Greek for 'small'. Leptons do not experience the strong nuclear force. Electrons, positrons, neutrinos and antineutrinos are examples of leptons. As explained on page 11, a neutrino is emitted in $\beta^+$ decay and an antineutrino is emitted in $\beta^-$ decay. These and some other changes involving neutrinos and antineutrinos are listed below.

(i) $p \rightarrow n + \beta^+ + \nu_e$

(ii) $n \rightarrow p + \beta^- + \bar{\nu}_e$

(iii) $p + e^- \rightarrow n + \nu_e$

(iv) $p + \bar{\nu}_e \rightarrow n + \beta^+$

(v) $n + \nu_e \rightarrow p + \beta^-$

These observed reactions led to the assignment of a quantum number, the **lepton number**, to each lepton on the basis of **conservation of the total lepton number**. Assigning a lepton number of +1 to the electron and the neutrino and -1 to the positron and the antineutrino fits the rule that the total lepton number is unchanged in any interaction. The lepton number of any hadron is 0.

Thus, in each reaction above, the total lepton number is unchanged by the reaction:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (i) | 0 | = | 0 | + | -1 | + | 1 |
| (ii) | 0 | = | 0 | + | 1 | + | -1 |
| (iii) | 0 | + | 1 | = | 0 | + | 1 |
| (iv) | 0 | + | -1 | = | 0 | + | -1 |
| (v) | 0 | + | 1 | = | 0 | + | 1 |

The **muon** (symbol μ) is a heavy electron, discovered in 1936 from cosmic ray interactions observed in a cloud chamber. Its mass was estimated at about 200 $m_e$, where $m_e$ is the mass of the electron. Just as the positron is the antiparticle of the electron, the antimuon ($\mu^+$) is the antiparticle of the muon ($\mu^-$).

Muons can be produced artificially by directing protons from a proton synchrotron at a target to create pions which then decay into muons and neutrinos.

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

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

Muons produced artificially using the Brookhaven proton synchrotron in 1962 established the existence of two types of neutrinos, **the electron neutrino $\nu_e$**, and **the muon neutrino $\nu_\mu$**. Pions created in collisions between protons and a stationary target decay into muons and neutrinos. The muons and other particles were then stopped by 13 m of iron whilst the neutrinos were unaffected by the iron. Spark counters containing thick aluminium plates were positioned in the path of the neutrinos to detect neutrino-nucleon reactions, capable of distinguishing between muons and electrons created by neutrino-nucleon reactions. The results showed clearly that the neutrinos from pion decay created muons, not electrons, in collisions with neutrons.

Stage 1 — Collisions between protons and a stationary target create pions which decay into muons and neutrinos.

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

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

Stage 2 — Iron stops the muons and pions. The neutrinos then pass into spark chambers containing thick aluminium plates to create muons not electrons.

$$\nu_\mu + n \rightarrow p + \mu^-$$

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

The results showed that neutrinos and antineutrinos produced when muons are created are not the same as neutrinos and antineutrinos produced when electrons or positrons are created. In other words, there are two distinct 'generations' of neutrinos. **The lepton conservation rule must therefore be applied to each type of lepton**. Further investigations have proved the existence of the 'tau-particle' (symbol τ), an even heavier electron than the muon, and a corresponding third generation of neutrinos, referred to as tau neutrinos, which are created when 'τ particles' interact or decay.

## Chapter 4 Quarks & Antiquarks

This section draws together facts from preceding sections to reveal the underlying pattern of quarks and antiquarks that explains the properties of hadrons. Although the specification is limited to the up, down and strange quark, the topic could be extended to include the most recent developments although questions will not be asked on these further aspects of the quark model. Notes provided on such aspects are therefore supplied in Appendix B as further background material for teachers and not as an amplification of the specification.

**Summary of Hadrons in the preceding sections**

| Particle | Symbol | Charge | Baryon number | Strangeness | Decay products |
|---|---|---|---|---|---|
| Proton | p | +1 | +1 | 0 | stable |
| Neutron | n | 0 | +1 | 0 | p, $e^-$, $\nu$ |
| Charged Pion | $\pi^+$, $\pi^-$ | +1, −1 | 0 | 0 | μ, $\nu$ |
| Neutral Pion | π | 0 | 0 | 0 | γ |
| K-mesons | $K^+$, $K^0$, $K^-$ | +1, 0, −1 | 0 | +1, +1, −1 | π, μ, $\nu$, e |
| Λ hyperon* | Λ | 0 | +1 | −1 | π, p |
| Σ hyperon* | $\Sigma^+$, $\Sigma^0$, $\Sigma^-$ | +1, 0, −1 | +1 | −1 | π, p, n |
| *not on specification | | | | | Λ ($\Sigma^0$ only) |

### The Quark Model

The quark model was put forward in 1964 by Murray Gell-Mann to explain the properties of hadrons. The main properties of the three quarks in Gell-Mann's model are given below.

| | Charge | Baryon number | Strangeness |
|---|---|---|---|
| Up quark | $+\frac{2}{3}$ | $+\frac{1}{3}$ | 0 |
| Down quark | $-\frac{1}{3}$ | $+\frac{1}{3}$ | 0 |
| Strange quark | $-\frac{1}{3}$ | $+\frac{1}{3}$ | −1 |
| Up antiquark | $-\frac{2}{3}$ | $-\frac{1}{3}$ | 0 |
| Down antiquark | $+\frac{1}{3}$ | $-\frac{1}{3}$ | 0 |
| Strange antiquark | $+\frac{1}{3}$ | $-\frac{1}{3}$ | +1 |

The quarks shown in the previous table combine to form hadrons according to the following rules:

A meson is a combination of a quark and an antiquark.
A baryon is a combination of three quarks or three antiquarks.

Quarks in isolation have never been detected. All the experimental evidence up to the present time leads to the conclusion that free quarks do not exist. Experiments based on the same principles as Millikan's oil droplet experiments have been carried out in recent years and no evidence for free fractional charge has been found.

Quarks are confined within hadrons. A quark and an antiquark can be created as a pair if sufficient energy is available. This is why particles are created in a high energy collision; an attempt to force a quark out of a hadron creates quark-antiquark pairs which rearrange themselves to form new hadrons. Quarks can change from one type to another, but only through the weak interaction.

Further background information on the development of the quark model is provided in Appendix B.

## Using the Quark Model

### (a) Pion production

One possible reaction in which a pion is created is shown below:

$$p + p \rightarrow \pi^+ + n + p$$

In terms of quarks,

$$uud + uud \rightarrow u\bar{d} + udd + uud$$

The collision creates a down quark-antiquark pair from the available energy. The down antiquark combines with one of the up quarks from a proton and the down quark joins the other two quarks from this proton to form a neutron.

### (b) Beta decay

In $\beta^-$ decay, a beta particle and an antineutrino are created and emitted when a neutron changes to a proton. This is an example of a weak interaction and the neutron emits a $W^-$-boson which then decays into an electron and an antineutrino.

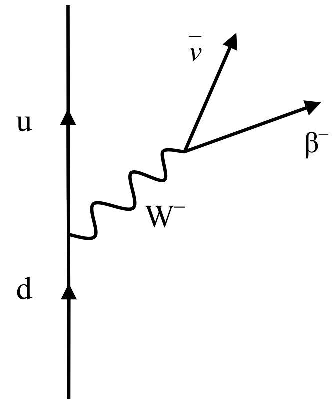
$$n \rightarrow p + W^-$$
$$\hookrightarrow \beta^- + \bar{\nu}$$

In quark terms, a down quark in the neutron changes into an up quark by emitting a $W^-$-boson which then decays into an electron and an antineutrino.

$$d \rightarrow u + W^-$$
$$\hookrightarrow \beta^- + \bar{\nu}$$

The Feynman diagram for this process is shown below.

**Figure 9**



## Appendix A Accelerators

The notes below are written for teachers and provide background knowledge to support general principles. They do not represent amplification of the specification.

Accelerators in different countries have contributed to particle research although the cost of developing, building and operating machines at higher energies has led to such research being concentrated at fewer centres such as CERN, Fermilab and Stanford. Accelerator facilities elsewhere are in use on a wide range of less fundamental research projects.

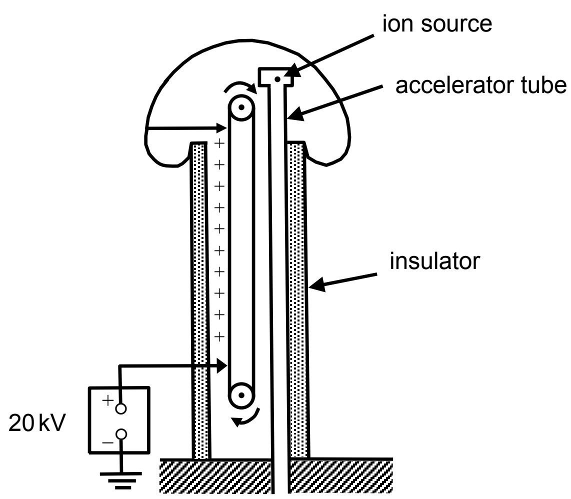
This section offers an opportunity to reinforce key physics principles from the A-level core through a survey of the development of accelerators over the past 60 years. Historic discoveries in particle physics have followed when new accelerators have been brought into successful operation.
The design of a new accelerator, determined by theoretical considerations, therefore leads to experimental results which carry particle theory forward. It is therefore important to relate the introduction of a new accelerator to the reasons for its design and the results of its operation.

Particle energies throughout the section are expressed in MeV or GeV (= 1000 MeV). Particle momenta and masses are expressed in MeV/c and MeVc$^2$ respectively (or GeV/c and GeV/c$^2$). Students are expected to know that mass can be converted to energy and vice versa on a scale given by $E = mc^2$. Students should also know that the total energy, $E$, of a particle of rest mass $m$, which possesses kinetic energy $T$ is equal to $T + m_0c^2$. For example, a proton accelerated from rest through a pd of 200 MV would possess total energy equal to 1138 MeV and its mass would therefore be 1138 MeV/c$^2$.

### (a) The Van de Graaff Accelerator

This was invented by Van de Graaff at MIT in 1932. Charged particles are accelerated through potentials up to 20 MV to collide with a fixed target. Beam currents up to 200 μA are possible. The maximum potential is limited by insulation failure and charge leakage through corona discharge which is minimised by enclosing the apparatus in a steel chamber containing air or nitrogen at pressures up to 1500 kPa (15 atmospheres). The device has been used to produce proton beams to study proton-proton scattering and induced nuclear reactions.

**Figure 10**
Vertical cross-section of a Van de Graaff generator



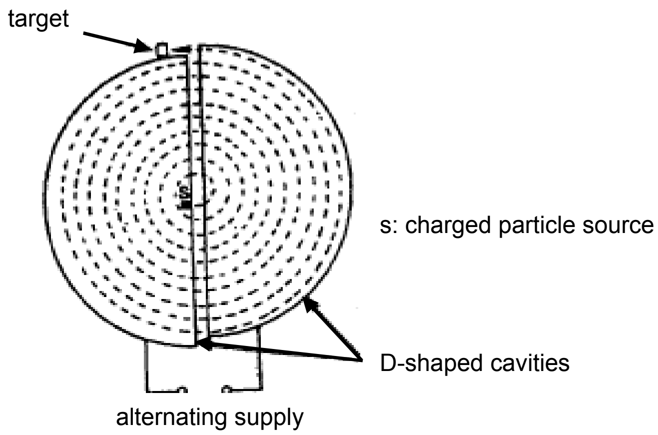
**(b) The Cyclotron**

Ions are accelerated to high speeds without the use of high voltages in this device. A 1.5 m cyclotron can produce charged particle beams with kinetic energies up to 10 MeV. The first cyclotron, invented by E.O. Lawrence in 1930 in California, was 0.28 m in diameter and produced 1.2 MeV protons.

In operation, a high-frequency alternating potential difference is applied between two hollow D-shaped semicircular metal boxes. A uniform magnetic field is directed perpendicular to the plane of the 'dees'.

**Figure 11**

The Cyclotron




The cyclotron contains gas at low pressure. Ions are produced at the centre of the cyclotron and these are attracted into whichever dee is oppositely charged at that time. The magnetic field bends the ions through 180° and as the ions leave the dee, the alternating pd reverses so the ions are accelerated into the opposite dee. The magnetic field again bends the ions through 180° and as the ions leave this dee, the alternating pd reverses so the ions are accelerated into the opposite dee.

In this way, the speed of the ions is increased each time they pass from one dee to the other. The radius of orbit of the beam increases as its speed increases and the beam emerges tangentially from the cyclotron at the edge to strike the target in its path.

The radius $r$ of the beam can be derived from the speed $v$ as follows:

$$Bqv = \frac{mv^2}{r}$$

Hence

$$r = \frac{mv}{Bq}$$

where $m$ = particle mass
$q$ = particle charge
$B$ = magnetic flux density

The frequency $f$ of the alternating pd must be the same as the frequency of rotation of the beam. Hence, from the above equation,

$$f = \frac{\omega}{2\pi} = \frac{v}{2\pi r} = \frac{Bq}{2\pi m}$$

The final ke of the ions,

$$\frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{BqR}{m}\right)^2 = \frac{B^2R^2q^2}{2m}$$

where $R$ is the cyclotron radius. Hence the final ke is independent of the peak alternating pd.

The beam from a cyclotron is not as uniform in speed as that from a Van de Graaff machine. The relativistic increase of particle mass with speed limits the maximum beam energy from a cyclotron operating at fixed frequency because the rotation frequency decreases as the speed increases. Cyclotrons have been used to study nuclear reactions induced directly by beams of protons or alpha particles or indirectly by neutron beams produced by bombarding suitable targets with proton beams.

**(c) The Synchrotron**

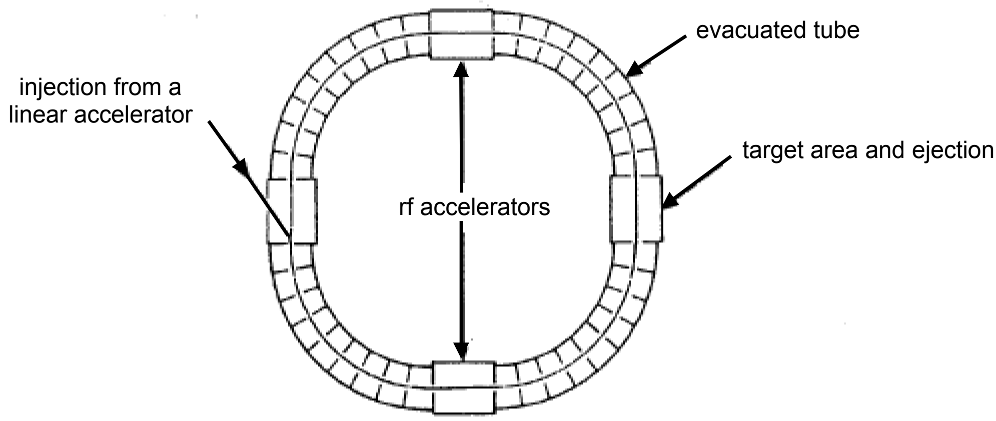
In the synchrotron, the magnetic field is increased to keep the charged particles in orbit at constant radius as they are boosted to higher and higher speeds. Since the radius is constant, semi-circular 'dees' are not necessary and the particles move round a ring-shaped vacuum chamber in a ring-shaped magnet.

One or more resonant cavities are used to accelerate the particles each time they pass through. A radio-frequency alternating pd is applied to the cavity so the particles are attracted to it as they approach and repelled from it as they leave. Electrons attain relativistic speeds at much lower energies than protons, hence the frequency of the alternating pd is constant in an electron synchrotron but needs to be increased in a proton synchrotron as the protons gain speed each time they pass through the resonant cavity.

Synchrotron radiation is much more significant for electrons than for protons or heavier charged particles. This type of radiation is produced by a charged particle being accelerated on a circular path. The radiation loss becomes greater at higher energies and is much greater the lower the mass of the charged particles. Also, for circular orbits, the smaller the beam radius, the greater the energy loss. The Large Electron-Positron (LEP) 4.2 km diameter ring at CERN is capable at present of accelerating electrons to 55 GeV. In contrast, the Super Proton Synchrotron (SPS) at CERN has a diameter of 2.2 km and is capable of accelerating protons up 450 GeV.

In comparison with a cyclotron, much higher particle energies can be achieved with a synchrotron although the particles are produced in 'bursts', unlike in a cyclotron which can produce a steady stream of particles.

**Figure 12**
The Synchrotron



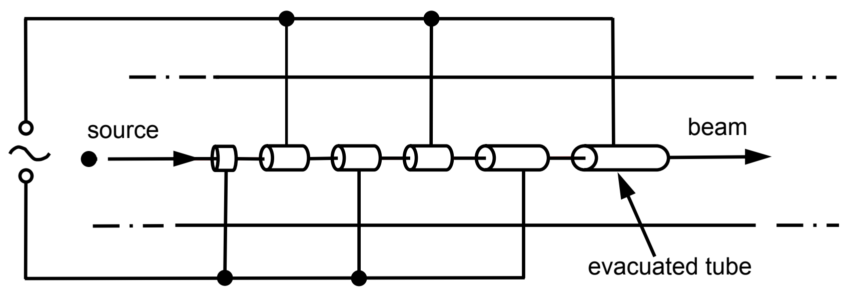
**(d) The Linear Accelerator**

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.

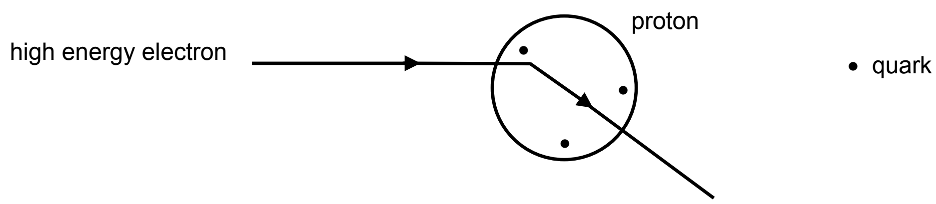
**Figure 13**

The Linear Accelerator




Evidence for point charges inside nucleons was first produced in 1968 using the Stanford linear accelerator to bombard a stationary target with a beam of 50 GeV electrons. Analysis of the measurements showed that the electrons were scattered by point charges of $+\frac{2}{3}\mathrm{e}$ and $-\frac{1}{3}\mathrm{e}$ inside the nucleons, in a similar way to Rutherford scattering of alpha particles by the nucleus. These point charges are called quarks.

**Figure 14**



**(e) The Super Proton Synchrotron**

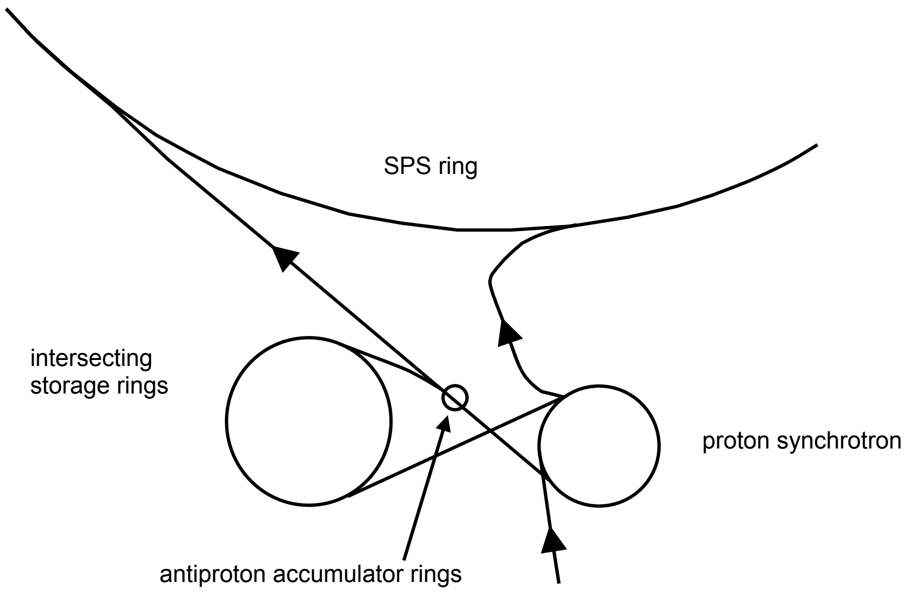
The CERN Super Proton Synchrotron started operating in 1976, initially to create collisions between high energy protons and a stationary target. Protons from a 50 MeV linear accelerator are boosted to 10 GeV in a smaller proton synchrotron before being injected into the 2.2 km diameter main ring of the 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.

**Figure 15**
CERN's SPS




The CERN SPS has been modified so that it can be used either to bombard a fixed target with 450 GeV protons or to produce collisions between moving protons and antiprotons at over 300 GeV. The maximum available energy from such a colliding beam experiment is significantly less than 600 GeV because protons and antiprotons are composite bodies. Such proton-antiproton collisions produce many different types of particles and complex detectors are necessary to measure and analyse the results. Nevertheless, CERN's SPS produced the first acceptable evidence for $W^+$- and $W^-$-bosons in January 1983. A further particle, the $Z^0$-boson, was discovered in June 1983.

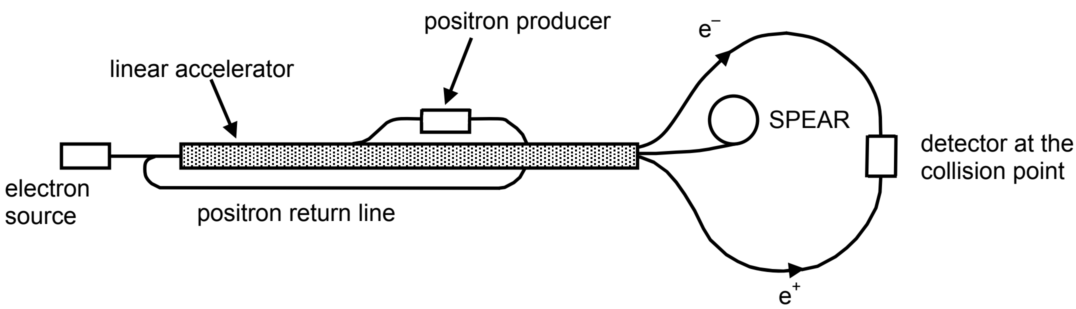
### (f) Recent Colliders

**The Fermilab Tevatron** is capable of accelerating protons and antiprotons to more than 1000 GeV. This has also been used to produce and study the $Z^0$-boson. In 1994, scientists at Fermilab announced the discovery of the top quark, estimating its mass at 170 GeV/$c^2$, although presently this awaits confirmation from other laboratories.

**CERN's LEP**, commissioned in 1989, is capable of producing head-on collisions between 55 GeV electrons and positrons thus creating large numbers of $Z^0$-bosons and subsequent decay products. High energy electron-positron collisions can create $Z^0$-bosons ‘cleanly’ without producing a zoo of additional particles as in proton-antiproton collisions. LEP is currently being upgraded to double the beam energy.

Plans for the **Large Hadron Collider (LHC)** at CERN are currently at an early stage and first operation of this massive 7000 GeV colliding beam proton accelerator is not likely until 2008.

**Figure 16**
Standford Linear Collider




**The Stanford linear accelerator** became part of the SPEAR ring at Stanford in the mid-1970. SPEAR was designed to store bunches of electrons and positrons produced by the linear accelerator in the SPEAR synchrotron ring at energies up to 8 GeV. The bunches of electrons and positrons can be kept circulating in opposite directions in the ring around separate arcs, intersecting in detectors at specified positions. Experimental evidence for the charmed quark was discovered at SPEAR in 1974 when the $J/\Psi$ particle at 3.1 GeV was detected for the first time. This particle was also created at the same time at the Brookhaven proton synchrotron. Samuel Ting of Brookhaven and Burton Richter of SPEAR were jointly awarded the Nobel Prize for their discoveries.

The Stanford Linear accelerator is now part of the **Stanford Linear Collider (SLC)** which is designed to create collisions between 50 GeV electrons and positrons. The SPEAR ring at SLC is a storage ring which uses considerable power to keep bunches of electrons and positrons circulating for hours. SLC is a much larger ring which guides 50 GeV electrons and positrons from the linear accelerator into one-off collisions at a detector complex. Synchrotron radiation is much less significant in the SLC ring than the SPEAR ring because the SLC ring is much larger and each particle travels no more than half a turn round the ring. Unlike SPEAR, almost all of the energy from the linear accelerator is therefore available to create new particles.

## Appendix B The Development of the Quark Model

### (a) The discovery of the $\Omega^-$ particle

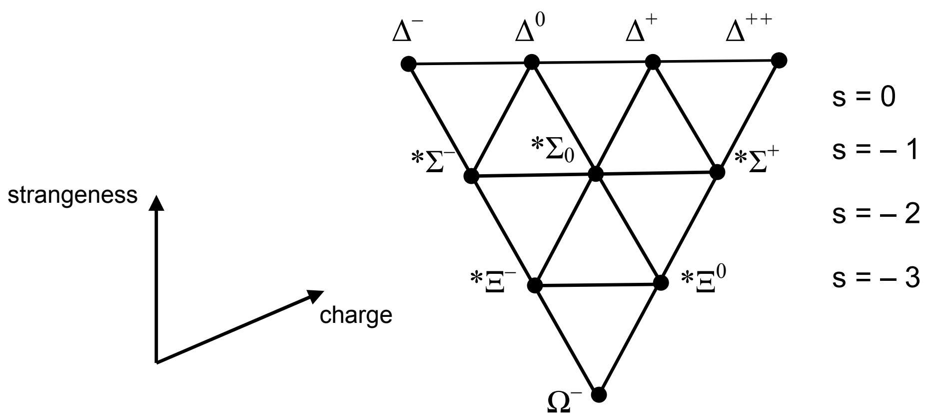
In addition to the hyperons described in chapter 3, a further type of hyperon, the 'cascade' hyperon denoted by the symbol $\Xi$, was discovered in particle photographs taken when a beam of K- mesons from a proton synchrotron was passed through a bubble chamber. Further investigations revealed that this new particle decays into a $\Lambda$ hyperon and a pion, possesses strangeness -2 and exists either uncharged or with charge -1. Its rest energy was measured at about 1320 MeV comparison with hyperons of rest energy about 1190 MeV and nucleons of rest energy about 940 MeV.

The hyperons were found to exist with short lifetimes (of the order of $10^{-23}$ s) or with much longer lifetimes (in excess of $10^{-10}$ s). The short-lived varieties are denoted by an asterisk.

Further unstable particles called $\Delta$ particles were discovered from proton scattering experiments. Four types of particles were identified, corresponding to charge states - 1, 0, + 1 and + 2. The $\Delta^0$ and $\Delta^+$ particles were found to possess much shorter lifetimes than the $\Delta^-$ and $\Delta^{++}$ particles.

Murray Gell-Mann and Yuval Ne'eman working independently put forward a classification scheme for baryons that predicted the existence of a short-lived negative baryon with strangeness -3. This was labelled the $\Omega^-$ particle. Its discovery in 1964 at Brookhaven led Gell-Mann to put forward the **quark model** which has since proved extremely successful in explaining the properties of hadrons.

**Figure 17**
Predicting the $\Omega^-$ particle

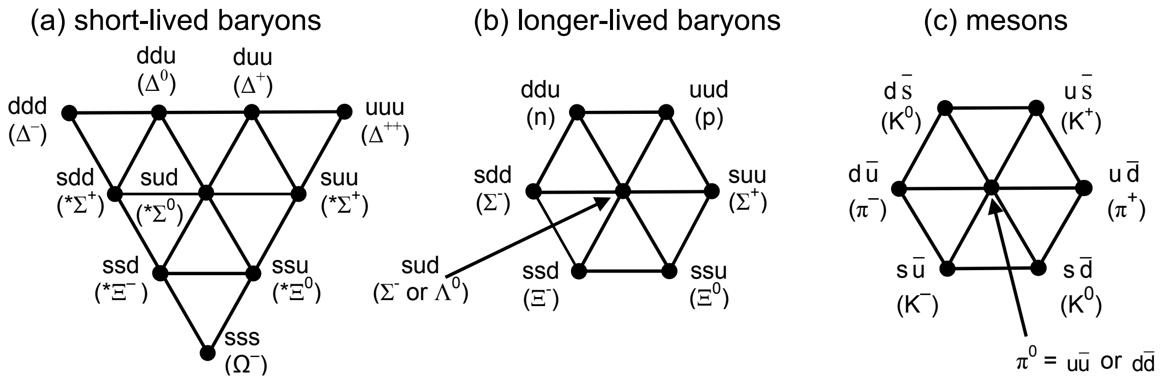


## (b) The extended quark model

The quark model was extended to include a fourth quark, the charmed quark (symbol c), as a counterpart of the strange quark. Experimental evidence for the charmed quark was produced in 1974 when the J/Ψ particle predicted from quark theory was detected at Stanford's electron-positron SPEAR collider and at the Brookhaven proton-proton collider. Two further quarks, the bottom quark and the top quark, were predicted from the quark model and these too have been detected experimentally as predicted.

The specification does not require knowledge of the charmed quark, the bottom quark or the top quark. Nevertheless, there is no reason why the full picture should not be presented to students, including a description of the gluon as the exchange particle of the force field between quarks.

**Figure 18**




The strong nuclear force is a residual effect of gluon exchange between quarks in a nucleon, in the same sense as the Van der Waals force between uncharged molecules is a residual effect of the force between electrons and nuclei. The explanation of pion exchange in terms of quarks is that gluons are exchanged between quarks in adjacent nucleons.

Throughout the preceding notes, no reference has been made to spin. Students may know that 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).

The law of force between colour charges is simple.

Like charges repel.
Unlike charges attract.
Opposite charges attract more strongly.

A red quark will repel another red quark but attract a blue quark. The red and blue quarks will then attract a green quark to form a baryon.

A meson is formed when a quark attracts an antiquark of the opposite colour (e.g. a red quark attracts an antired antiquark). The quark may be any one of the six quark types (e.g. up or down etc) and the antiquark may be any one of the six possible antiquarks.

Quarks and leptons each form three generations of increasing mass, as summarised below.

| The Quark Family | | The Lepton Family | |
|---|---|---|---|
| u | (≈ 0.005) | $e^-$ | 0.55 MeV/$c^2$) |
| d | (≈ 0.007) | $\nu_e$ | (30 eV/$c^2$?) |
| s | (≈ 0.15) | $\mu^-$ | (0.106) |
| c | (≈ 1.3) | $\nu_\mu$ | ? |
| b | (≈ 5) | $\tau$ | (1.78) |
| t | (≈ 170) | $\nu_\tau$ | ? |

mass values in GeV/$c^2$ unless otherwise stated

The discovery of three generations of quarks and three generations of leptons presents a remarkable symmetry in the pattern of subnuclear particles. Gluons are the exchange particles of the force field between quarks. The photon and the two W-bosons are the exchange particles of the force field responsible for 'electroweak' (i.e. electromagnetic and weak nuclear) interactions.
The Large Hadron Collider (LHC) is intended to probe the sub-nuclear world at even higher energies than at present to find out if there is a deeper underlying pattern.

Grand Unification Theories (GUTS) attempting to unify the electroweak and the strong nuclear forces predict that the proton is unstable.

Experiments to find out if the proton decays have been underway since the early 1980s. Results thus far suggest the proton lifetime is in excess of $10^{35}$ years.

## Appendix C Chronology of Particle Physics

| | |
|---|---|
| **1928** | Antimatter predicted by Dirac |
| **1930** | Cyclotron invented by Lawrence in California |
| **1931** | Neutrinos predicted by Fermi |
| **1932** | Neutron discovered by Chadwick |
| | Positron discovered by Anderson in cloud chamber experiments |
| | Van de Graaff machine used to accelerate protons to 20 MeV |
| **1935** | Exchange particles predicted by Yukawa to explain strong nuclear force |
| **1936** | Muons detected by Anderson and Neddermeyer in cosmic rays in cloud chamber experiments |
| **1947** | Pions detected by Powell in cosmic ray tracks in photographic emulsion |
| | K-mesons discovered by Butler and Rochester in cosmic radiation |
| **1948** | Pions produced by a cyclotron |
| **1952** | K-mesons and hyperons created in the Brookhaven proton synchrotron |
| | Strangeness introduced by Gell-Mann et al to explain production and decay of K-mesons and hyperons |
| **1955** | Antiprotons created in the 6 GeV proton synchrotron in California |
| **1956** | Neutrino detection experiments started in 1952 by Reines and Cowan successful |
| **1959** | 30 GeV proton synchrotron completed at CERN, Geneva |
| **approx 1955-63** | Cascade hyperons and delta particles discovered in accelerator experiments |
| **1962** | $\Omega^-$ predicted by Gell-Mann and Ne'eman as a result of classification of known particles |
| | Muon neutrino discovered at Brookhaven |
| **1963** | $\Omega^-$ discovered in bubble chamber photographs at Brookhaven |
| **1964** | Quark model proposed by Gell-Mann and Zweig to explain classification |
| **1961-67** | Weinberg-Salam model of the weak nuclear force developed W- and Z-bosons (and the Higgs boson) predicted |
| **1968** | Evidence for quark structure produced by deep inelastic scattering of 20 GeV electrons in the Stanford Linear Accelerator (SLAC) |
| **1970** | Charmed quark predicted by Glashow et al |
| | 8 GeV SPEAR electron positron collider completed at Stanford |
| **1973** | Electron-neutrino scattering detected in CERN's Gargamelle bubble chamber |
| **1974** | $J/\Psi$ particle discovered as evidence for charm at SPEAR and at Brookhaven |
| **1975** | Tau ($\tau$) heavy electron and z-neutrino discovered at SLAC |

| | |
|---|---|
| **1976** | CERN 450 GeV Super Proton Synchrotron completed |
| **1977** | Bottom quark discovered in proton-nucleon collisions at 1000 GeV Fermilab Tevatron |
| **1983** | CERN SPS converted to 300 GeV proton-antiproton collider W- and Z-boson detected at CERN, W- and Z-bosons detected at Fermilab Tevatron |
| **1989** | Z-bosons produced by new 50 GeV SLC electron positron collider (at Stanford) and at CERN's new 55 GeV electron positron LEP collider. Higgs boson not discovered |
| **1994** | Discovery of Top quark claimed at Fermilab |
| **2008** | Construction of the Large Hadron Collider (LHC) at CERN is currently nearing completion with the first operation of this massive 7000 GeV colliding beam proton accelerator due before the end of 2008. |