Cambridge Assessment International Education
Cambridge Pre-U Certificate

PHYSICS (PRINCIPAL) **9792/02**

Paper 2 Written Paper **May/June 2019**

PRE-RELEASED MATERIAL

The question in Section 2 of Paper 2 will relate to the subject matter in these extracts. You should read through this booklet before the examination.

The extracts on the following pages are taken from a variety of sources.
Cambridge Assessment International Education does not necessarily endorse the reasoning expressed by the original authors, some of whom may use unconventional Physics terminology and non-SI units.

You are also encouraged to read around the topic, and to consider the issues raised, so that you can draw on all your knowledge of Physics when answering the questions.

You will be provided with a copy of this booklet in the examination.

This document consists of **11** printed pages and **1** blank page.

DC (NH/SG) 195246/4

Extract 1: Models of the Nucleus

The strong force

The neutron-proton model explains nuclear charge and mass. However, the protons repel one another with an electrostatic repulsion which produces enormous forces on the nuclear scale and which falls off as an inverse-square law with distance. To hold the nucleus together there must be a new nuclear force which:

- binds nucleons to each other
- is stronger than electromagnetism on the scale of the nucleus
- is weaker than electromagnetism on the scale of the atom (otherwise all nuclei would clump together)
- is repulsive at very short range (to prevent the protons and neutrons collapsing still further).

The **strong nuclear force** acts on protons and neutrons equally but does not affect leptons. The limited range of the strong force means it only exerts a significant force between adjacent nucleons. This explains why very heavy nuclei are not stable – as more protons are added they are repelled by all the other protons already present but only attracted by the nucleons adjacent to them. Eventually the electrostatic repulsion will be too great for the strong force to overcome.

Fig. E1.1 shows the relationship between the strong force and proton separation.

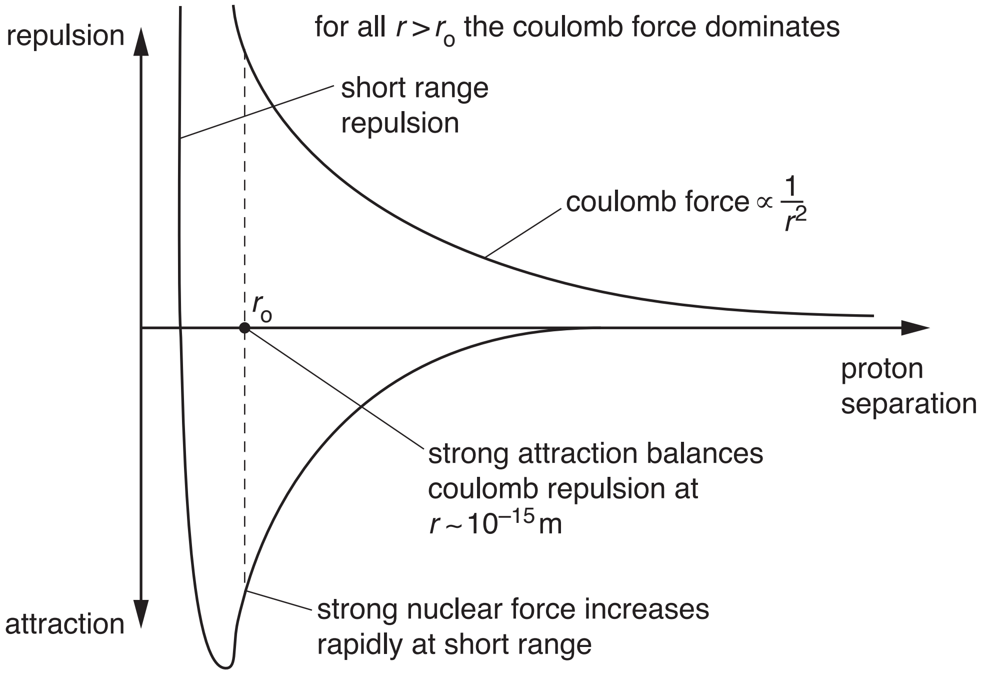


Fig. E1.1

The way the strong force varies with nucleon separation is very similar to the way the forces vary between molecules in a liquid (van der Waals forces). Niels Bohr suggested that the nucleus would therefore behave a bit like a charged liquid drop. The **liquid drop model** is particularly useful to explain fission (a drop is disturbed and eventually splits into two parts which repel one another because of the positive charge). It is interesting that the forces between nucleons arise as a kind of residual force from the interactions between quarks just as the Van der Waals force arises as a residual force from the electromagnetic forces that bind atoms into molecules.

Fig. E1.2 illustrates many aspects of nuclear behaviour that can be described by imagining the nucleus behaving as a charged liquid drop.

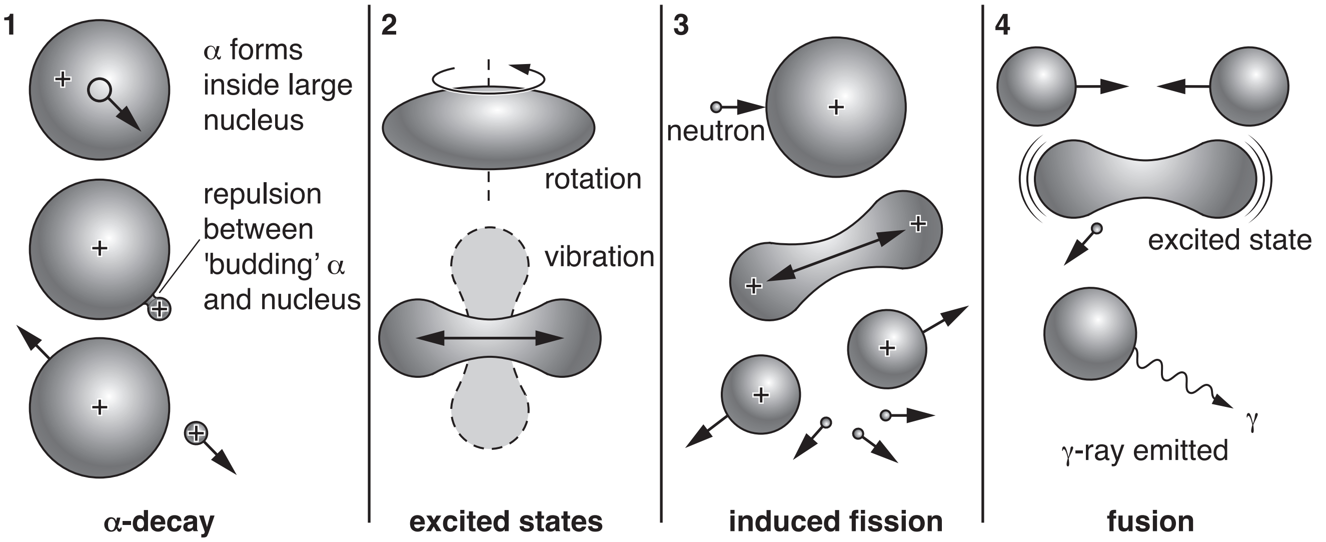


Fig. E1.2

The **close-packed model** or crystalline model suggested by the constant nuclear density is also sometimes useful. For example, rapidly rotating nuclei behave as if the nucleons stretched out in a line along the axis of rotation.

In the **shell model** nucleons move in discrete orbits inside the nucleus rather like the electrons in an atom. The allowed orbits are quantised so the nucleus can make energy jumps between excited states by absorbing or emitting photons. The forces in the nucleus are much larger than electronic quantum jumps – nuclei tend to absorb or emit gamma rays rather than visible (or near visible) light.

Adapted from: Particle Physics, Heinemann Advanced Science, Steve Adams.

Extract 2: Exchange Forces and Feynman Diagrams

Feynman diagrams

In a simple situation, such as two electrons scattering off each other, the event is completely described by stating the energy and momentum of each electron before and after. These are the only measurements that can be made without ruining the reaction. Fig. E2.1 below shows a Feynman diagram for one possible electron-electron scattering event.

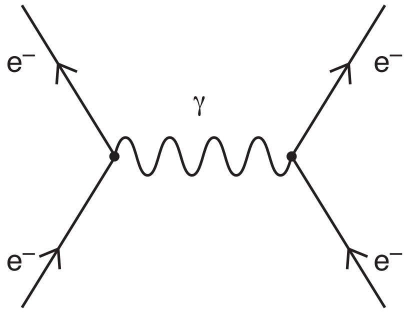


Fig. E2.1

In a Feynman diagram the straight lines represent the electrons and the wavy line is the energy and momentum being passed from one to the other in the reaction. As the reaction is happening because of the electromagnetic force between the charged electrons, the energy and momentum are symbolised as a photon, γ.

Applying Feynman's ideas to other forces

Following Feynman's basic principle, the likelihood of any reaction for any force can be calculated using Feynman diagrams. The only difference is that you have to use the different exchange particles for the different forces.

The exchange particles are given in the table.

force	exchange particle	charge	mass
electromagnetic	photon, γ	0	0
strong	gluon, g	0	0
weak	W^+ W^- Z^0	$+e$ $-e$ 0	$89m_p$ $89m_p$ $89m_p$

Just as a photon is a packet, or quantum, of energy moving through the electromagnetic field, a gluon, for example, is a packet of energy moving through the field of the strong force. It is the exchange of gluons between quarks that gives rise to the strong force between them. Fig. E2.2 shows gluons passing between quarks inside hadrons to produce the strong force.

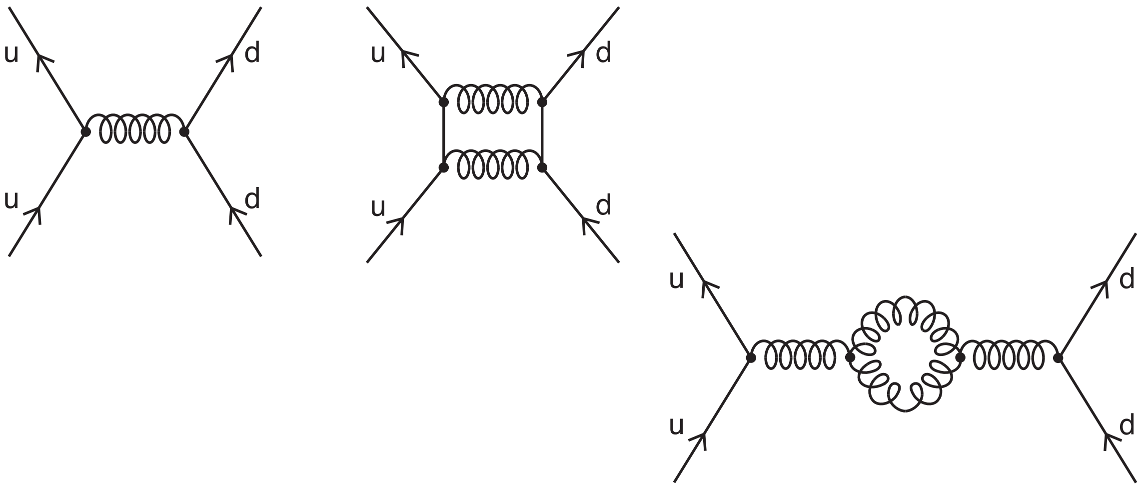
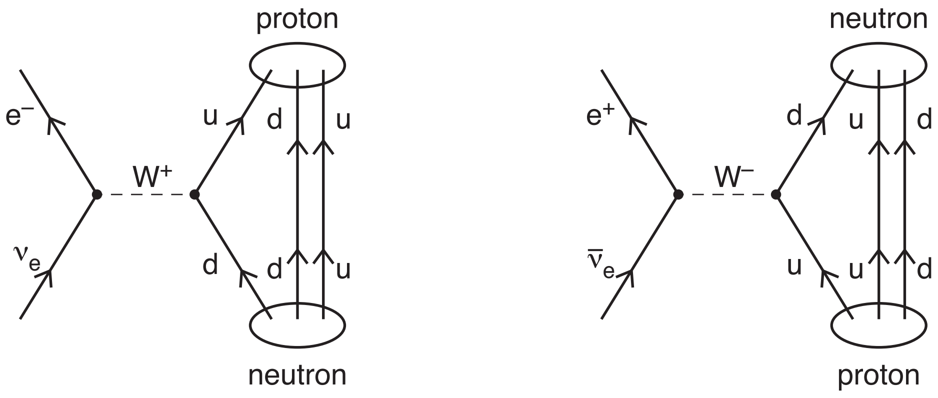


Fig. E2.2

The weak force has three different exchange particles. Two of them are charged. The exchange of these particles results in the reacting particles changing type. This is characteristic of the weak force. Fig. E2.3 shows two examples of this.



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

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

Fig. E2.3

The weak force is so short-range and so weak because of the great mass of the exchange particles. In order to react via the weak force, particles must get very close to each other so that there is a great deal of potential energy in the weak field (think of pushing like charges together). This energy is needed in order to stand any chance of creating a W or a Z^0.

Adapted from: Advanced Physics, Oxford University Press, Steve Adams and Jonathan Allday.

Extract 3: Strangeness

In the early days of hadron reactions, it became clear that there was a class of particle that could be produced quite easily in the reactions. These particles were quite massive and yet took comparatively long times to decay. The fact that they were produced relatively easily suggested that they were being created by the strong force, making them hadrons. If this were the case, then it was puzzling that they did not seem to decay via the strong force as well, as was clearly not the case given that their lifetimes were typically of the order of 10^{-10} seconds.

The other conspicuous feature was that these particles were only ever created in pairs, for example

$$\begin{array}{llll} & p + p & \longrightarrow p + \Sigma^+ + K^0 & \textbf{observed reaction} \\ \text{strangeness } S & 0 + 0 & \quad 0 - 1 + 1 & \\ & \quad 0 & = \ 0 & \end{array}$$

but never singly,

$$\begin{array}{lll} & p + p & \not\longrightarrow p + \Sigma^+ + \pi^0 \\ \text{strangeness } S & 0 + 0 & \quad 0 - 1 + 0 \\ & \quad 0 & \neq \ -1 \end{array}$$

In 1953, Gell-Mann, Nakano and Nishijima suggested that defining the existence of a new property of hadrons could solve the whole puzzle. They named this property **strangeness** (after the odd behaviour of the particles) and suggested that it must be conserved in strong interactions, which explained why the particles were produced in pairs. In the observed reaction above, the protons both have strangeness $S = 0$ so the initial total is zero. After the reaction, the Σ^+ has $S = -1$ and the K^0 has $S = +1$ making the total zero again.

When strange particles come to decay, they can decay into another strange particle if there is a less massive one in existence, for example

$$\begin{array}{lccc} & \Sigma^{*+} & \longrightarrow & \Sigma^{+} + \pi^{0} \\ \text{strangeness } S & -1 & & -1 + 0 \\ & -1 & = & -1 \end{array}$$

which would be a fast strong decay. However, if there were no lighter strange particle available then the strong force could not be used as the decay would have to involve a loss of strangeness.

$$\begin{array}{lccc} & \Sigma^{+} & \longrightarrow & p + \pi^{0} \\ \text{strangeness } S & -1 & & 0 + 0 \\ & -1 & \neq & 0 \end{array}$$

The assumption was that the weak force did not conserve strangeness and that hence could mediate the decay, explaining the lengthy lifetimes.

This suggestion of the new internal property of strangeness put Murray Gell-Mann and others on the road to the classification of hadrons and eventually to the discovery of quarks, the strange quark being represented by the letter s.

Adapted from: Quarks, Leptons and the Big Bang, IOP, Jonathan Allday.

Extract 4: Early Particle Detectors

Ionisation is the basis of detectors used in observing the particles produced in high-energy physics experiments.

Spark chambers

A spark chamber usually consists of a series of aluminium plates, each about 2.5 cm thick, vertically arranged. They are separated by 1 cm gaps filled with gas, and there is a high voltage between neighbouring plates. As a high-energy particle passes through the spark chamber, it ionises the gas and causes sparks to jump between the plates. A track is seen and recorded by time-lapse photography.

Bubble chambers

The first bubble chamber was invented by Donald Glaser, an American scientist, in 1952. The story goes that he was sitting in a bar, staring into a glass of beer, watching the bubbles rise to the surface. He realised that bubbles formed when the dissolved gas in the beer had some irregularity on which to develop – a mark on the glass, perhaps. He wondered whether the ionisation produced by radiation would be suitable to initiate the formation of bubbles in a superheated liquid. His first bubble chamber contained just 30 ml of diethyl ether, warmed to just above its boiling point. As particles passed through they caused ionisation, which triggered the formation of lines of bubbles of ether vapour.

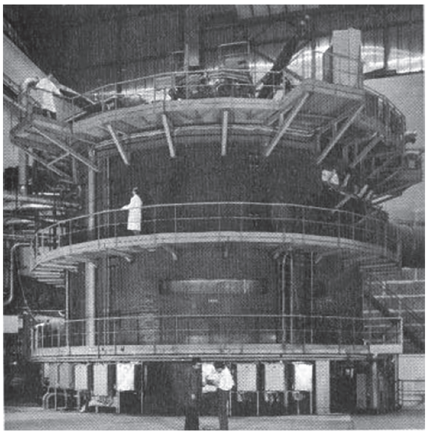


Fig. E4.1

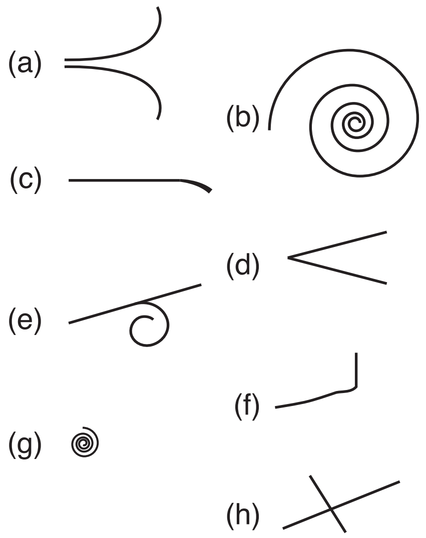
Since then much bigger bubble chambers have provided countless thousands of spectacular photographs of events involving subatomic particles. In practice bubble chambers usually contain liquid hydrogen.

Fig. E4.1 shows the Big European Bubble Chamber at CERN. Magnetic field coils are wound around the chamber.

The photographs of particle tracks from bubble chambers can be very complex. However, with an understanding of the behaviour of particles in magnetic fields it is possible to learn a great deal from such images.

In the past bubble chamber photographs had to be studied by experienced technical staff.

Fig. E4.2 shows some important features that are to be found in bubble chamber photographs.



(a) Electrons and positrons leave thin continuous tracks which curve in opposite directions in the magnetic field.

(b) Electron spirals appear because moving electrons radiate energy as they cause ionisation. As they travel more slowly, their tracks become more curved.

(c) Particles stopping leave tracks which become denser at the end, as slow particles cause more ionisation.

(d) Uncharged particles leave no tracks. If they decay into charged particles, these are likely to show up as a V shape.

(e) Delta rays are the short tracks of electrons, branching off from the main track, a result of the ionisation process.

(f) Kinks show where a particle has emitted one or more neutral particles (which leave no track).

(g) An electron that appears as an isolated spiral is known as a Compton electron. An electron has been knocked out of an atom by a gamma ray passing through the chamber.

(h) Reference marks are usually crosses. These mark positions in the bubble chamber so that photographs taken from different orientations can be compared.

Fig. E4.2

Drift chambers

The principle of a drift chamber is similar to that of a Geiger counter. The chamber contains an array of fine wires, with high voltages between them. As particles pass through they cause ionisation and a pulse of current flows into the nearest wire. Electronic circuits record the arrival of these pulses, and from their positions and the times at which they arrive, the track of the original particle can be reconstructed by computer.

Drift chambers have largely replaced bubble chambers as there is little delay between recordings of particle tracks. Fig. E4.3 shows a computer re-creation of the tracks of particles formed during an event detected by ALEPH at CERN.

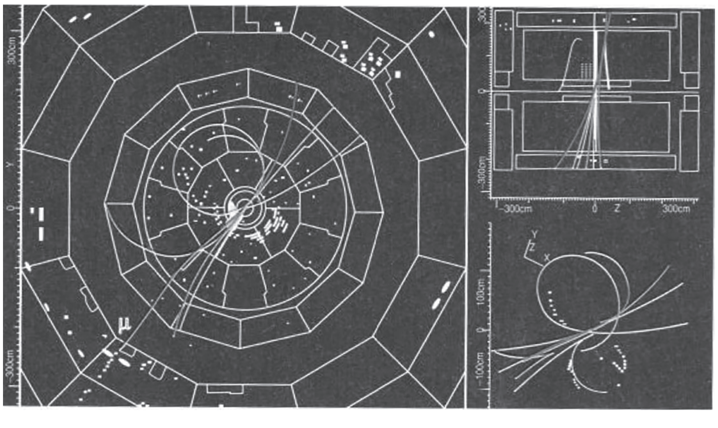


Fig. E4.3

Adapted from: University of Bath, Science 16–19, Nuclear and Particle Physics, David Sang.

Extract 5: The Omega-Minus

Fig. E5.1 shows one of the most famous pictures in particle research. One of a set of 80 000 photographs from the 200 cm bubble chamber at the Brookhaven National Laboratory on Long Island, it was the first picture to show the production and decay of an omega-minus particle, and it caused tremendous excitement when it was announced in February 1964. Here was the final piece in a jigsaw that had been accumulating over the previous few years.

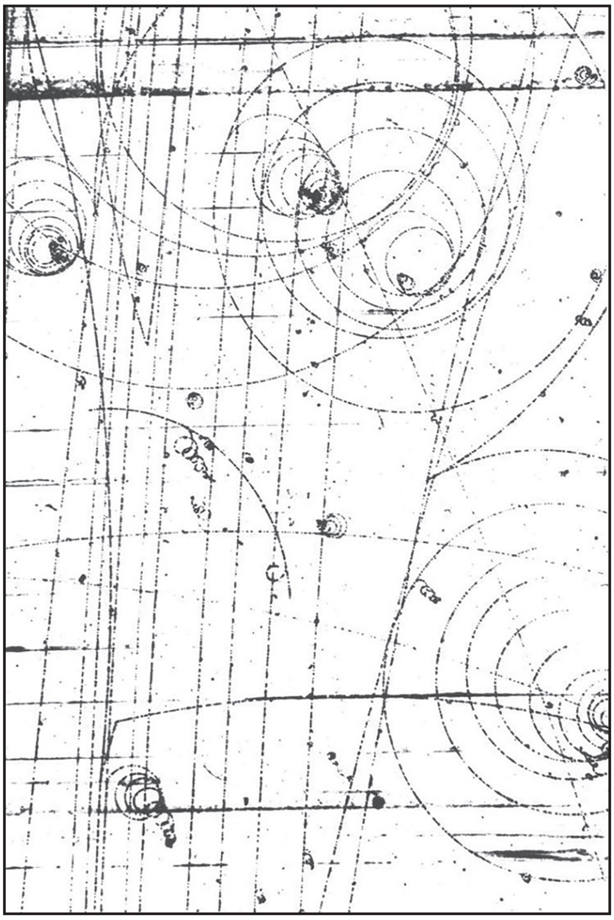


Fig. E5.1

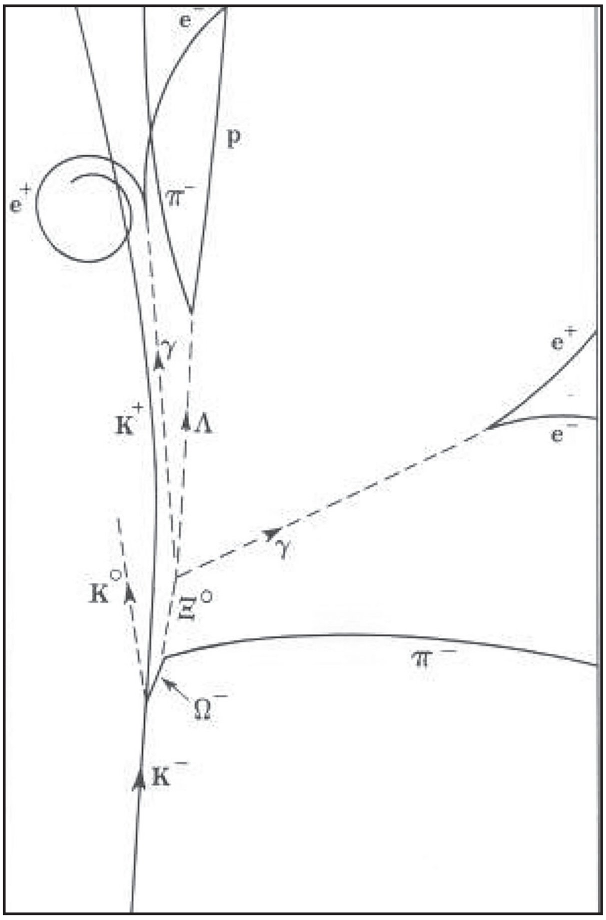


Fig. E5.2

This historic picture shows a negative kaon, K^-, colliding with a proton to produce three particles: an omega-minus, Ω^-, a positive kaon, K^+, and an unseen neutral kaon, K^0, which is represented by a dashed line in Fig. E5.2. The omega-minus travels a short distance, 2.5 cm, and then decays, emitting a pi-minus, π^-, that veers sharply to the right and a neutral xi, Ξ^0, which itself decays into three more neutral particles: a lambda, Λ, and two gamma ray photons, γ. These neutrals are also marked by dashed lines in Fig. E5.2. The neutrals reveal themselves by decaying into visible ‘Vs’: the gamma rays into electron-positron pairs and the lambda into a proton and a pi-minus, π^-.

The proliferating quantity of subatomic particles encouraged the theorists to try and find some order in the confusion. In 1960–1961 Murray Gell-Mann of Caltech and Yuval Ne’eman, who was studying physics in London, independently proposed a method for classifying all the particles then known. This model became the Eightfold Way, as suggested by Gell-Mann. What Mendeleyev’s table had done for atoms and chemistry, the Eightfold Way did for particles and high-energy physics. In the Eightfold Way, the particles are classified into ‘families’ according to such characteristics as their electric charge and their strangeness. Fig. E5.3 shows two such families, one with eight members, an octet, and one with ten members, a decuplet. Each particle has a particular position in its family according to the quantity of electric charge and strangeness the particle has.

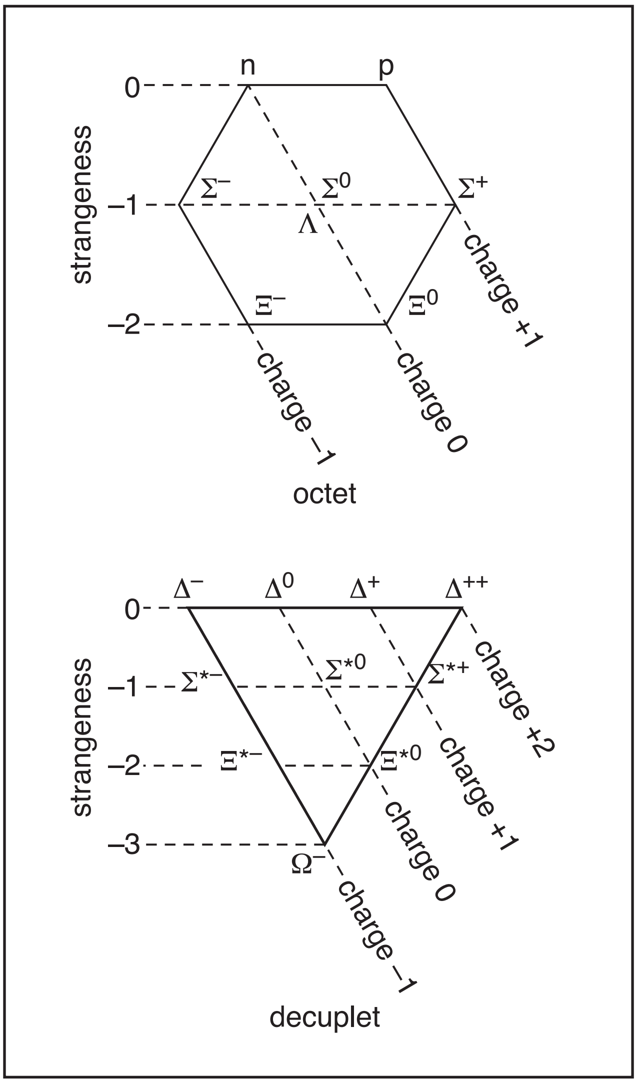


Fig. E5.3

In 1962 the Eightfold Way was still very new and poorly understood by all but a handful of theorists. Some critics thought its clever symmetries more accidental than fundamental, especially since it served only to classify known particles. In July 1962 Gell-Mann and Ne’eman attended an international conference at CERN and both were in the audience when a group from the University of Los Angeles announced the discovery of two new particles, a negative and a neutral xi-star, Ξ^{-*} and Ξ^{0*}. Both Gell-Mann and Ne’eman realised that the two xi-stars would almost complete a new decuplet in the Eightfold Way.

The next day’s session, 10 July, included a review of the known strange particles. At the end of the talk the chairman called for comments from the floor. Both Ne’eman and Gell-Mann raised their hands. The chairman called for Gell-Mann, who was, at the time, the acknowledged leader in theoretical physics. Gell-Mann then strode to the blackboard and announced his prediction of a triple strange particle to complete the new decuplet.

Gell-Mann called it the omega-minus: minus because it should have a negative charge, and omega, the last letter in the Greek alphabet, because it would complete the decuplet. Moreover, Gell-Mann predicted its mass at 1680 MeV.

In February 1964 the Brookhaven team found the first ‘gold-plated’ example of an omega-minus, the picture shown in Fig. E5.1. Calculations gave a mass of around 1686 MeV. CERN found a similarly clear example a few weeks later.

The Eightfold Way clearly worked, but why it worked remained a mystery.

… the answer is quarks.

Adapted from: The Particle Explosion, Oxford University Press, Frank Close, Michael Marten and Christine Sutton.

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