7 Hadrons - Isospin and Strangeness

In this Section we try to bring order into the hadron spectrum. We start out with a historical account of particle physics before quarks were known, with emphasis on strong interactions. Afterwards, isospin and strangeness, two important quantum numbers associated with hadrons, are introduced. These two concepts are still very useful today and are discussed in detail.

7.1 The Particle - Hadron Zoo "A Historical Interlude"

When discussing the history of particle physics one should do it *cum grano salis*[16]. You will only hear about the great successes and not about the many paths down dead-end routes which eventually had to be abandoned. While it is interesting from a philosophical point of view to to start with Democritus and the Greeks who invented the indivisible atom, modern particle physics started at the end of the nineteenth century. There are several experiments that could lay claim to being the first of the new field. H. Hertz discovered the photo-electric effect in 1888, but could not find an explanation. In 1895, W.C. Röntgen discovered X-rays. The first one to observe natural radioactivity was H. Becquerel in 1896. As discussed in Chapter 2, the **electron** was discovered by J.J. Thompson in 1897, see Figure 1. In textbooks, the choice of who should be given the honour of having started elementary particle physics varies. It arguably depends on the nationality of the author. These experiments and many more, all with unexpected results, triggered a frantic activity which lead to two totally new physical concepts on which *modern particle physics* is based: the formulation of **special relativity** (1905) and **quantum mechanics** (1926).

By 1930, only three elementary particles were known: the electron, and the photon and the proton which became established in the following experiments:

- In 1911, E. Rutherford discovered the structure of the atom by scattering α particles - ionised helium atoms - off a thin foil of gold and observing that a small fraction is scattered at large angles, approaching $180°$.[17] He concluded that the positive charge and almost all the mass is concentrated at the centre of the atom and that it occupies only a tiny fraction of the size of the atom. He gave the name **proton** to the nucleus of the lightest atom, hydrogen.

- In his famous experiment in 1923, Compton established that light scattered from a particle at rest is shifted in wavelength. This effect is readily explained by treating light as a particle of zero rest mass with energy $E = h\nu$ where ν is the frequency of the **photon**.

As a consequence, Pauli only very reluctantly postulated the existence of an additional new particle, the **neutrino**, in 1930. The neutrino hypothesis allowed to explain why the observed electron energy spectrum in β-decay was not monochromatic.

[16] "with a grain of salt" (Latin). I suspect this statement holds for the history of any field.

[17] In Rutherford's words: "It was quite the most incredible event ... in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

In 1914, Niels Bohr was able to calculate the spectrum of hydrogen in spectacular agreement with experiment[18]. Hence it was natural to postulate that nuclei of heavier atoms were composed of two or more protons. Unfortunately, the second lightest atom, helium, weighs four times as much as hydrogen. A nucleus with charge Z was thought to be made up of $2Z$ protons and Z electrons and held together by a possibly modified electromagnetic interaction. However in 1932, Chadwick established the existence of the **neutron**, a neutral partner of the proton. For example the helium nucleus, α, is made up of two protons and two neutrons. Hence a new **strong force** was required to hold a nucleus together. The basic properties of this force were quickly established and the field of *modern nuclear physics* was born.

- The force must be strong enough to overcome the Coulomb repulsion felt by the protons in a nucleus. The typical binding energy is about 8 MeV per **nucleon** (p, n).

- The range of the force is limited to about 1.5 fm. The radius r of a nucleus varies as $r = r_0 A^{1/3}$ where A is the number of nucleons in the nucleus and $r_0 \approx 1.4\,\mathrm{fm}$.

Caveat: The strong force, experienced by the nucleons in a nucleus, is not fundamental. Like the van der Waals force that holds the neutral atoms together, it is a residual force, a remnant of the fundamental strong force felt by the quarks and gluons that constitute the proton and neutron.

The first theory of the strong force was proposed by Yukawa in 1934. He postulated that protons and neutrons were attracted to each other by a *field*, mediated by the exchange of a massive particle. The strong force field has a short range R and is spherically symmetric. The corresponding Yukawa potential $V(r)$ is a static solution of the Klein-Gordon Equation which will be discussed in Chapter 9:

$$\nabla^2 V(r) = \frac{1}{r^2}\frac{\delta}{\delta r}\left(r^2 \frac{\delta V}{\delta r}\right) = \frac{m^2c^2}{\hbar^2} V(r) \qquad \Longrightarrow \qquad V(r) = \frac{g_0}{4\pi}\frac{1}{r}\exp\left(-r/R\right) . \tag{98}$$

This equation is analogous to the Coulomb field for electromagnetic interactions which is mediated by the photon ($m = 0$). Thus, g_0 can be interpreted as the strong charge. Equation 98 relates the range R of the strong force to the mass m of this particle:

$$R = \frac{\hbar}{mc} \approx 1.4\,\mathrm{fm} \qquad \Longrightarrow \qquad m \approx 140\ \mathrm{MeV} . \tag{99}$$

The Yukawa hypothesis predicts a spinless particle with a mass of about 140 MeV.

Until the 1950s, the only available source of high energetic particles were **cosmic rays**. These consist principally of high-energy nuclei of atoms, from Hydrogen to Uranium, which traverse the galaxy. Upon interacting in the earth's upper atmosphere cosmic rays seed secondary particle showers. These showers consist of two parts: a *soft* electromagnetic shower containing $e^{\pm}$ and γ

[18] Note that Bohr arrived at the correct result for the hydrogen spectrum 12 years before the formulation of quantum mechanics!

particles, and a *hard* component which penetrates the atmosphere. In 1932, Anderson discovered the **positron**, e^+, the first antiparticle, in a cloud chamber[19] exposed to cosmic rays, see Figure 2.

By measuring cosmic rays in a cloud chamber on the top of a mountain in 1937, Anderson and Neddermeyer as well as Street and Stevenson discovered a new particle, the **muon**, $\mu^\pm$. At first, the muon was *incorrectly* identified with the strongly interacting Yukawa particle. After all, the muon had the expected mass. In the 1940s, the lifetime of the muon was measured to be $\approx 2.2 \times 10^{-6}$ μs, and no evidence for strong interactions of (negative) muons with nuclei was found. It became apparent that the muon could not be the strong quantum predicted by the Yukawa interaction.

The puzzle was solved in 1947. Marshak and Bethe suggested that there were actually two particles, a heavier strongly interacting meson producing the lighter muon in its decay. Using photographic emulsions exposed to cosmic rays on top of Pic du Midi, on balloons and on high

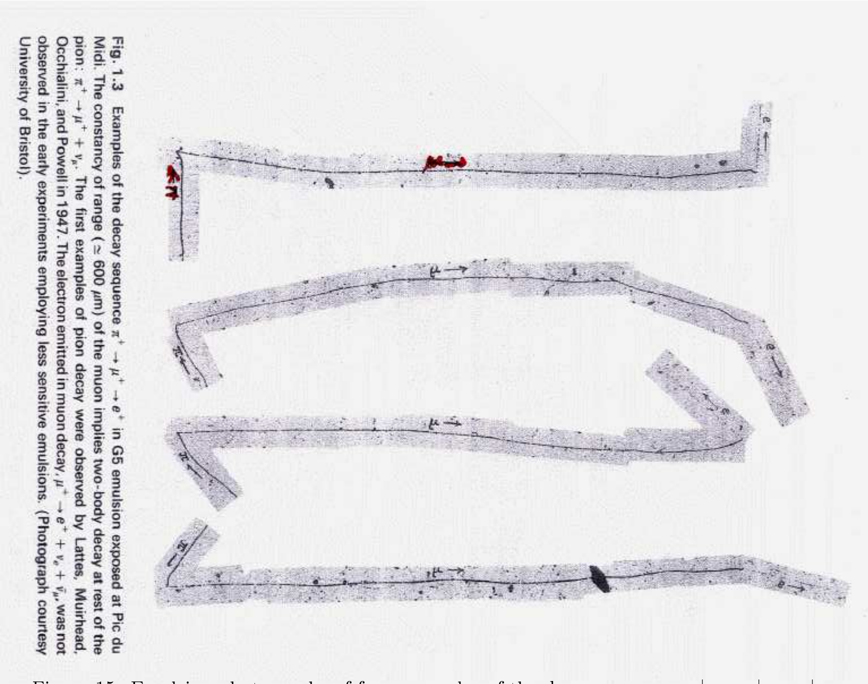

Figure 15: Emulsion photographs of four examples of the decay sequence $\pi^+ \to \mu^+ \to e^+$.

[19]The **cloud chamber** was invented by C.T.R. Wilson in 1912. It consists of a tank of gas saturated with water vapour. By applying a sudden expansion the gas becomes supersaturated and ionising particles leave a trail of condensed water droplets which are photographed.

altitude aircraft a group in Bristol (Lattes *et al.*) observed the decay sequence $\pi^+ \to \mu^+$. After improving the sensitivity of their emulsions they also observed the sequence $\pi^+ \to \mu^+ \to e^+$ which corresponds to the decay chain

$$\begin{aligned} \pi^+ \to & \mu^+ \nu_\mu \\ & \hookrightarrow e^+ \nu_e \bar{\nu}_\mu \end{aligned} \tag{100}$$

and is shown in Figure 15. The pion has a mass of about about 140 MeV, spin 0 and interacts strongly; thus it seemed to be the particle which Yukawa had predicted. The muon does not undergo any strong interactions. It interacts exactly like a heavier version of the electron and seemed quite unnecessary. To discover such a particle was totally unexpected and prompted I.I. Rabi to ask: “Who ordered that?” Even today, we still do not have a satisfactory answer to this question. Why does Nature replicates itself in a second and third generation?

At this stage, particle physics was thought to be understood and the the number of known elementary particles was manageable. The $e^\pm$, γ, p, n, $\pi^\pm$, $\mu^\pm$, and ν combined with quantum electron dynamics, Yukawa’s strong interaction and Fermi’s theory of weak decay seemed to be able to explain all of nuclear and atomic physics. Only the muon did not fit in properly.

But this was not to last. At the end of the year 1947, Rochester and Butler discovered two additional heavy and unstable particles when exposing a cloud chamber to cosmic rays. Shown in Figure 16, they observed a “V” event where a neutral particle, V^0, decayed in two charged

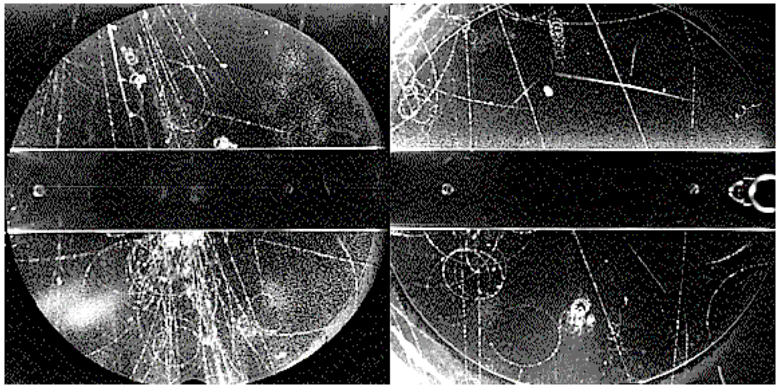

Figure 16: First observation of “V” events in a cloud chamber by Rochester and Butler (1947). The left picture is of a neutral V^0, probably due to the decay $K^0 \to \pi^+\pi^-$; look for the two “forked” tracks a few millimetres below the lead plate. The right picture reveals a charged K, probably due to $K^+ \to \mu^+\nu_\mu$; look for the short track in the top right-hand corner which has a “kink” towards the left in it.

particles, characterised by a *fork*. In a second picture a heavy charged meson decays in flight which shows up as a *kink*.

With the arrival of a new detection technique, the bubble chamber[20] invented by D. Glaser in 1952 and the operation of modern particle accelerators, the Berkeley synchrocyclotron in 1950, the Brookhaven Cosmotron in 1952, and the Berkeley Bevatron in 1954, it was possible to design experiments with known kinematics and soon the rate of new particles proliferated. Many more weakly decaying particles and strong resonances were found in the 1950s: the V, θ^+ and τ^+, η, ϕ, ρ, ω, Λ, and Δ, just to name a few. In 1955, W Lamb began his Nobel Prize acceptance speech with the words "... the finder of a new particle used to be rewarded by a Nobel prize, but such a discovery ought to be punished by a $ 10000 fine."

By 1960 the situation had grown into a particle "zoo," and hadron physics could only be described as chaos. Spin assignments, if experimentally known, allowed to divide the hadrons into mesons and baryons. **Baryons** are fermions and have half-integer spin 1/2, 3/2, 5/2, ... whereas **mesons** are bosons and have spin 0, 1, 2, ..., respectively. Concepts such as isospin and strangeness had been developed to categorise groups of particles with similar mass but different charge. In Tables 10 and 11 we show a list of mesons and hadrons in 1960 and their properties. But there was no real understanding of an underlying order of how the particles should all fit together and why there were so many. This reminded physicists of the situation in chemistry in the nineteenth century before the arrival of the Periodic table.

Mesons	⟨Mass⟩	J^{PC}	I	S
π^-, π^0, π^+	138.0	0^{-+}	1	0
K^0, K^+	495.7	0^-	1/2	+1
$K^-, \overline{K}^0$				−1
η	547.3	0^{-+}	0	0
ρ^-, ρ^0, ρ^+	770.0	1^{--}	1	0
ω	781.9	1^{--}	0	0
$K^{\star 0}, K^{\star +}$	893.7	1^-	1/2	+1
$K^{\star -}, \overline{K}^{\star 0}$				−1
η'	957.8	0^{-+}	0	0
ϕ	1019.5	1^{--}	0	0

Table 10: Well established mesons in 1962, and their basic quantum numbers; the mass (in MeV) shown is the average of all the members of a multiplet. The charge parity C is only defined for neutral members of a multiplet.

[20]A **bubble chamber** consists of a vessel filled with a cryogenic liquid held under pressure above its normal boiling point. Through a sudden decompression the liquid is superheated and boiling will start with the formation of bubbles along atoms ionised by particle tracks. The bubbles are allowed to grow for about 10 ms and are then photographed. The bubble chamber has excellent spatial resolution.

Baryons	⟨Mass⟩	J^P	I	S
p, n	938.9	$1/2^+$	1/2	0
Λ	1116	$1/2^+$	0	−1
$\Sigma^-, \Sigma^0, \Sigma^+$	1193	$1/2^+$	1	−1
$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$	1232	$3/2^+$	3/2	0
Ξ^-, Ξ^0	1318	$1/2^+$	1/2	−2
$\Sigma^{\star -}, \Sigma^{\star 0}, \Sigma^{\star +}$	1385	$3/2^+$	1	−1
$\Xi^{\star -}, \Xi^{\star 0}$	1533	$3/2^+$	1/2	−2

Table 11: Well established baryons in 1962, and their basic quantum numbers; the mass (in MeV) shown is the average of all the members of a multiplet.

7.2 Isospin

After the neutron was discovered by Chadwick in 1932, Heisenberg observed that apart from the obvious fact that the proton carried charge and the neutron did not, the two particles were very much the same. Their masses, $m_p = 938.28$ MeV and $m_n = 939.57$ MeV are nearly equal and, when neglecting the Coulomb potential which causes protons in a nucleus to repel each other, their interactions are very similar[21]. Hence, the nuclear potentials are approximately charge-independent:

$$V_{pp} \approx V_{pn} \approx V_{nn} \ . \tag{101}$$

Heisenberg proposed that if one could "switch off" the electric charge of the proton, the two particles became indistinguishable and p and n would be two states of a single entity:

$$\begin{pmatrix} p \\ n \end{pmatrix} \qquad \text{nucleon} \ . \tag{102}$$

This notation is analogous to the two spin states $(|\uparrow\rangle, |\downarrow\rangle)$ of a spin $\frac{1}{2}$ particle. To further discuss the similarity between the proton and the neutron, we proceed with this analogy and introduce a mathematical copy of spin which is called **isospin** I. Note that I is not a vector in the 3-dimensional space, but in an abstract *isospin space*. Hence, its components are dimensionless. They are usually labelled, I_1, I_2, I_3. Heisenberg postulated each nucleon to have isospin $I = \frac{1}{2}$ with the third component $I_3 = \pm\frac{1}{2}$ for protons and nucleons, respectively. The proton is isospin "up", the neutron is isospin "down".

$$p = \left|\tfrac{1}{2}\tfrac{1}{2}\right\rangle \qquad\qquad n = \left|\tfrac{1}{2} - \tfrac{1}{2}\right\rangle \tag{103}$$

As we will see soon, isospin is a very useful concept. The introduction of isospin has the following consequences:

[21]In nuclear physics this feature is used very successfully when describing the structure of nuclei with the shell and liquid drop models.

- The strong force is invariant under rotations is isospin space, i.e. exchanging all neutrons with protons in a nucleus will not change the nuclear potentials.
- It then follows, via Noether's theorem, that isospin I is *conserved* in all strong interactions, Consequently strong reactions only depend on I. The third component I_3 is an additive quantum number which is also conserved.
- In the language of group theory we call this a SU(2) symmetry: The strong interactions are invariant under rotations of the symmetry group SU(2), and the nucleons constitute a 2-dimensional representation of the group.

In 1932, this was quite a bold suggestion, but it turned out to be correct and very useful in classifying all the hadrons to be discovered over the next three decades. Ultimately, the quark model will provide an explanation of why isospin works so well.

There is much evidence that the nuclear force is independent under isospin transformations. For example consider the three nuclei ^{6}He, ^{6}Li, and ^{6}Be which can be regarded as a nn, np, and pp system attached to a ^{4}He core which has I = 0. After correcting for the Coulomb repulsions between the protons and the $n - p$ mass difference, the observed masses are nearly degenerate.

Isospin symmetry allows us to arrange hadrons in multiplets which, in the language of group theory, are n-dimensional representations of SU(2). Below we give examples of multiplets for n = 1, 2, 3, 4.

$$\eta = |0, 0\rangle$$

$$p = \left|\tfrac{1}{2}, \tfrac{1}{2}\right\rangle \qquad n = \left|\tfrac{1}{2}, -\tfrac{1}{2}\right\rangle$$

$$\pi^+ = |1, 1\rangle \qquad \pi^0 = |1, 0\rangle \qquad \pi^- = |1, -1\rangle$$

$$\Delta^{++} = \left|\tfrac{3}{2}, \tfrac{3}{2}\right\rangle \qquad \Delta^{+} = \left|\tfrac{3}{2}, \tfrac{1}{2}\right\rangle \qquad \Delta^{0} = \left|\tfrac{3}{2}, -\tfrac{1}{2}\right\rangle \qquad \Delta^{-} = \left|\tfrac{3}{2}, -\tfrac{3}{2}\right\rangle$$

Particles which belong to a multiplet have similar masses but different charges. The number of particles in a multiplet is equal to $2I + 1$. For example, the pion exists in three charge states and consequently is assigned isospin $I = 1$. Within a doublet, the particle with the highest charge is assigned the maximum value $I_3 = I$, and the others are filled in order of decreasing charge. The charge Q of a particle is related to the third component of isospin I_3 by

$$Q = I_3 + \tfrac{1}{2}B \tag{104}$$

where B is the baryon number; $B = 1$ for baryons and $B = 0$ for mesons, respectively. Note that the neutral pion, π^0, had been predicted in 1938 by N. Kemmer (Edinburgh) by applying Isospin invariance to the Yukawa theory. The π^0 was discovered in 1950 through the observation of the decay $\pi^0 \to \gamma\gamma$.

7.3 Isospin in Nucleon - Nucleon System

The isospin of a system of two nucleons $N + N$ can be constructed in exact analogy to the addition of two spin $\frac{1}{2}$ states, see Equation 82. We obtain a symmetric triplet and a antisymmetric singlet.

$$\begin{aligned} |1, 1\rangle &= pp \\ |1, 0\rangle &= \sqrt{\tfrac{1}{2}}(pn + np) && \text{triplet} \\ |1, -1\rangle &= nn \\ |0, 0\rangle &= \sqrt{\tfrac{1}{2}}(pn - np) && \text{singlet} \end{aligned} \tag{105}$$

Experimentally only p and n form a bound state, the **deuteron**. There are no pp or nn bound states. The total wavefunction of the deuteron, d, can be written as

$$\psi(\text{total}) = \phi(\text{space})\alpha(\text{spin})\chi(\text{isospin})$$

The spatial wavefunction ϕ has symmetry $(-1)^l$ under interchange of the two nucleons, see Equation 88. The two nucleons in the deuteron have angular momentum $l = 0$, thus ϕ is symmetric. The deuteron has spin $s = 1$, which is also symmetric under interchange, see Equation 82. In order to satisfy that the total wave function ψ(total) is antisymmetric, χ must be antisymmetric It follows that $I = 0$; and we can identify the deuteron as an isosinglet $|0, 0\rangle$.

Isospin invariance can be used to deduce relations for hadronic cross sections. As an example, consider the following nucleon-nucleon scattering processes:

$$\begin{aligned} &\text{a)} \quad p + p \to d + \pi^+ \\ &\text{b)} \quad p + n \to d + \pi^0 \\ &\text{c)} \quad n + n \to d + \pi^- \end{aligned} \tag{106}$$

Since the deuteron carries $I = 0$ the isospin states on the right-hand side of Equation 106 are $|1, 1\rangle$, $|1, 0\rangle$, and $|1, -1\rangle$, respectively. The final state is pure $I = 1$. Since isospin is conserved, only the $I = 1$ combinations can contribute to this reaction. Hence we can calculate the ratios of the scattering amplitudes or matrix elements $M_i = \langle d + \pi| H_1 |N + N\rangle$ for these processes. The cross sections, σ, are proportional to the square of the matrix elements, M_i^2, (see Equation 45) and we obtain the following ratios:

$$\begin{aligned} M_a : M_b : M_c &= 1 : \sqrt{\tfrac{1}{2}} : 1 \\ \sigma_a : \sigma_b : \sigma_c &= 2 : 1 : 2 \; . \end{aligned} \tag{107}$$

Reaction c) is very difficult to set up in the laboratory - how to produce a beam of neutrons? -, but the measured cross sections for reactions a) and b) are in agreement with the predicted ratio.

7.4 Isospin in Pion - Nucleon Scattering

The pion is the lightest meson. As soon as particle accelerators became available in the 1950s, charged pion beams could readily be produced. An important application of isospin conservation arises in the strong interactions of non-identical particles which generally consist of mixtures of different isospin states. Let us consider pion-nucleon scattering $\pi N \to \pi N$. There are six elastic and four charge exchanging or inelastic processes. Let us look at the following reactions, which are studied by firing charged pions onto a hydrogen target and measuring the scattered particles.

$$\begin{aligned} &\text{a)} \quad \pi^+ p \to \pi^+ p \\ &\text{b)} \quad \pi^- p \to \pi^- p \\ &\text{c)} \quad \pi^- p \to \pi^0 n \end{aligned} \tag{108}$$

The pions have isospin $I_\pi = 1$ and the nucleons $I_N = \frac{1}{2}$. Using Table 8 to read off the Clebsch-Gordan coefficients we find the following decompositions for the addition of these isospins:

$$\begin{aligned} &1 \otimes \tfrac{1}{2} = \tfrac{3}{2} \oplus \tfrac{1}{2} \\ \pi^+ p: \quad & |1,1\rangle \left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle = \left|\tfrac{3}{2},\tfrac{3}{2}\right\rangle \\ \pi^- p: \quad & |1,-1\rangle \left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle = \sqrt{1/3}\left|\tfrac{3}{2},-\tfrac{1}{2}\right\rangle - \sqrt{2/3}\left|\tfrac{1}{2},-\tfrac{1}{2}\right\rangle \\ \pi^0 n: \quad & |1,0\rangle \left|\tfrac{1}{2},-\tfrac{1}{2}\right\rangle = \sqrt{2/3}\left|\tfrac{3}{2},-\tfrac{1}{2}\right\rangle + \sqrt{1/3}\left|\tfrac{1}{2},-\tfrac{1}{2}\right\rangle \end{aligned} \tag{109}$$

Since $I_\pi = 1$ and $I_N = \frac{1}{2}$, the total isospin is $I = \frac{1}{2}$ or $\frac{3}{2}$. The matrix elements for $\pi N \to \pi N$ scattering only depend on the total isospin which can be written in terms of two amplitudes:

$$M_3 = \left\langle \tfrac{3}{2} \right| H_3 \left| \tfrac{3}{2} \right\rangle \qquad M_1 = \left\langle \tfrac{1}{2} \right| H_1 \left| \tfrac{1}{2} \right\rangle$$

$$\begin{aligned} M_a(\pi^+ p \to \pi^+ p) &= M_3 \\ M_b(\pi^- p \to \pi^- p) &= 1/3\ M_3 + 2/3\ M_1 \\ M_c(\pi^- p \to \pi^0 n) &= \sqrt{2}/3\ M_3 - \sqrt{2}/3\ M_1 \end{aligned}$$

To calculate cross sections, we need to take the squares of the matrix elements. If the $I = \frac{3}{2}$ or the $I = \frac{1}{2}$ amplitude were to dominate we obtain the following ratios of cross sections:

$$\begin{aligned} M_3 \gg M_1: \quad &\Longrightarrow \quad \sigma_a : \sigma_b : \sigma_c = 9 : 1 : 2 \\ M_1 \gg M_3: \quad &\Longrightarrow \quad \sigma_a : \sigma_b : \sigma_c = 0 : 2 : 1 \end{aligned} \tag{110}$$

We use experimental data to decide whether one isospin amplitude actually dominates. In Figure 17, we plot the $\pi^\pm p$ total and elastic cross sections. At a centre-of-mass energy of $E_{CoM} = 1.232$ GeV, a large resonance is observed. The cross sections at the peak of the resonance are:

$$\begin{array}{ccccc} \sigma(\pi^+ p) & : & \sigma_{\rm total}(\pi^- p) & : & \sigma_{\rm elastic}(\pi^- p) \\ \approx 200\ \text{mbarn} & : & \approx 70\ \text{mbarn} & : & \approx 23\ \text{mbarn} \\ \approx 9 & : & \approx 3 & : & \approx 1 \end{array}$$

When taking into account that the total cross section $\sigma_{\rm total}(\pi^- p)$ is equal to the sum of the cross sections for processes b) and c), $\sigma_{\rm total}(\pi^- p) = \sigma_b + \sigma_c$, we conclude that the data favours $I = \frac{3}{2}$ and identify this resonance with the $\Delta(1232)$ particle which was discovered by Fermi in 1951.

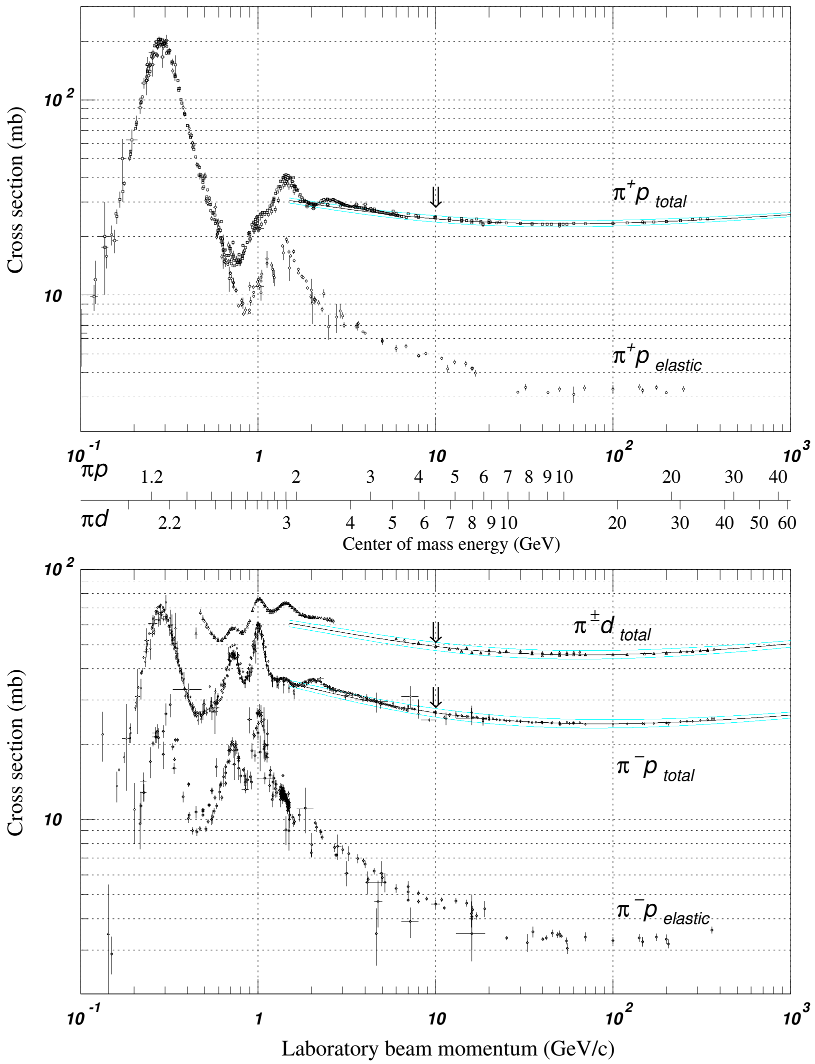

Figure 17: Experimental $\pi^\pm p$ total and elastic cross sections as a function of the pion beam momentum or the centre-of-mass energy.

7.5 Strangeness

The observation of the first V and K^+ particles in 1947 (Figure 16) was the first in a series of discoveries of V (K^0, Λ) and $K^\pm$ particles with peculiar properties. Some of these, the Λ, $\Sigma^\pm$, and Ξ^-, are heavier than nucleons and are called **hyperons**. In Figure 18, we show a bubble chamber photograph of the reaction $\pi^- p \to K^0\Lambda$ as an example.

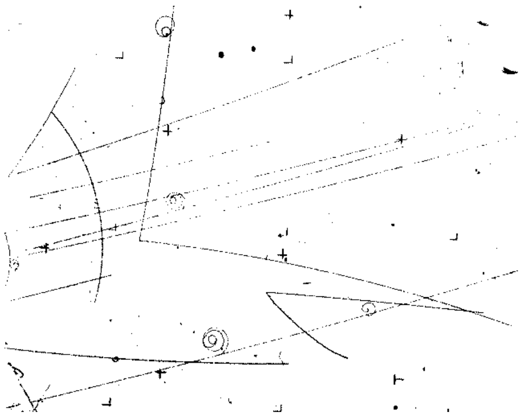

Figure 18: A bubble chamber picture of the reaction $\pi^- p \to \Lambda K^0$ in which the neutral Λ decays weakly to $p\pi^-$, bottom narrow V, and the K^0 decays weakly to $\pi^+\pi^-$, top wide V.

The discovery of these particles was not only unexpected. They are all produced copiously but decay relatively slowly with observable decay lengths, hence resulting in *forks* and *kinks* when observed in a detector. This becomes apparent when comparing the time scales involved in the creation and disintegration of these particles:

$$\begin{aligned} \pi^- p \to K^0\Lambda \qquad & \tau = \mathcal{O}(10^{-23})\ \text{s} \\ K^0 \to \pi^+\pi^- \qquad & \tau = 0.89 \times 10^{-10}\ \text{s} \\ \Lambda \to \pi^- p \qquad & \tau = 2.63 \times 10^{-10}\ \text{s} \end{aligned}$$

This suggests that the production mechanism for these particles is totally different from the process which governs their decay. The first attempt to solve this apparent paradox was made by Pais who, in 1952, proposed the *associated production* hypothesis: Kaons and hyperons must be created in pairs. Soon after in 1953 Gell-Mann and Nishijima argued that a new additive quantum number called the **Strangeness** S needs to be introduced. Strangeness is conserved in the associated strong production of *strange* particles with opposite strangeness but violated in weak interactions. Strangeness is also conserved in electromagnetic transitions.

The assignment of strangeness is arbitrary for some particles. The K^+ and K^0 are given strangeness $S = 1$ and the hyperons $S = -1$, respectively. From this definition, all other assignments follow and are summarised below. Pions and nucleons clearly must have $S = 0$.

$$\begin{aligned} S = 0 :\quad & \pi, N, \Delta, ... \qquad & S = 1 :\quad & K^+, K^0, ... \\ S = -1 :\quad & K^-, \bar{K}^0, \Lambda, \Sigma, ... \qquad & S = -2 :\quad & \Xi^- \end{aligned} \tag{111}$$

As an example, we demonstrate the conservation of strangeness for the reaction shown in Figure 18:

$$\begin{array}{ccccccccc} & \pi^- & + & p & \to & \Lambda & + & K^0 \\ I & 1 & & \frac{1}{2} & & 0 & & \frac{1}{2} \\ I_3 & -1 & & \frac{1}{2} & & 0 & & -\frac{1}{2} \\ S & 0 & & 0 & & -1 & & 1 \end{array}$$

Just as pions and nucleons, strange hadrons are grouped in isospin multiplets. The Λ has $I = 0$. The kaons are grouped in two isospin doublets:

$$K^+ = \left|\tfrac{1}{2}, \tfrac{1}{2}\right\rangle \qquad K^0 = \left|\tfrac{1}{2}, -\tfrac{1}{2}\right\rangle \qquad \text{and} \qquad \bar{K}^0 = \left|\tfrac{1}{2}, \tfrac{1}{2}\right\rangle \qquad K^- = \left|\tfrac{1}{2}, -\tfrac{1}{2}\right\rangle \ .$$

Historically this scheme met some resistance. First, because K^+ and K^- are in different multiplets, and second, because experimentally K^0 and $\overline{K^0}$ are not seen. The observed states, K^0_S and K^0_L, are essentially 50-50 mixtures of the K^0 and the $\overline{K^0}$. The hyperons $\Sigma^\pm$, which are strange baryons, have Isospin $I_3 = \pm 1$ as can be inferred from their production mechanism:

$$\pi^\pm + p \to \Sigma^\pm + K^+ \ .$$

Applying isospin conservation we must put the $\Sigma^\pm$ into a isospin triplet, $I = 1$, which requires the existence of a neutral Σ^0 state with $I_3 = 0$. The Σ^0 was found in 1956 through its electromagnetic decay $\Sigma^0 \to \Lambda + \gamma$. When kaon beams became available at accelerators, the cascade particle, Ξ^-, a hyperon with strangeness $S = -2$ was discovered in the reaction

$$K^- + p \to \Xi^- + K^0 \ .$$

In 1953, Gell-Mann and Nishijima pointed out that Equation 104 could be adapted to include strangeness. The charge Q of a hadron is related to the strangeness S and the third component of isospin I_3 as follows:

$$Q = I_3 + \tfrac{1}{2}\,(B + S) \ . \tag{112}$$

The strangeness quantum number can be violated in weak decays of particles with S not equal to zero. Examples are: $K^0 \to \pi^+\pi^-$, $\Lambda \to \pi^- p$, $K^+ \to \mu^+\nu_\mu$, $\Sigma^+ \to p\pi^0, n\pi^+$ and $\Xi^- \to \Lambda\pi^-$. All these decays can be described by the following two selection rules:

$$|\Delta S| = 1 \qquad \text{and} \qquad \Delta S = \Delta Q \ . \tag{113}$$

The quark model will provide a very simple explanation for these selection rules.