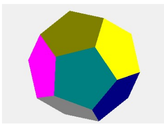
Elementary Particles

Chapter 10 of the textbook
Elementary Physics 3

This is an article from my home page: www.olewitthansen.dk



Ole Witt-Hansen 1980 (2017)

Informative remark: The present chapter is a translation from the Danish textbook: Elementary Physics 3. However, the texts, when it appears in the figures are not translated. On the other hand the figures and the supplementing text should speak for themselves.

Contents

1. The interactions of elementary particles

Elementary particles physics originates from a wish to understand and describe the interactions between the least particles of our material world, the so called elementary particles.
An elementary particle can be described as a particle which is present in the material world, and which is not composed of other particles. Thus an atom is not an elementary particle, whereas the electron and the proton are.
The Newtonian concept of force can no longer be applied in particle physics, as it is the case in quantum mechanics instead the interactions between elementary particles are based on the conservation of energy and momentum.
In the relativistic quantum field theory it is possible to describe the interactions once the quantum fields are known. For the electromagnetic field such a description has successfully been achieved since the fifties, followed by weak interaction in the sixties, and the field theoretical approach has (almost) been completed for the strong interactions, with the appearance of the *standard model* developed in the seventies.
In the modern physics of matter, we operate with four fundamental interactions. They are designated according to rising strength:

Gravitational forces, Weak interactions, Electromagnetic interactions and Strong interactions.

The strong interactions are also known as Nuclear forces.

In the classical physics (before 1900) there existed only the gravitational and electromagnetic forces, whereas the weak and strong interactions belong to the physics of nuclear particles described by quantum physics. The forces are presented below ordered by increasing strength.

1) **Gravitational forces:** It is the Gravitational forces that hold the universe together, while they are completely insignificant at the atomic and nuclear level.
The Coulomb repulsion between two protons is about 10^{36} times stronger than their gravitational attraction between them.
This can be understood, since the gravitational force is proportional to the mass, that is, proportional to r^3, while they decrease with r^{-2}. The electromagnetic forces are independent of the size of the object. Their significance of the gravitational forces are therefore proportional with $r^3 r^{-2} = r$, and the gravitational forces are thus totally insignificant at the atomic or nuclear level.

2) **Weak Interactions**: The weak interactions are the latest discovered of the four fundamental interactions. Their existence were proposed by E. Fermi in 1934 to explain the β-decay.
So it is the weak interactions, which is the cause of the β-decay. Processes caused by the weak interactions are always accompanied by the emission of neutrinos.
All particles (except the photon) have weak interactions. The neutrino is, however, the only particle which has no other interactions.
This means that a neutrino can pass through the earth (and it usually does), without having a single interaction with another particle. The very small probability of interaction derives both from the weak strength and that the range of the weak interactions is extremely short, less than the radius of the nucleus. This is in contrast to gravitational and electromagnetic forces having infinite range.

Weak interactions also have a strange property that they seem to break some symmetry conservation laws like parity conservation laws, which are valid for strong interaction.

3) **Electromagnetic interactions**:
All elementary particles except the neutrino have electromagnetic interactions. This means that the particles are affected by the electromagnetic field and that they interact with the electromagnetic quantum the photon.
It may seem surprising that a neutral particle like the neutron have electromagnetic interactions, but in fact the neutron has a magnetic moment, and the direction on the neutron spin can be affected by an external magnetic field.

The electromagnetic interactions are the only ones which have a complete theoretical description. The electromagnetic interaction has therefore served as a model for the description for the strong and the weak interactions.

4) **The strong interactions** are what we also refer to as nuclear forces. The strong interactions keep the nuclei together in the nucleus in spite of the electrical repulsion from the protons.
Particles having strong interactions are denoted *hadrons*. They are separated in baryons, with baryon number 1 (the baryon number is the same as the atomic mass number in the atomic description) and mesons which have the baryon number 0. Apart from the nucleons over hundred non stables baryon resonances have been discovered since the beginning of the sixties.

The baryon number is, (like the charge), a conserved quantity in all reactions between elementary particles.

Thus, the concept of a interaction field has been transferred from electromagnetic interactions to include the strong and the weak interactions. In quantum electrodynamics the forces between the particles are mediated by the photon, and in the same manner the strong interactions are mediated by the π-mesons, and the weak interactions by the *W* and Z-bosons.
The very short range of the weak and strong interactions have the consequence that the mediating particles must (in contrast to the photon) have a mass. The larger the mass of the mediating particles are, the shorter the range of the interaction must be.
This is a consequence of Heisenberg's uncertainty principle: $\Delta E \Delta t > h$. If a virtual particle e.g. a π-meson is to be created it requires an uncertainty in energy $\Delta E = 140\ MeV$. It can only exist in a time interval $\Delta t = \frac{h}{\Delta E} = \frac{4.15\,10^{-15}\ eVs}{140\,10^{6}\ eV} = 4.\,10^{-23} s$, and in this time interval the virtual particle can at most travel a distance: $c\Delta t = 3\,10^{8}\ m/s\ 4\,10^{-23}\ s \approx 4\,10^{-15}\ m\ =\ 4 fm$. This is about the size of the nucleus.
So roughly speaking: The range of a interaction is rougly inversely proportional to the mass of the mediating particles.
Since the photon has zero mass, it explains why the electromagnetic interactions have infinite range.

The physics of the strong interactions has turned out to be very complex. The first attempt to give the strong interactions a field theoretic interpretation was done by Japanese physicist Yukawa in 1937.
Since the many and very different theories has been brought forward From the sixties The notorious quark model, which has prevailed, The Veneziano model, which was based on the mathematics of complex functions of three variables. It developed in the seventies to *the String model*, and several others. These models are however now abandoned in favour of *the standard model*

After 2000 the best bid of a unified model for the three fundamental forces has been the Standard Model, based by an extended quark model, but it is still incomplete compared to quantum electrodynamics.
No theory has until now been able to predict the masses and other properties of the elementary particles.

The range of the strong interactions may be estimated from the results of scattering experiments on nuclei, and from such experiments Yukawa concluded that the quantum mediating the strong interactions had to have a mass of about 100 MeV/c^2.
In 1947 the π-mesons were observed in the cosmic radiation, and the following year accelerators were constructed being powerful enough to induce productions of π-mesons, by shooting protons into atomic nuclei.
Rather quickly it appeared that the mesons formed a charge triplet (π^-, π^0, π^+), where the three particle have nearly the same mass 140 *MeV*.

Even if the discovery of the π-meson, was a triumph for Yukawa's theory, it became very soon clear the theory could not account for details of the interaction between the nuclei in the atomic nucleus.
Understanding the physics of strong interactions has been one of the greatest challenges in theoretical physics for more than 60 years.
At lower energies, one may to a good approximation represent the nucleon - nucleon interaction by a potential function, but in collisions at higher energies the interaction is characterized by a steady production of particles. Not only grows the number of particles with higher energies, but also the collisions at higher energies have revealed the existence of new hitherto unknown hadrons (unstable resonances), so today over two hundred such particles have been discovered.

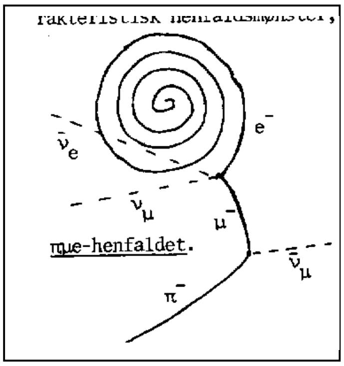
Right from the sixties the research in particle physics has been vastly intensified. This has been expressed in the building of gigantic accelerators in CERN Switzerland, and in many other places.

2. Mesons and myons

π-mesons can for example be observed in collisions between two protons. We may imagine the following processes.

$$p + p \rightarrow p + p + \pi^0 \qquad p + p \rightarrow p + n + \pi^+ \qquad p + n \rightarrow p + p + \pi^-$$

If the π-meson production happens in a bubble-chamber, one may observe the traces from charged particles. The π^- and the π^+ mesons have a characteristic decay pattern, which appears frequently in bubble chamber photos, and is shown below.

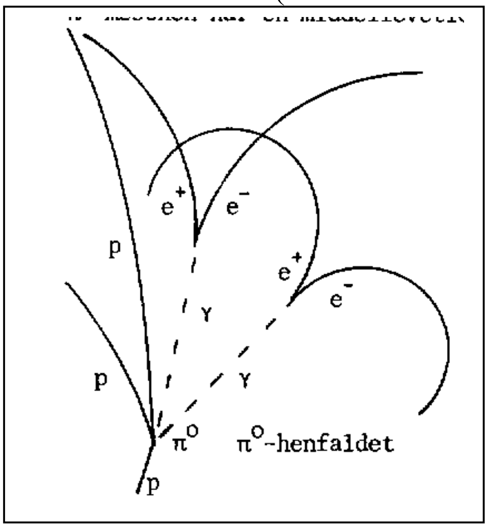


The decay shows the traces from three charged particles, separated by some cracks, indicating the emission of a neutral particle.
The π-meson is the lightest hadron, and therefore it cannot decay via strong interactions. Instead it decays through weak interactions to a myon (designated μ) and a neutrino of the μ-type.
The myon is a lepton, having a strong resemblance with the electron. The only difference is that the myon is 207 times heavier and that another type of neutrino is associated with it.
In the same manner as the electron e^- has an anti-particle e^+ the positron, the myon forms at charge doublet (μ^- , μ^+) .

The myon is not stable, but it decays into an electron (or positron) and two neutrinos.
The highly spiral formed traces in the bubble chamber always come from either electrons or positrons. The spiral form comes about, because of their very small mass, the electrons quickly loose energy by ionization. The decay of the π-meson can hereafter be written:

$$\pi^+ \to \mu^+ + \nu_\mu \quad \text{and} \quad \pi^- \to \mu^- + \bar{\nu}_\mu \qquad (\tau = 2.6\,10^{-8}\ s)$$
$$\pi^+ \to e^+ + \bar{\nu}_\mu + \nu_e \quad \text{and} \quad \pi^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad (\tau = 2.2\,10^{-6}\ s)$$

Having a mean life-time: $\tau = 2.6\,10^{-8}\ s$, and if the mesons move with the speed $0.1c$,the π^+ and π^- mesons make a trace of 78 cm in the bubble chamber.
Until the end of the seventies the only known leptons were the electron the myon and their associated neutrinos. For theoretical reasons there were speculations about a third lepton, the tau meson. Although there was indirect evidence from high energy collisions between electrons, the existence of the tau meson was not confirmed until 1995. The reason for that is partly its very large mass 1782 MeV/c^2. (The mass of the proton is 938 MeV/c^2).



On page 8 is shown a bubble chamber photo, which among other decays show the decay of the π^+ meson.
The neutral π^0 cannot bee seen directly, but it decays electromagnetically into two γ-quanta.
Since the electromagnetic interactions are much stronger than the weak, the decay time is much less, about 2 10^{-16} s. In a bubble chamber photo that means that it decays in the same place, where it is created, since even if it moved with the speed of light, it can only move an atomic diameter in its lifetime. The decay of π^0 is illustrated in the figure to the left.
The decay can however be observed indirectly if one or both of the γ-quanta, collide with a nucleus resulting in the creation of one or even two e^+, e^- pairs.
The illustration above shows an incoming proton hitting a proton at rest and creating a π^0, and the two protons from the collision. Followed by the two γ, each hitting a proton creating a e^+, e^- pair, where the peak is pointing to the point of creation.
Bubble chamber pictures with two e^+, e^- pairs are quite rare, but important, since they can be used to a precise determination of the rest mass of the π^0-meson.

3. Baryon resonances

The relation between the energy of a particle, its momentum $\vec{p}$, and the rest mass m_0 is given by the relativistic equation:

(3.1) $$E^2 - p^2c^2 = m_0^{\ 2}c^4$$

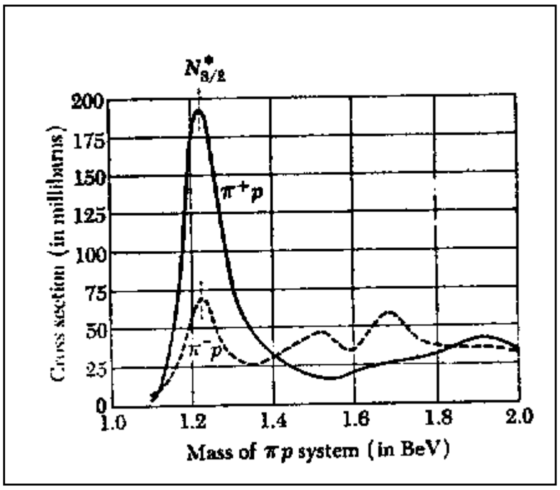
If an unstable particle decays into two particles, we have conservation of energy and momentum.

$$E = E_1 + E_2 \qquad \text{and} \qquad \vec{p} = \vec{p}_1 + \vec{p}_2$$

If it is possible to measure the energies and the momentums of the decay particles the rest mass of the decaying particle M_0 can be calculated from (3.1): $(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = M_0^{\ 2}c^4$.
The momentum of a charged particle can be determined from a bubble chamber photo, where the radius in circular motion is determined. Since the magnetic field is known, then the momentum may be determined by the usual formula: $mv = qBr$. In general one has to apply the relativistic mass *m*.
If the particle is identified by its mass and charge, then the energy can be found from (3.1).

One may for the pion production processes on the preceding page calculate the relativistic invariant mass of the nucleon-pion system in the final state according to (3.1).

(3.2) $$M_{N\pi}c^2 = \sqrt{E^2 - \vec{p}^2c^2} = \sqrt{(E_N + E_\pi)^2 - (\vec{p}_N^{\ 2} + \vec{p}_\pi^{\ 2})c^2}$$



Doing this, one will find that some rest masses *M* of the ($N\pi$) system are far more frequent than others. Thus if we map the number of ($N\pi$) pairs as a function of their relativistic invariant mass, you will se some characteristic peaks, as shown in the figure to the left. The peaks are called resonances. The most prominent resonance is observed at an invariant mass of 1258 *MeV*, both in the π^+p and the π^-p system. It is also observed in all other systems of a pion and a nucleon. They can not be observed directly, since they involve at least one neutral particle π_0 or *n*.
Apart from the fact that these resonances are unstable and decay via strong interactions in about 10^{-23} s, and leave no trace in a bubble chamber, they have all the properties that characterize an elementary particle, that is, a mass, and the quantum numbers charge, spin, parity and iso-spin.
(We have not yet introduced the last two quantum numbers).
It becomes therefore natural, from a theoretical point of view, to consider them as elementary particles on equal foot with the already known particles. For one reason that they must be a part of a field theoretical description of the strong interactions. The reason why they are unstable is, that there exists to hadrons $N\pi$, that together have a lesser mass, so they can decay to that system via strong interactions.
The $N\pi$ resonance at 1238 *MeV* is called for $N_{\frac{3}{2}}^*$. It is a baryon having spin $\frac{3}{2}$.
Since the 1238 *MeV* resonance appears in all combinations of a $N\pi$ pair it can have four different charges: $N_{\frac{3}{2}}^{*++}(\pi^+p)$, $N_{\frac{3}{2}}^{*+}(\pi^+n\ \ or\ \ \pi^0p)$, $N_{\frac{3}{2}}^{*0}(\pi^0n\ \ or\ \ \pi^-p)$, $N_{\frac{3}{2}}^{*-}(\pi^-n)$.
As it is shown in the figure the 1238 resonance has a certain width. This width could be ascribed to the uncertainty in the determination of the mass. But this is actually not the case.
The $N_{\frac{3}{2}}^*$ has namely a lifetime about 10^{-23} *s*, and according to Heisenberg's uncertainty principle the fluctuation in energy is determined by this relation. So for the lifetime Δt of a resonance, the uncertainty in energy is given by the uncertainty relation:

$$\Delta E \Delta t > h$$

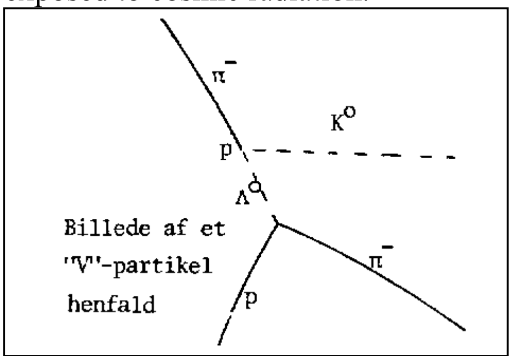
The uncertainty in mass is mostly estimated by the half width of resonance peak. The half width is denoted Γ. We have thus: $\Gamma = \Delta E = \Delta mc^2$.
Reading the half width from the resonance peak, we find $\Gamma = 120\ MeV$.
This value can then be inserted in Heisenberg's uncertainty to find the mean life time.

(3.5) $$\Gamma = \Delta E = \Lambda mc^2 \quad \wedge \quad \tau = \frac{h}{\Delta E} \quad \Rightarrow \quad \tau = \frac{4.15\,10^{-15}\,eVs}{120\,10^{6}\ eV} = 3.5\,10^{-23}\,s$$

The very short life-time 10^{-23} s for the resonance $N_{\frac{3}{2}}^{*}$ (1238) is characteristic for the resonances which decay via strong interactions.
On the other hand, a particle which live long enough to draw a trace in a bubble chamber, must be stable against decay via electromagnetic and strong interactions. They decay then via the weak interactions.
Right from the first generation of the large particle accelerators in the sixties, an abundance of particles has been found. These may in principle also be considered as elementary particles even if they are not stable.
However over 100 elementary particles are theoretically not palatable. This jumble of particles shows however to fit into a larger system of families with similar properties.
We shall return to this issue, when we have introduced another group of new particles.

4. Strange particles

In 1947 were discovered some V-shaped traces in photos from a cloud-chamber, which had been exposed to cosmic radiation.



In the figure to the left is schematically shown such an event. Placed in a magnetic field, it is seen that the V-shaped traces must be two particles with opposite charge, since they bend opposite. The V, can therefore be interpreted as the "trace" of a neutral particle (that cannot bee seen), which decays into two charged particles.
A further investigation showed that the two particles were a proton and a negative pion π^-. Since no known hadron could behave like this, it had to be a new unknown particle.
The new hypothetical particle was called Λ^0, and the decay can be written.

(4.1) $$\Lambda^0 = p + \pi^-$$

The discovery of the Λ_0 initiated the discovery of a series of new particles, which decays to nucleons, pions, myons and electrons $(p, n, \pi^+, \pi^-, \mu^+, \mu^-, e^+, e^-)$.
As examples of the new particles, we can mention: The K-mesons (K^+, K^-, K^0) and the Σ-hyperon $(\Sigma^+, \Sigma^-, \Sigma^0)$. These particles may decay in several different ways, from which some of the possibilities are:

(4.2) $$K^+ \to \pi^+ + \pi^0 \qquad K^0 \to \pi^+ + \pi^0 + \pi^-$$

(4.3) $$\Sigma^- \to \pi^- + n \qquad \Sigma^0 \to \Lambda_0 + \gamma$$

In contrast to the $N^*_{\frac{3}{2}}$ (1238) (having a life-time of about 10^{-23} *s*) the new particle are characterized by a relatively long life-time ($10^{-10} - 10^{-8}$ *s*), a life-time that enables us to see their trace (for the charged ones) in a bubble chamber.
Life times of this length are characteristic for particles decaying caused by the weak interactions!
Since the shown decays (except for the Σ^0, which decays electromagnetically), decays into hadrons, it is from the hitherto experiences inexplicable why the new particle Λ^0 did not decay caused by the strong interactions. The only explanation is that something forbids it to decay caused by strong interactions.
Such forbidden decays are in quantum physics related to the conservation of a quantum number. This quantum number must then be conserved by the strong interactions, but is broken by the weak interactions.
Because of the unusual decay pattern the new particles were named: “Strange particles”.

Following the building of the big accelerations in the sixties, it was possible to produce strange particles in the laboratories and observe them in a bubble chamber.

It showed up that reactions op the type $\pi^- + p \rightarrow \Lambda_0$ (which is the inverse to the decay of Λ_0) were never seen, and they were therefore considered impossible.

But the experiments also showed that the strange particles were always produced pair wise in an interaction between two non strange particles.
In the bubble chamber photo on the next page is shown a typical example of such an associated production.
A π^- meson hits a proton and two neutral particles are produced. The decays of both particles can be seen on the photo. The two neutral particles are hereafter identified as Λ_0 and K^0.

The long life time of the strange particles, and their associated production, caused the American physicist M. Gell-Mann to postulate the existence of a new quantum number, which he named *strangeness*, and denoted *S.* Strangeness is conserved by the strong and the electromagnetic interactions, but not by the weak interactions.

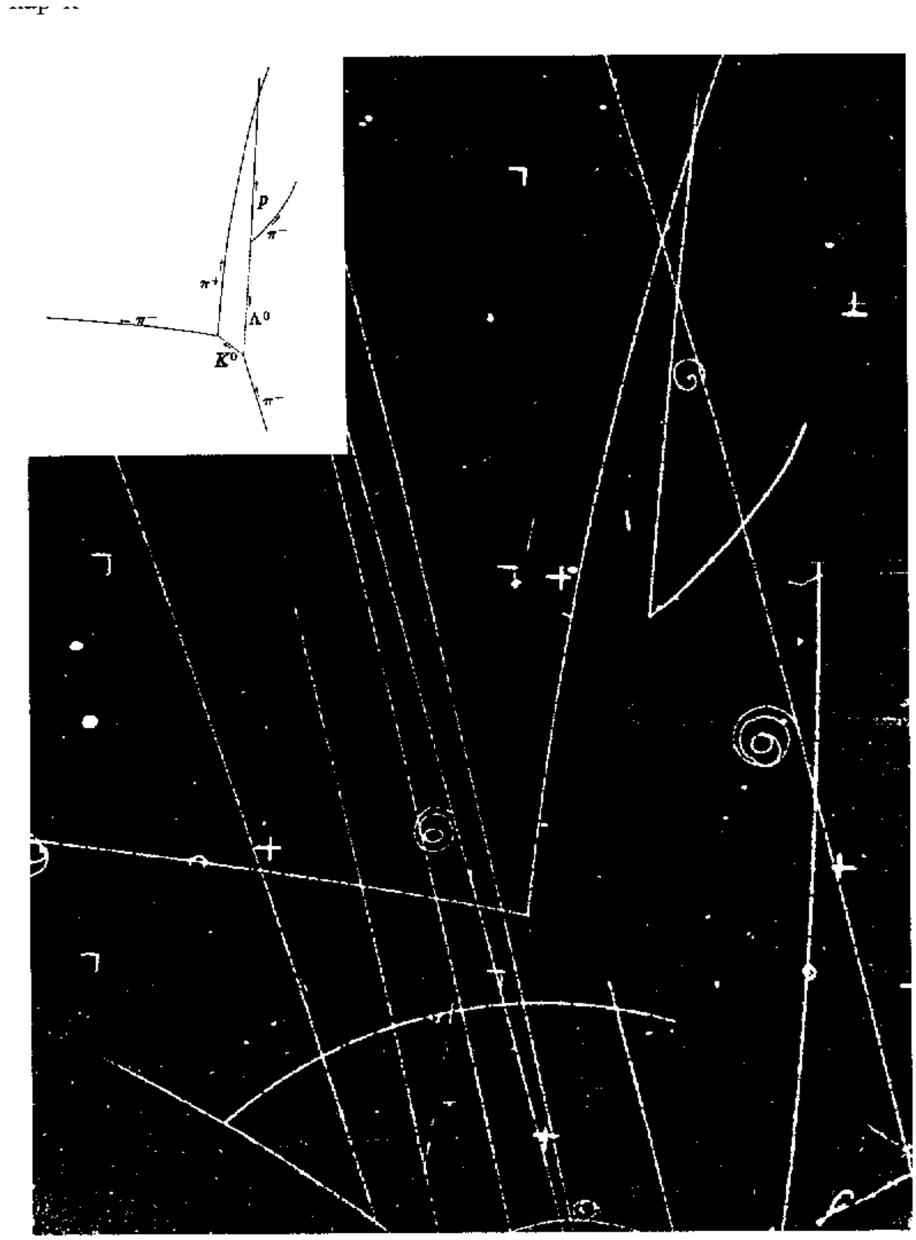
This explains in a simple manner, why the strange particles (having $S = 1$ *or* $S = -1$) cannot decay via the strong interactions to hadrons e.g. $\pi^- + p$, since both have $S = 0$.
The conservation of strangeness also explains the associated production of strange particles.

If a proton *p* is hit by a π^--meson, then $S = 0$ in the initial state. The conservation of strangeness, therefore requires that together with a particle with strangeness $S = -1$, (the Λ_0 hyperon), is produced a particle with $S = +1$ (the K^0-meson). See the figure on the next page.

5. The quantum numbers of the elementary particles

An elementary particle is characterized by its mass and perhaps by its resonance width Γ, together with a series of so called internal quantum numbers. From the internal quantum numbers, we already know: Charge *Q*, spin *s*, baryon number *B* and strangeness *S.*

We shall now introduce another pair of quantum numbers, which have only significance in the world of elementary particles.



Bubble-chamber picture showing the following reactions:

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

1) **Parity.** A quantum mechanical system which is described by a coordinate function of state ψ, may be even: $\psi(-\vec{x}) = \psi(\vec{x})$ or odd $\psi(-\vec{x}) = -\psi(\vec{x})$. In the first case the system is said to have the parity *P* = +1, and in the second case the parity *P* = -1. As the product of an even function and a odd function is odd, and the product of two odd functions is even, we find the parity of a composite system as the products of the single particles parity.

When it is also possible to ascribe *parity* to a single elementary particle, it is based on that most elementary particle are unstable, and decay to a composite system of particles. The composite system can be ascribed a parity as the product of the parity of the single particles, and hereby the parity of the decaying particle can be found. From such experiments it has been found that:

If the decay is caused by the electromagnetic or strong interactions the parity quantum number is conserved.

A system with even parity is said to have mirror symmetry. Since we must assume that nature does not distinguish between left and right, then theoretically the conservation of parity can be shown to be a consequence of mirror symmetry.

Therefore we should expect that corresponding to a particle with parity $P = +1$, there should exists a particle with parity $P = -1$. But this is, as we shall see, exactly the case with the so called anti-particle, where charge and all the other internal quantum numbers are reversed.

However, experiments done in the fifties have revealed the surprising fact about the weak interactions, that they sometimes break parity. So it seems that the weak interactions have a built in left-right orientation.

2) **Isospin**: It is an experimental experience that the strong interactions between two nuclei are independent of whether the nuclei are protons or neutrons. What concerns the strong interactions the proton and neutron are identical particles.
Analogous to the atom with a definite energy, having an angular momentum L, the angular momentum has $2L+1$ possible projections on a z-axis. When the atom is placed in a magnetic field, however, the degeneration of the energy states are separated. The physicist Heisenberg suggested that the proton and the neutron,(as far as the strong interactions are concerned), can be perceived as two charge-states of the same particle the nucleon.
In the same manner as a spin $\frac{1}{2}$ particle has two states (spin-up $+\frac{1}{2}$ and spin-down $-\frac{1}{2}$), Heisenberg suggested that the proton and the neutron were two charge state of the same particle, the nucleon.

To describe this formally Heisenberg invented the concept of isospin T.
The nucleon has isospin $\frac{1}{2}$, and there are $2\cdot\frac{1}{2}+1=2$ states of the nucleon, namely the proton, which has iso-spin $T_3 = +\frac{1}{2}$, and the neutron which has iso-spin $T_3 = -\frac{1}{2}$.
The two states are only separated by their charge and their mass.

It might be difficult to comprehend the significance of the concept of iso-spin, but one of the consequences is that isospin can be added as ordinary spin. Thus two nucleons may form a charge triplet with isospin $T = 1$ (*pp, np, nn*) $T_3 = (1, 0, -1)$ or a charge singlet with $T = 0$ (np).
On may continue to form more complicated iso-spin states.

The charge independence of the strong interactions can be explicated in a manner that nucleons with the same iso-spin T (but with different T_3, that is, charge) are identical, against the strong interactions, and that they can only be distinguished by the electromagnetic interactions. So:

The iso-spin is conserved in processes caused by the strong interactions.

On the other hand, the iso-spin is not a conserved by the electromagnetic or the weak interactions. The projection of the iso-spin on the 3-axis is however always conserved, since it is equal to the charge of the system..

The iso-spin is only defined for particles having strong interactions.

The π-meson is the lightest meson. It has spin $s = 0$ and parity $P = -1$. The π-meson has iso-spin $T = 1$ and the $2T + 1 = 3$ states of charge form a iso-spin triplet (π^-, π^0, π^+). The π-meson has strangeness $S = 0$, and baryon number $B = 0$.

Bubble-chamber picture showing the following reactions:

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

$$\Sigma^- \rightarrow \pi^- + n$$

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

$$\quad \hookrightarrow \mu^+ + \nu$$

$$\qquad \hookrightarrow e^+ + \nu + \bar{\nu}$$

The Σ-hypereron is a baryon with iso-spin $T = 1$, and it has therefore $2T + 1$ charge states $(\Sigma^-, \Sigma^0, \Sigma^+)$. It is a spin $s = \frac{1}{2}$ particle with parity $P = +1$. The Σ-hypereron has strangeness $S = -1$. It can be produced in the reaction $\pi^- + p \to \Sigma^- + K^+$. The production is shown in the bubble chamber photo above. In the photo is also seen the decay of Σ^-, K^+ and the π, μ, e decay.

The Λ-hyperon is a baryon with iso-spin 0. (iso-singlet). It has spin $s = \frac{1}{2}$ and parity $P = +1$.
It has strangeness $S = -1$. It can be produced in the reaction: $\pi^- + p \to \Lambda^0 + K^0$. The decay of the Λ-hypereron: $\Lambda \to p + \pi^-$**,** is a weak decay, so neither strangeness S nor iso-spin are conserved. The decay products $\pi^- p$ both have strangeness $S = 0$, and their iso-spin $T = 1$ and $T = \frac{1}{2}$ cannot be combined to give $T = 0$.

The K-meson has iso-spin $T = \frac{1}{2}$. This iso-spin doublet has strangeness $S = +1$. The negative K meson K^- is the anti-particle to K^+. K^0 has also an anti-particle which is designated $\overline{K}^0$. $\overline{K}^0$ is distinguished from K^0 , having strangeness $S = -1$. $K^0, \overline{K}^0$ also form a iso-spin doublet. The masses of the K-mesons are about 800 MeV.

The Ξ-hyperon is also called the cascade particle. It is a spin $s = \frac{1}{2}$ baryon, with iso-spin $\frac{1}{2}$ and is therefore a charge doublet (Ξ^-, Ξ^0). The Ξ - hyperon has strangeness $S = -2$.
It can be produced in the reaction:

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

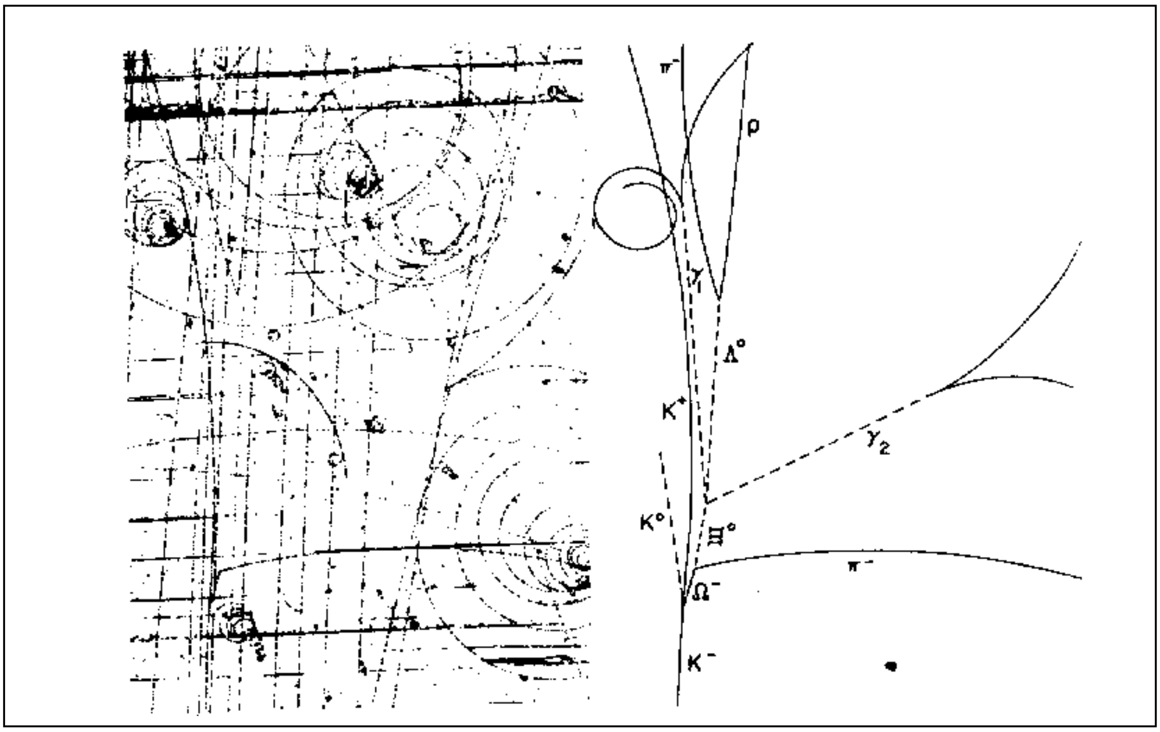
Strangeness: $S = -1 + \ 0 = \ -2 \ + 1 \qquad S = -1 + \ 0 \ = \ -2 + \ 1$

The Ξ-hyperon with mass 1320 MeV is the most massive of the hyperons mentioned until now. The mass is, however, not sufficient for it to decay into two strange particles (K, Λ), and it decays therefore weak into (π, Λ).

$$\begin{array}{ll} \Xi^- \to \pi^- + \Lambda & \qquad \Xi^0 \to \pi^0 + \Lambda \\ \qquad\qquad\quad \downarrow & \qquad\qquad\qquad \downarrow \\ \qquad\qquad \pi^- + p & \qquad\qquad\quad \pi^- + p \end{array}$$

Since strangeness is not conserved in the decay of the The Ξ-hyperon, it decays via the weak interactions, and the lifetime of the Ξ^-- hyperon is long enough to see its trace in a bubble chamber.

The Ω^- hyperon is together with the other particles mentioned the only one which is stable against the strong interactions. Ω^- is a baryon with a spin $s = \frac{3}{2}$. In spite of its large mass (1675 MeV) it is stable because of its strangeness $S = -3$. is interesting because its existence was theoretically predicted, before it was observed in a bubble chamber photo in 1964.
Below is shown a bubble chamber photo, which is interpreted as production and decay of a Ω^-.



The part of the bubble chamber photo that concerns the Ω^- is sketched to the right. The sequence is:

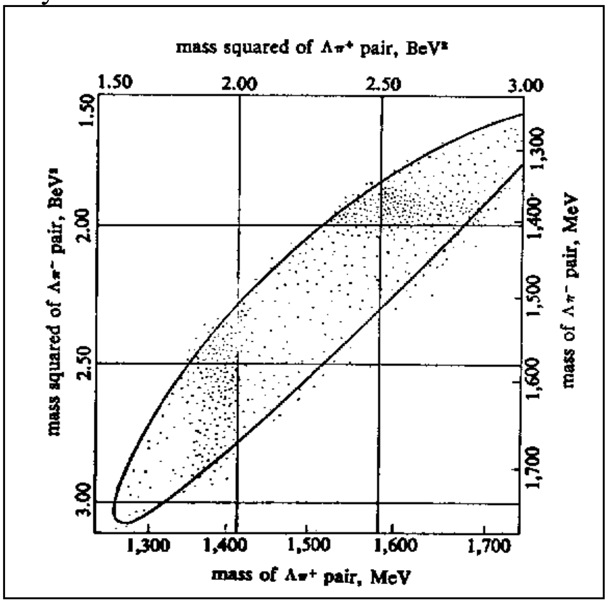
$$K^{'-} + p \to \Omega^- + K^+ + K^0$$
$$\Omega^- \to \Xi^0 + \pi^-$$
$$\Xi^0 \to \Lambda + \pi^0 + \gamma + \gamma \quad (\gamma \to e^+ + e^-)\ (\gamma \to e^+ + e^-)$$
$$\Lambda \to \pi^- + p$$

Notice that the strangeness must be conserved in the production process, and since S = -1 before the production, the production of two K-mesons with S = +1 is necessary.
The photo is also remarkable, because both of the produced gamma-particles produce an $e^+ e^-$ pair, a so called Dalitz-pair.
The verification of the existence of the Ω^- had a great impact on the confidence of the SU_3 symmetry of the hadrons, a theoretical approach we shall discuss later.

Besides the particles, which are stable against strong interactions over 100 so called resonances have been found. The resonances have well defined quantum numbers, but they are not stable against strong interactions, and therefore they have life-times of the order of 10^{-23} s.

Their short life-time excludes that they can be observed directly in a bubble chamber, but they show up as a peak in the invariant mass of the decay products. This has already been discussed, when we mentioned the N^* resonance on page 5.
The N^* resonance has spin $s = \frac{3}{2}$, parity P = +1. It has iso-spin $T = \frac{3}{2}$, and is therefore found in $2T$+1 = 4 charge states (N^{*++}, N^{*+}, N^{*0}, N^{*-}), which is in accordance with the fact that N^* is a pi-nucleon resonance (iso-spin 1 and $\frac{1}{2}$). They can couple to iso-spin T= $\frac{3}{2}$ and iso-spin $T = \frac{1}{2}$, and

iso-spin is conserved in strong interactions. N^* has strangeness S = 0, the same as the pi-nucleon system.



Corresponding to the N^*(1238) resonance in the πp or πn system, there are resonances in the $\pi\Lambda$ system, and they are called Y^*. The resonance is seen in the reaction:

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

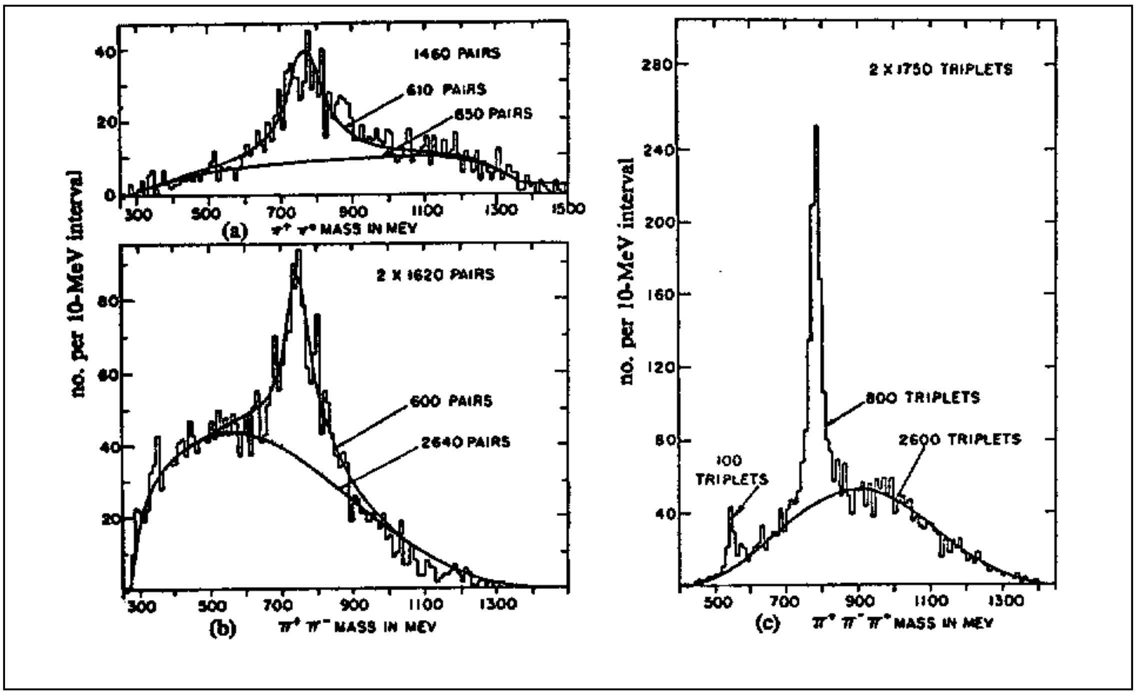
If we for every event calculate the square of the invariant mass of $\pi^+\Lambda$ *and* $\pi^+\Lambda$, you may plot it as a point in a $M^2(\pi^+\Lambda)$, $M^2(\pi^-\Lambda)$ diagram. This is a so called Dalitz plot, as shown in the figure to the left. It is seen that the points have a strong concentration around a mass of 1385 *MeV* both in the $\pi^-\Lambda$ and the $\pi^+\Lambda$ system.
The distribution of points in the Dalitz plot suggests that the process goes like one of the possibilities shown below.

$$K^- + p \rightarrow Y^{*+} + \pi^- \qquad K^- + p \rightarrow Y^{*-} + \pi^-$$
$$Y^{*+} \rightarrow \Lambda + \pi^+ \qquad Y^{*-} \rightarrow \Lambda + \pi^-$$

So Y^* (1385) must be a resonance with strangeness S = -1. Since the iso-spin is conserved in the strong interaction decay $Y^* \rightarrow \Lambda + \pi$, then Y^* must have T = 1, since $T_\Lambda = 0$ *and* $T_\pi = 1$.
As the Dalitz plot also shows, the Y^* has the resonance width 47 *MeV*. It has the same spin $s = \frac{3}{2}$ as the N^* and the Ω^-, positive parity. It therefore belongs to the same SU_3 family as these particles.
It appears in three charge states. (Y^{*-}, Y^{*0}, Y^{*+}),

Correspondingly we find a resonance in the $\pi\Xi$ system, which is denoted $\Xi^*(1530)$. Like the resonance Y^* it has the spin $s = \frac{3}{2}$. It has iso-spin $T = \frac{1}{2}$, and is therefore found in two charge states (Ξ^{*-}, Ξ^{*+}). It has strangeness S = -2, and it decays according the schema: $\Xi^* \rightarrow \Xi + \pi$.

Also the mesons have prominent resonances:



The diagrams above are based on reactions, where a π-meson hits a proton *p*, and where one, two or three new π-mesons in the final state.
Figure a) is made on the basis of the reaction $\pi^+ + p \to \pi^+ + \pi^0 + p$, and for each event is calculated the invariant mass of the (π^+ π^-) system. It is seen that *M* (π^+ π^0) has a nice peak about 700 *MeV*, with a resonance width Γ = 112 *MeV*. This resonance is called the **ρ^+-meson**.
Figure b) is the result from the reaction:

$$\pi^+ + p \to \pi^+ + \pi^+ + \pi^- + p$$

Plotting the invariant mass *M* (π^+ π^-), we again find a peak at 700 *MeV*.
This resonance is interpreted as another charge state of the ρ-meson.
Since the ρ-meson decays into two π-mesons, both having iso-spin *T* = 1, then the ρ-meson may have iso-spin *T* = 0, 1 or 2. *T* = 2, however, would imply the existence of double charged mesons, but they have never been observed, so the ρ-meson must have iso-spin *T* = 1. It is found in three charge states: (ρ^-, ρ^0, ρ^+). The most common decays of the ρ-meson is:

$$\rho^+ \to \pi^+ + \pi^0 \qquad \rho^0 \to \pi^+ + \pi^- \qquad \rho^- \to \pi^- + \pi^0$$

When studying the angular distribution of the π-mesons, one may conclude that the meson has spin *s* = 1. It is therefore called a vector meson. Figure c) is data from the reaction:

$$\pi^+ + p \to \pi^+ + \pi^+ + \pi^0 + \pi^- + p\,.$$

In this figure has been evaluated the invariant mass *M* (π^+, π^-, π^0), and the figure shows a prominent peak at 783 *MeV*. This meson is called the **ω-meson**.
The ω-meson has *T* = 0 (an iso-spin singlet). It belongs to the vector mesons, so it has spin *s* = 1, and parity *P* = -1, The ω-meson has a remarkably narrow resonance width, only about 10 *MeV*.

The other somewhat lesser peak, have centre around a mass of 549 *MeV*, with a resonance width under 10 *MeV*. This resonance is called the **η-meson.** The η-meson is like the ω-meson an iso-spin singlet ($T = 0$). It has spin $s = 0$, parity $P = -1$, and it belongs to the same SU_3 family as the π-mesons.
We shall end this section with a survey over, how the quantum numbers "behave" (conserved, not conserved) against reactions with one of the three interactions.

Interaction	**weak**	**electromagnetic**	**strong**
Charge *Q*	conserved	conserved	conserved
Baryon number	conserved	conserved	conserved
Lepton number	conserved	conserved	conserved
Isospin *T*	not conserved	not conserved	conserved
Parity P	not conserved	conserved	conserved
Strangeness *S*	not conserved	conserved	conserved

A survey over the most prominent elementary particles is found on page ….

6. Particles and anti-particles

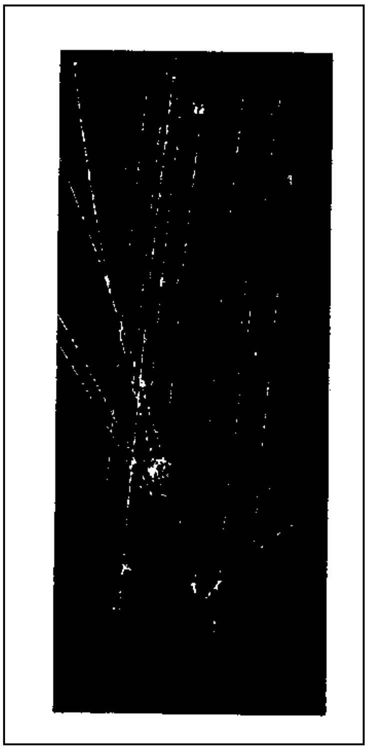
The British physicist P.A.M. Dirac predicted in 1932 the existence of a positive electron the *positron*. Shortly afterwards the positron was found in the cosmic radiation by Anderson.
The positron is identical to the electron, apart from the fact that the "internal quantum numbers" *charge* and *lepton number* have changed sign. The positron has charge $+e$ and lepton number -1. The positron is called the anti-particle to the electron.

An anti-particle can be defined as identical to the particle, but where all the internal quantum numbers have changed sign.

According to the conservation laws, then a particle anti-particle pair can be created from vacuum. The only condition is that the sufficient energy is present. Such a pair creation, we already know from the Dalitz pairs, where an energetic photon (E_γ > 1.022 *MeV*) near a nucleus is converted to a (e^+,e^-) pair.

After the discovery of the positron it was obvious to seek for antiparticles to other particles e.g. the baryons. The conservation of baryon number requires, however, that together with the creation of an anti-baryon, is always created a baryon. An anti-proton may for example be created in the reaction:

(6.1) $$p + p \rightarrow p + p + \overline{p} + p$$



In the example (6.3) below it is shown that the creation of a proton - antiproton pair requires an energy at least 5.6 *GeV* of the incoming proton. Not until 1955 such an accelerator was available (the betatron in Berkeley) .
Shortly after the accelerator was brought into function, the first anti-protons were observed. The anti-proton is a negatively charged particle with the same mass as the proton.
Characteristic for all particle-antiparticle pairs are that the can annihilate. For the proton antiproton pair the annihilation goes to π mesons. In the annihilation is formed a characteristic star of equal numbers of π mesons.
In the bubble chamber photo to the left is shown a proton anti-proton annihilation in 4 π^+ and 4 π^- mesons, and possibly also some π^0, (but they are not seen)
The bubble chamber photo on the next page is an excellent demonstration of the particle – antiparticle symmetry.
An anti-proton hits a proton, and a pair of hyperon – anti-hyperon is created. The photo shows both the decay of the Λ and the $\overline{\Lambda}$, together with the annihilation of the antiproton from the $\overline{\Lambda}$ -decay

$$\Lambda \to p + \pi^- \qquad \overline{\Lambda} \to \overline{p} + \pi^+$$

6.3 Example. We shall now calculate the necessary energy an incoming proton must have in a proto-proton collision to create a proton-antiproton pair. To ease the calculations we put the speed of light $c = 1$.
Several times, we shall use the relation:

$$E^2 - p^2c^2 = m_0^{\ 2}c^4 \text{ . With the convention } c = 1 \text{ it reads: } E^2 - p^2 = m_0^{\ 2}$$

We shall then find the threshold energy, that an accelerated proton must have to generate the process:
$p + p \to p + p + \overline{p} + p$. If the relativistic energies of the accelerated proton and the proton at rest are E_1 and E_2 and their momentums $\overline{p}_1$ and $\overline{p}_2$, one may calculate the invariant mass of the system as:

$$(E_1 + E_2) - (\vec{p}_1 + \vec{p}_2)^2 = M_0^{\ 2}$$

Obviously one must claim that the invariant mass must be greater than 4 proton masses to make the process possible. M_0 corresponds to the relative energy of the incoming protons, which is equal to their energy in an inertial system, which follows the centre of mass of the two protons. In the laboratory system, we have:

$$E_1 = E_{lab} \quad , \quad E_2 = m_p \quad , \quad p_1 = p_{lab} \quad , \quad p_2 = 0 \, .$$

Obviously we shall determine E_{lab} by the inequality:

$$(E_{lab} + m_p)^2 - p_{lab}^2 \geq 16 m_p^2$$

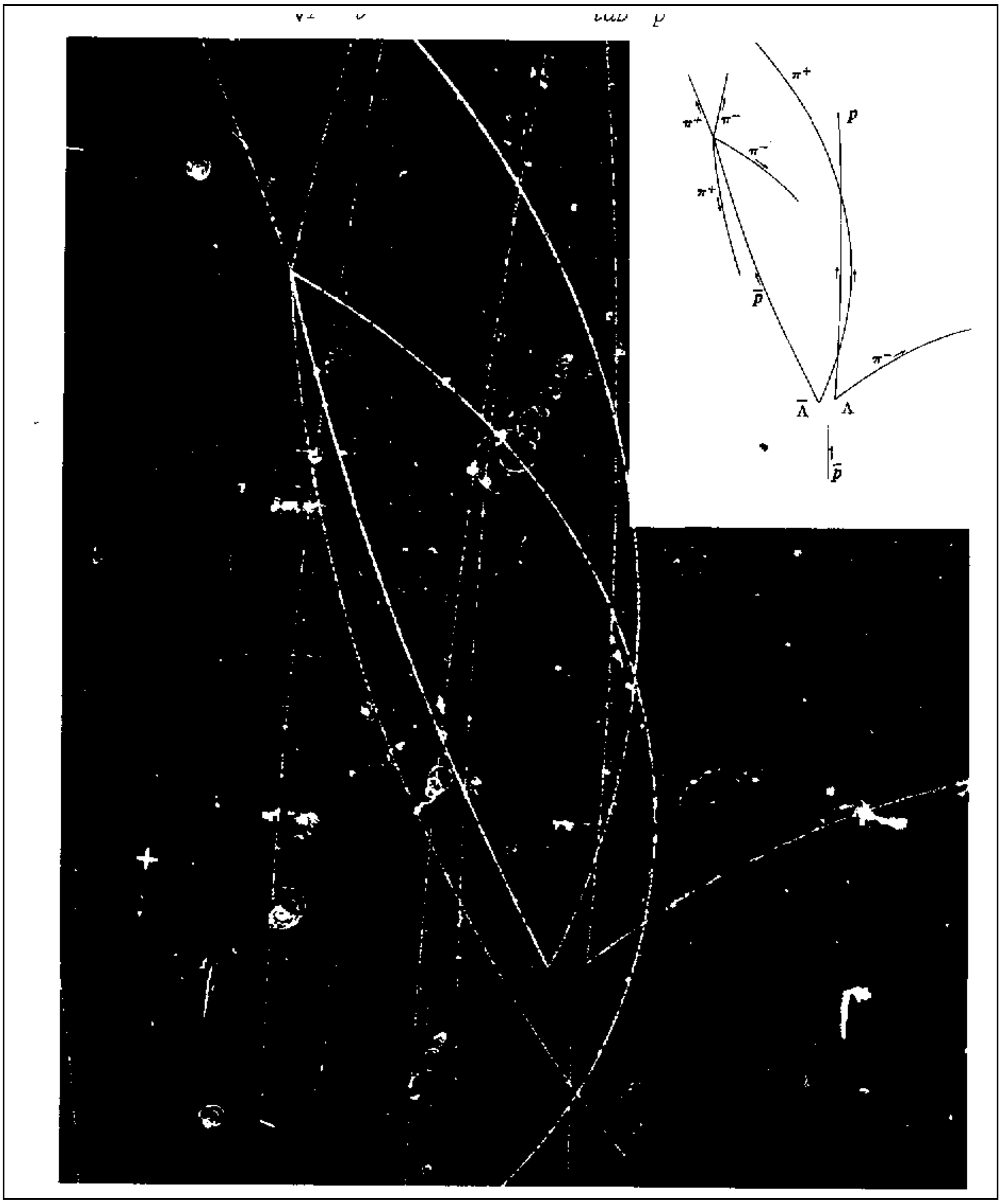
If we use $E_{lab}^{\ \ 2} - p_{lab}^{\ \ 2} = m_p^{\ 2}$ to eliminate $p_{lab}^{\ \ 2}$, we get:

$$E_{lab}{}^2 + m_p{}^2 + 2m_pE_{lab} - E_{lab}{}^2 + m_p{}^2 p_{lab}{}^2 + m_p{}^2 \geq 16m_p^2 \quad \Leftrightarrow$$
$$2m_pE_{lab} \geq 14m_p^2 \quad \Leftrightarrow \quad E_{lab} \geq 7m_p$$

Since the mass of the proton is 938 *MeV*, we find the threshold energy $E_{lab} \geq 6566\ MeV$. This again corresponds to a kinetic energy: $E_{kin} = E_{lab} - m_p = 5628\ MeV$.
The velocity of the incoming proton under these circumstances, can be calculated from the formula:

$$E_{lab} = \frac{m_p}{\sqrt{1-v^2}} \quad \Rightarrow \quad v = \frac{\sqrt{(E_{lab}/m_p)^2 - 1}}{E_{lab}/m_p} \quad \Rightarrow \quad v = 0.984\, c$$

Bubble chamber photo showing an annihilation of a proton and an antiproton into to a Λ and a $\overline{\Lambda}$ hyperon together with their decay.



The anti-particles of the baryons have the same mass, spin and life-time as the particles themselves. Using Heisenberg's uncertainty relation $\Delta E \Delta t \geq h$, one may find the relation between the mean life-time of a particle τ, and the resonance width Γ: $\tau = \dfrac{h}{\Gamma c^2}$.

7. Symmetries in particle physics

The name "elementary particle" is really reserved to denote the fundamental building blocks of the atoms. It is therefore a somewhat unsatisfactory situation when the number of elementary particles has grown to more than 200, and from where the main part are hadrons.
The only known leptons were until 1978 the electron and the myon with their associated neutrinos. The mystery of the myon has been cleared after the discovery in 1978 of yet another super-heavy lepton, the τ-meson.

In a certain sense there has been made up for the vast number of "elementary particles", since it has been realized that the baryons and mesons can be collected in symmetry groups, where the particles are almost "equal". These groups of particles are called "the eightfold way".

We have already discussed these symmetry properties, when we introduced the concept of iso-spin. The iso-spin represents an abstract mathematical description of the fact that the strong interactions are charge independent. So when it concerns the strong interactions the proton and the neutron are identical particles. The same applies for (π^-, π^0, π^+), $(\Sigma^-, \Sigma^0, \Sigma^+)$ and (Ξ^-, Ξ^0).
The charge independence of the strong interaction is denoted iso-spin invariance, and as mentioned several times, the iso-spin is a conserved quantum number in strong interactions.

It belongs to one of the deep theorems in physics that there is a one to one correspondence between an "invariance against a transformation" and a conserved quantum number.
For example it is shown in the analytical mechanics that "translation invariance" implies conservation of momentum, and "rotational invariance" implies conservation of angular momentum. Similarly, (but more abstract) charge invariance implies conservation of iso-spin.

So after the discovery of the conserved quantum number strangeness *S*, it seemed natural (from a theoretical point of view) to seek for a mathematical description of the underlying invariance.

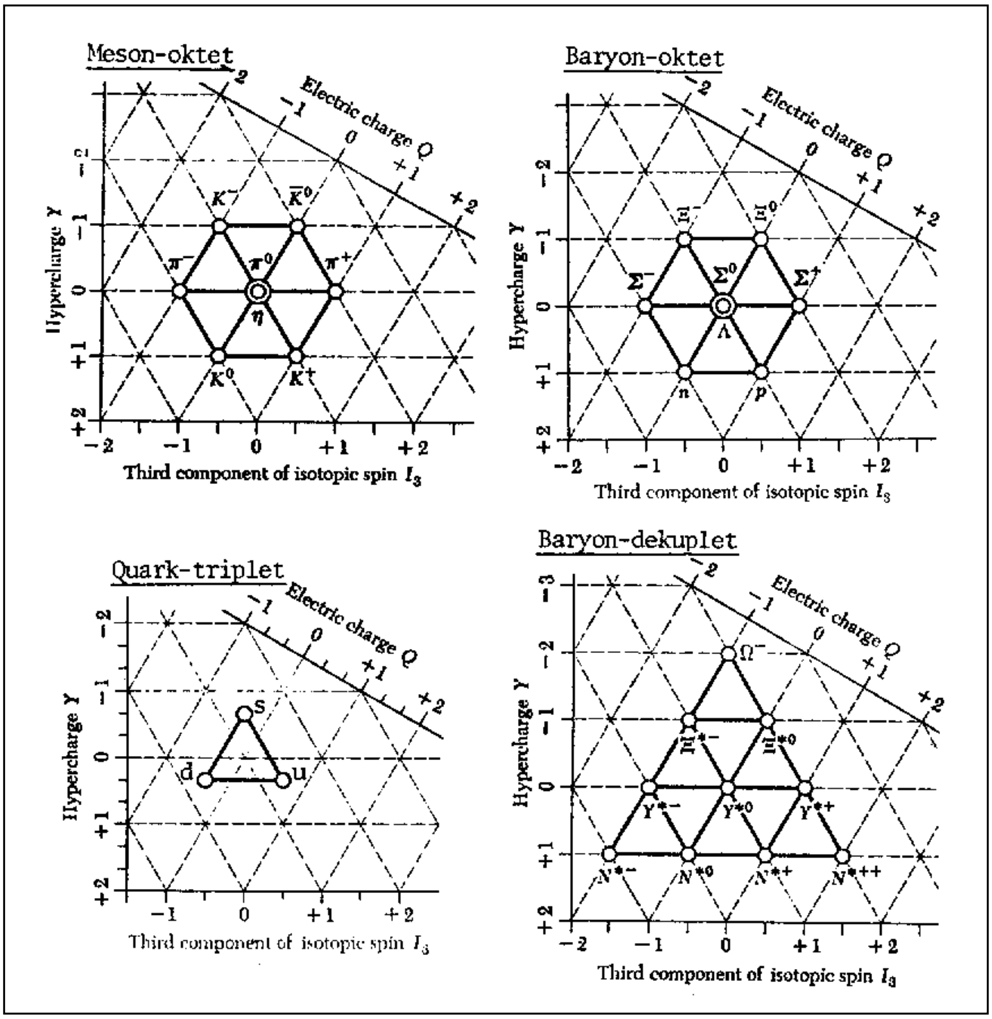
It turns out that group theory is the framework in which such a description can be formulated.
The isospin invariance can be formulated in the theoretical framework of the group SU_2, and isospin and strangeness together can be formulated in the theoretical framework of the group SU_3, called "The eightfold way".

In 1962 the two physicists M. Gell-Mann and Y. Ne'eman showed that the strong interactions had a built in SU_3 symmetry, that implied the invariance of iso-spin *T* and strangeness *S*.
As a consequence of the group theoretical framework they could predict the symmetry patterns of the strongly interacting particles.

It was therefore an experimental challenge to verify that the existing particles actually fitted in these SU_3 symmetry patterns. That this is actually the case is demonstrated in the figures below.

Notice, however, that instead of the strangeness *S*, the plots use the hypercharge $Y = B + S$.

In the figure on the top to the right is shown the baryon octet. It consists of (Ξ^-,Ξ^0), $(\Sigma^-,\Sigma^0,\Sigma^+)$, (Λ) and (n, p), and it is remarkable that the known baryons with spin s = ½, and parity P = -1 fit exactly into the octet.
On the top to the left, it is shown how the known mesons with spin s = 0, and parity P = +1 also fit nicely into a meson-octet.

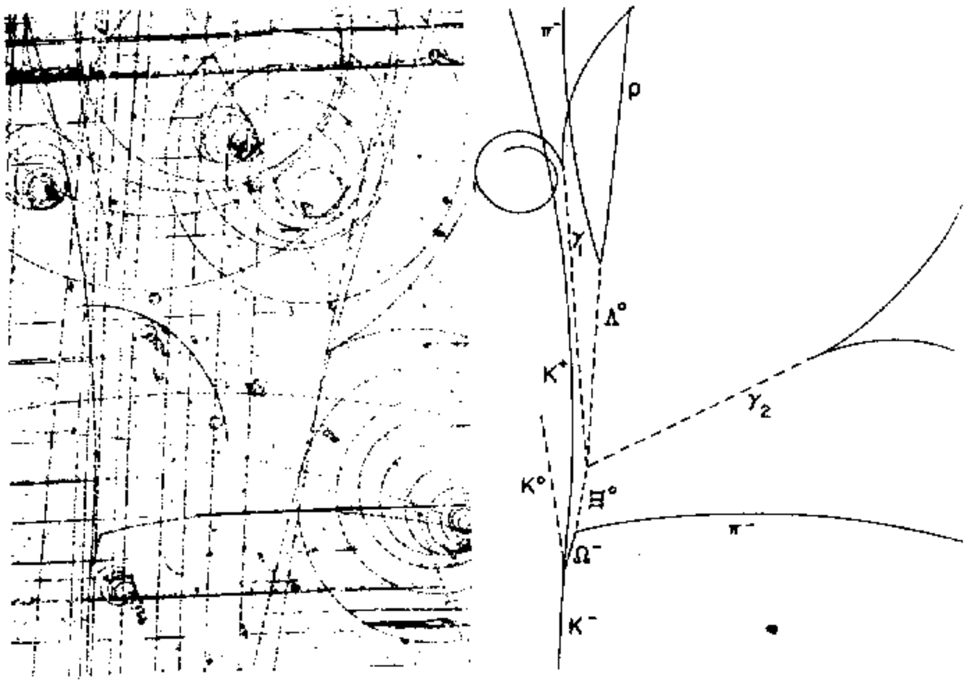


The figure below to the right, it is shown how the known baryon resonances with spin s = $\frac{3}{2}$ and parity P = +1 fits in a SU_3 pattern with 10 members. With this family, however, the SU_3 invariance was brought on a critical test.

When the SU_3 theory was brought forward only the N^* and the Y^* were known. Shortly afterwards the Ξ^* was found, but the particle in the top the Ω^- was still lacking. The existence of the Ω^- then constituted the decisive test on the SU_3 theoretical framework.

Gell-Mann baptized the missing particle the Ω^-. From its place in the SU_3 pattern Gell-Mann could predict that it had to be a particle having spin $s = \frac{3}{2}$, Parity P = +1, mass 1675 MeV and strangeness S = -3! The strangeness of -3 made the particle interesting, because there are no two particles, that together have strangeness -3 and masses less than 1675 MeV.

The Ω^- therefore had to decay via the weak interactions and with a life-time which was sufficient, that it could be seen as a trace in the bubble chamber.
A veritable race to be the first to discover the Ω^-, was initiated. In 1963 the race was won by Brookhaven laboratory. They presented the first convincing photo of the Ω^- and its decay.
The bubble chamber photo has been shown earlier, but we repeat it here.



8. Quarks

We shall return to the charge independence of the strong interactions, what we call iso-spin conservation. The mathematical framework, on which the iso-spin is based is called SU_2.
In the SU_2 symmetry, there are two fundamental building blocks, namely a doublet corresponding to iso-spin $T = \frac{1}{2}$, and there are $2T + 1 = 2$ elements in the doublet corresponding to $T_3 = -\frac{1}{2}$ and $T_3 = +\frac{1}{2}$. From this doublet it is then possible to build all the other multiple SU_2 patterns.
This happens in quite the same manner as the addition of angular momentum and spin.

The proton and the neutron form a SU_2 doublet. If two doublets are brought together there are $2{\cdot}2 = 4$ possibilities. According to the rules for addition of two SU_2 doublets, the 4 possibilities separate into a triplet corresponding to $T = 1$ and a singlet $T = 0$. ($2T + 1 = 1$ member).

If the doublet is represented by a neutron n, and a proton p it gives the following nuclei:
$T = 1$: (nn), $(np)+(pn)$, (pp) and for $T = 0$: $(np) - (pn)$. $(np)+(pn)$ and $(np) - (pn)$, represents symmetric and anti-symmetric states, respectively.
Three doublets give $2^3 = 8$ possibilities. ($T = 1$ and $T = \frac{1}{2}$), may result in $T = \frac{3}{2}$ (4 members) or $T = \frac{1}{2}$ (2 members), while ($T = 0$ and $T = \frac{1}{2}$) can only give $T = \frac{1}{2}$ (2 members).

In the SU_3 – symmetry there are 3 fundamental building blocks. The fundamental multiplet is therefore a triplet. If we make new multiplets from two triplets, there are $3^2 = 9$ possibilities, and it turns out that they separate in an octet and a singlet. (3)x(3) = 8 +1. If we form multiplets from 3 triplets, then the mathematical formalism shows that the 3^3 =27 possibilities will separate into a decuplet (10 members), 2 octets (8 members) and a singlet. (3)x(3)x(3) = (10)+(8)+(8)+(1).

What is remarkable, however, is that even if all known particles fit in these multiplets (as shown in the figure in page 19), then the fundamental triplet has never manifested itself in nature.

The missing triplet encouraged Gell-Mann to suggest that all the hadrons (baryons and mesons) were built from three fundamental particles and their anti-particles.
These hypothetical particles were called *quarks*. In this theory the mesons are bound states of a quark and an anti-quark, while the baryons are composed from 3 quarks, the anti-baryons of 3 anti-quarks.
Within the mathematical framework of SU_3 it follows immediately that the mesons constitute octets or singlet, since the mesons are composed of two SU_3 triplets and (3)x(3) = (8)+(1).

Gell-Mann named the 3 quarks *u* (up), *d* (down) and *s* (strange) the corresponding anti-quarks are ($\overline{u}, \overline{d}, \overline{s}$). According to Gell-Mann, they are all spin $s = \frac{1}{2}$ particles. The *u*, and *d* quarks have strangeness $S = 0$, while the *s* quark has strangeness $S = -1$.

One of the most controversial properties of the quarks was that it is simple mathematics to find out the quarks cannot have integral charges or integral baryon numbers! Non integral charges or baryon numbers have, however, never been observed in nature.

All three quarks have baryon number $B = \frac{1}{3}$. The *u* quark has charge $q = \frac{2}{3}e$, the *d* quark and the *s* quark have charge $q = -\frac{1}{3}e$.
Until the mid eighties only these three quarks constituted the theoretical framework of SU_3 , the eightfold way. The quark scheme worked perfectly, but there where nevertheless theoretical problems with the model. A more serious one was the building of the baryons seem to conflict with Pauli's exclusion principle.
Another thing was that although only 2 leptons were known until 1978, (together with their neutrinos), but one more lepton (the τ -meson) has were identified as a resonance. So there are 6 leptons, and by symmetry in nature, it would be nice if there were also 6 quarks.
We shall, however, neither not go into details about the 3 new quarks nor the new leptons.
Below is listed as we now know about the 6 quarks and the 6 leptons.

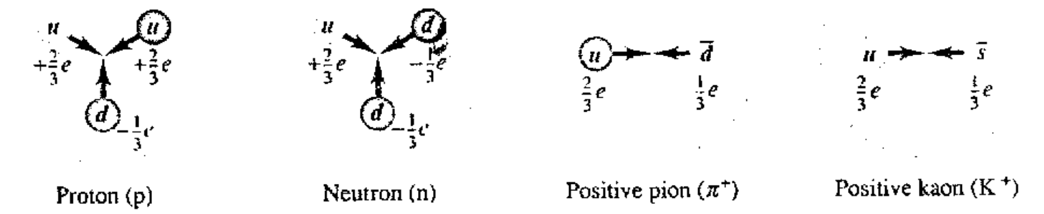
The Leptons

Particle name	Symbol	Anti-particle	Rest mass (MeV/c^2)	L_e	L_μ	L_τ	Lifetime (s)	Principal Decay Modes
Electron	e^-	e^+	0.511	+1	0	0	Stable	
Neutrino (e)	ν_e	$\bar{\nu}_e$	0(?)	+1	0	0	Stable	
Muon	μ^-	μ^+	105.7	0	+1	0	2.20×10^{-6}	$e^-\bar{\nu}_e\nu_\mu$
Neutrino (μ)	ν_μ	$\bar{\nu}_\mu$	0(?)	0	+1	0	Stable	
Tau	τ^-	τ^+	1784	0	0	+1	$<4 \times 10^{-13}$	[illegible]$_\mu\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$
Neutrino (τ)	ν_τ	$\bar{\nu}_\tau$	0(?)	0	0	+1	Stable	

Properties of Quarks

Symbol	Q/e	Spin	Baryon number, B	Strangeness, S	Charm, C	Bottomness, B'	Topness, T
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
d	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
s	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	-1	0	0	0
c	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	$+1$	0	0
b	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	$+1$	0
t	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	$+1$

Below is shown schematically the quark content of 4 hadrons



Quark content of four hadrons. The various color combinations needed for color neutrality are not shown.

Below is a list of the most well known hadrons.

Some Known Hadrons and Their Properties

	Particle	Mass (MeV/c^2)	Charge ratio, Q/e	Spin	Baryon number, B	Strangeness, S	Mean lifetime (s)	Typical decay modes	Quark content
Mesons	π^0	135.0	0	0	0	0	0.87×10^{-16}	$\gamma\gamma$	$u\bar{u}, d\bar{d}$
	π^+	139.6	$+1$	0	0	0	2.6×10^{-8}	$\mu^+ \nu_\mu$	$u\bar{d}$
	π^-	139.6	-1	0	0	0	2.6×10^{-8}	$\mu^- \bar{\nu}_\mu$	$\bar{u}d$
	K^+	493.7	$+1$	0	0	$+1$	1.24×10^{-8}	$\mu^+ \nu_\mu$	$u\bar{s}$
	K^-	493.7	-1	0	0	-1	1.24×10^{-8}	$\mu^- \bar{\nu}_\mu$	$\bar{u}s$
	η^0	548.8	0	0	0	0	$\approx 10^{-18}$	$\gamma\gamma$	$u\bar{u}, d\bar{d}, s\bar{s}$
Baryons	p	938.3	$+1$	$\frac{1}{2}$	1	0	Stable	—	uud
	n	939.6	0	$\frac{1}{2}$	1	0	898	$pe^- \bar{\nu}_e$	udd
	Λ^0	1116	0	$\frac{1}{2}$	1	-1	2.63×10^{-10}	$p\pi^-$ or $n\pi^0$	uds
	Σ^+	1189	$+1$	$\frac{1}{2}$	1	-1	0.799×10^{-10}	$p\pi^0$ or $n\pi^+$	uus
	Σ^0	1193	0	$\frac{1}{2}$	1	-1	7.4×10^{-20}	$\Lambda^0 \gamma$	uds
	Σ^-	1197	-1	$\frac{1}{2}$	1	-1	1.48×10^{-10}	$\eta\pi^-$	dds
	Ξ^0	1315	0	$\frac{1}{2}$	1	-2	2.90×10^{-10}	$\Lambda^0\pi^0$	uss
	Ξ^-	1321	-1	$\frac{1}{2}$	1	-2	1.64×10^{-10}	$\Lambda^0\pi^-$	dss
	Δ^{++}	1232	$+2$	$\frac{3}{2}$	1	0	10^{-23}	$p\pi^+$	uuu
	Ω^-	1672	-1	$\frac{3}{2}$	1	-3	0.822×10^{-10}	$\Lambda^0 K^-$	sss
	Λ_c^+	2285	$+1$	$\frac{1}{2}$	1	0	1.91×10^{-13}	$\Sigma^+ \pi\pi\pi$	udc

The quark theory seemed to be a success, but with only three quarks it had many problematic issues. Firstly there are the non integral baryon number and non integral charge.

Secondly the quarks have never been observed. This has been explained by the assumption that the quarks are bound so hard that if you try to separate them the energy will instead go production of new quark anti- quark pairs. Hitherto everything points in the direction that neither particles with non integral charges or baryon numbers can exit freely in nature.

The third obstacle is the violation of the exclusion principle. The best example is the Ω^- particle, consisting of 3 *s* quarks. Since (*sss*) is a completely symmetric state and the *s* quarks are spin $s = \frac{1}{2}$ fermions, it is forbidden by the exclusion principle.

In 1974 a new particle ψ at 3.1 *GeV*, was detected, and its existence could only be explained by introducing a new conserved quantum number, which prevents it from decaying via the strong interactions. But a new conservation law implies a new quark, now accepted as the *c* quark.

This quark has in 1977 been follow by two other quarks, the *t* and the *b* quarks, which on one hand opens up for the quark-hypothesis, but on the other hand complicates it.
Three new conserved quantum numbers besides strangeness have been added the quark theory: Charm C, Bottom-ness *B'*, and Top-ness *T'*.