Introduction to Quantum Chromodynamics

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Chapter 2:
The road to quarks

1. What are the nuclei made of, what forces hold them together?
   - First glimpse of nuclear force
   - Birth of the “new” quantum mechanics
   - Pauli and neutrino hypothesis
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2. 1938–1947: decade of uncertainty
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4. 1956–1960: paving the eightfold way
5. 1961-1964: from resonances to quarks

Literature

Our discussion is based on

Quarks, partons and Quantum Chromodynamics

by Jiří Chýla

Available at http://www-hep.fzu.cz/ chyla/lectures/text.pdf

Prehistory

- 1914, three years after the discovery of atomic nucleus it became generally accepted that the nucleus is the seat of all radioactive processes and all nuclei are specified by the numbers A and Z. Moreover, all data supported the conjecture that the interaction between the α-particle and nuclei is purely electromagnetic.
- In attempts to understand the mechanism behind the radioactive processes within the Bohr Model of atom, in 1913 by van den Broek, assumed that both α-particles and electrons are constituents of nuclei.
- His suggestion was taken up by **Rutherford** himself, who considered the α-particle to be composed of two *"four positive electrons (H-particles)*
- In general a nucleus X with mass number A and charge Z was assumed to be:

$$\mathrm{X} = A\mathrm{H} + (A - Z)\mathrm{e}. \tag{1}$$

Prehistory

- The situation is nicely summarized by Pais[1]:

  Thus Rutherford, though always cautious and averse to speculation, blithely assumed that electrons are nuclear constituents. Actually he would not conceive of this as assumption. Was it not self-evident? Did one not see electrons come out of certain nuclei, in β-processes? To Rutherford, as to all physicists at that time, it was equally sensible to speak of electrons as building blocks of nuclei as it was to speak of a house built of bricks or necklace made of pearls.

  In actual fact, the H-particle-electron picture of the nucleus is another example of simplicity as a necessary evil. It was a model as inevitable as it was wrong. It is not true that electrons are building blocks of nuclei .... Then how can one understand that electrons do emerge from nuclei in β-decay? Almost exactly 20 years after Rutherford spoke in the Royal Society, Fermi found the answer to that question, using the tools of quantum field theory.

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(1) A. Pais; Inward bound, Clarendon Press, New York, 1986

First glimpse of nuclear force

- Concerning forces binding H–particles and electrons inside the nuclei, Rutherford said:

> *“The nucleus, though of minute dimension, is in itself a very complex system consisting of positively and negatively charged bodies bound closely together by intense electrical forces.”*

- N.B. The fact that electron cannot be localized at distances smaller than its Compton wavelength $\lambda_e = m_e^{-1} \doteq 400$ fm, was not yet realized.
- This model of atomic nuclei has been generally accepted for two decades, though there were signals it had serious problems.
- However already in 1919 Rutherford himself observed the first clear evidence of the new force actually responsible for nuclear binding.
- This observation resulted from a series of experiments performed by Rutherford in 1916-1919 in his Manchester laboratory in which he had scattered α-particles from various nuclei, heavy as well as light, including the hydrogen.

First glimpse of nuclear force

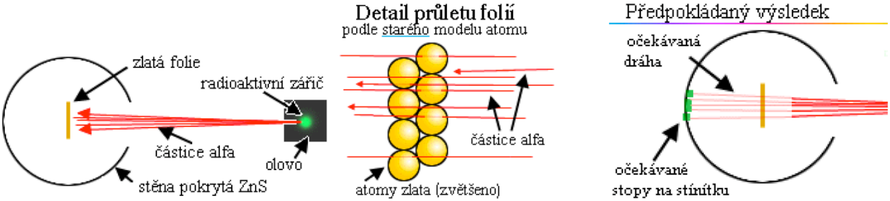


Figure: Layout of the Rutheford experiment and prediction of the “pudding” model of the atom.

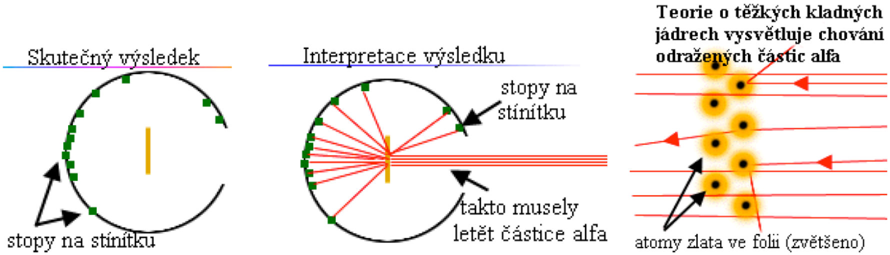


Figure: Results of the Rutheford experiment and their interpretation as evidence that positive of the atom charge must be concentrated in a small spatial region.

First glimpse of nuclear force

- Minimal distances (corresponding to head-on collision) accessible in α-H and α-Au scattering:
$$r_{\rm min}^{\alpha \rm p} = r_{\rm min}^{\alpha \rm Au} \frac{1}{Z_{\rm Au}} \left(\frac{m_\alpha + m_{\rm p}}{m_{\rm p}} \right) = \frac{2\alpha}{E} \left(\frac{m_\alpha + m_p}{m_p} \right). \qquad (2)$$
$\Rightarrow$ collisions are less effective for probing the structure of target H. For Au–target, the α-particle can get much closer to its center and the large angle scattering therefore probes much smaller distances.

- Rutherford measured the number $N(\vartheta)$ of protons recoiling at angles from zero to ϑ_p and compared it with the prediction of Darwin:
$$N_p(\vartheta) = C\alpha^2 E_{\rm kin}^{-2} \tan^2 \vartheta_p. \qquad (3)$$
C – constant depending on the composition and geometry of the target. (3) diverges for $\vartheta_p = \pi/2$, which corresponds to the soft collision when the incoming α-particle bounces off the target proton at very large b.

- Rutherford summed up his observations:

  For α-particles of range less than 4 cm of air, the distribution and absorption of H-atoms are in fair agreement with theory. .... For α-particles with range 7 cm (corresponding to the full 5 MeV energy) *the number of fast H-atoms produced is 30 times greater than the theoretical number.*

Birth of the “new” quantum mechanics

- In the middle of 20^{th} the "new" quantum mechanics was formulated by de Broglie, Heisenberg, Schrödinger and others (N.B. the "old" quantum theory was developed by Bohr and Sommerfeld).
- Soon afterwards, Dirac proposed his relativistically invariant equation for the electron thereby laying foundations for the quantum field theory.
- It is also worth noting that still within the framework of the "old" quantum theory of Bohr and a couple of months before the papers of Heisenberg Pauli invented in all but name the concept of the spin of electron. Analysing the spectra of anomalous Zeeman effect he introduced a new degree of freedom of the electron, which he called "the two-valuedness, not describable classically".

Pauli and neutrino hypothesis

- 1914 **Chadwick**: the spectrum of $e^{\pm}$ in the nuclear β-decay is continuous. This seemed to violate the sacred principle of energy and momentum conservation (Heisenberg and Bohr).
- 1930 **Pauli**: alternative explanation via so far unobserved particle (he called it first "neutron"), which should accompany e^- or e^+ in the nuclear β-decay.
- Interestingly, Pauli was more wrong than right in his description of the role of his "neutron". Nevertheless, he was right in the crucial point that his particle has spin 1/2 and is emitted together with electron in the β-decay.
- N.B. The true neutron was discovered by James Chadwick in 1932.
- Pauli thought his proposal of the "neutron" was too speculative, and did not publish it in a scientific journal until 1934, by which time **Fermi** had already developed a **theory of beta decay** incorporating the neutrino.
- Pauli's hypothesis got a general acceptance during the Solvay conference in October 1939, where Perrin put forward the conjecture that $m_\nu = 0$. However, it took two more decades before the existence of (electron) neutrino has been confirmed by Reines and Cowan who observed its collision with proton resulting in neutron and positron.

1932–34: three years that changed all

The two, almost simultaneous, but unrelated, experimental discoveries occurred in 1932 and concerned the observation of new particles of fundamental importance.

- **Positron:** In August 1932 **Carl Anderson** had observed, using cloud chamber placed in a magnetic field, the first example of *"a positively charged particle comparable in mass and magnitude of charge with an electron"*.
- **Neutron:**
  - Observed first by **Joliot-Curies** who did not interpret their measurement correctly. Title of their paper *The emission of high energy photons from hydrogenous substances irradiated with penetrating alpha rays* says it all . . .
  - **James Chadwick** repeating their experiment of Joliot-Curies bombarded Be- target with α-particles. Analyzing the recoil velocities of charged particles produced in collisions of the neutral particle "n" emerging from the reaction $\alpha + \mathrm{Be}^9 \rightarrow \mathrm{C}^{12} + \mathrm{n}$ in the hydrogen or nitrogen medium, he came to the conclusion that the neutral particle "n" must have the mass close to that of the proton and cannot therefore be the energetic photon, as conjectured by Joliot-Curies.

1932–34: three years that changed all

- The first step towards the theory of nuclear forces was done shortly after the discovery of the neutron by **Heisenberg** in his theory of nuclear structure based on the assumption that nuclei are composed of protons and neutrons.
- He built his theory on the analogy with molecular forces assuming that the electron provides a mechanism of new force between the proton and neutron by being "exchanged" between them, similarly as electron in the H_2^+ ion.
- The Heisenberg force was not of electromagnetic origin, merely the mechanism was modeled on it. No new force beside the Coulomb electrostatic forces was postulated to act between two protons. The main importance of Heisenberg theory, beside the fact that it assumed the proton-neutron structure of nuclei, was that it was formulated within the nonrelativistic quantum mechanics.
- The main obstacle to further progress: the natural idea at that time – the neutron is a sort of bound state of the proton and electron.

1932–34: three years that changed all

- 1933 – **Fermi** put forward new theory of the β-decay of nuclei and neutron.
    - First relativistic QFT. It banished forever the classical, but wrong idea that if something disintegrates, the decay products must have existed inside the decaying particle. There is no reason to assume electrons are constituents of nuclei, which in turn dealt a heavy blow to Heisenberg theory of nuclear forces.
    - First successful theory of intranuclear force beside the electromagnetic.
- 1934 – **Yukawa** found the relation between the range of a force and the mass μ of conjectured mediating particle.

$$U(r) \equiv \pm \frac{g}{r} \exp(-\mu r), \tag{4}$$

N.B. It was known for more than two decades that nuclear force acted at short distances only, of the order of a few fermi, but Heisenberg and other theorists still thought it could be mediated by exchange on electrons, which has a Compton wavelength 400 fm. In fact this step was crucial not only for the theory of strong interactions, but for the quantum field theory in general.

1935–1938: final touches

- Yukawa's new force acted between p and n only, p–p and n–n forces were not considered. ⇒ his original formulation of strong interactions was not charge invariant.
- Although the conjectured particles mediating his new force were charged, their interaction with electromagnetic field was not considered.
- The spin dependence of his new force was not discussed and thus no conjecture was made about the spin of Yukawa particle itself.

- The above shortcomings were removed during the following 4 years as a result of theoretical analyses of binding energies of light nuclei, like H^3 and He^4, and first experimental data on the scattering of protons and neutrons. The first of them showed convincingly that pp and nn forces are equal and the second suggested that they, moreover, equal to those acting between proton and neutron in the p–n symmetric state (which is the spin singlet state). Charge invariance of strong interactions had become established.

1935–1938: final touches

- The formalism incorporating charge invariance of strong interaction was developed by **Cassen and Condon**, who emphasized that proton and neutron can be understood as two members of a doublet, in the same way as two spin states of particles with spin $1/2$.
- They used Pauli matrices to describe the transformation of this doublet under the rotation in the space of internal degree of freedom of the nucleon (later called by Wigner "isotopic spin") to show that the available data implied that the form of the interaction potential must be of the form

$$W_{12}(r) = a + b\vec{\tau}^{(1)} \cdot \vec{\tau}^{(2)}. \tag{5}$$

- The assumption of isospin invariance of strong interactions ⇒ extension of the Pauli exclusion principle to isospin among the variables describing the state of the nucleon.

1935–1938: final touches

- 1938 **Kemmer**: theory of nuclear force that respects the isospin symmetry. To incorporate the charge independence of forces between p and n in the Yukawa theory he introduced a neutral companion of the charged Yukawa mesons, extending thereby the concept of isospin to particles mediating the strong force. Adding to $H_{\rm int}$ of the Yukawa theory:

$$H_{\rm int} = g\left(\overline{p}n\phi^* + \overline{n}p\phi\right) = \frac{g}{\sqrt{2}}\overline{\psi}\left(\tau_+\phi^* + \tau_-\phi\right)\psi = g\overline{\psi}\left(\tau_1\phi_1 + \tau_2\phi_2\right)\psi, \tag{6}$$

where τ_i, τ_+, τ_- are standard isospin matrices and

$$\phi_1 \equiv \frac{\phi^* + \phi}{2},\ \phi_2 \equiv \frac{\phi - \phi^*}{2\mathrm{i}},\quad \psi \equiv \begin{pmatrix} \psi_p \\ \psi_n \end{pmatrix}. \tag{7}$$

the third term involving the neutral scalar field ϕ)3 of the same mass as the charged fields ϕ, ϕ^*:

$$H_{\rm int} = g\overline{\psi}\left(\tau_1\phi_1 + \tau_2\phi_2 + \tau_3\phi_3\right)\psi = g\overline{\psi}\vec{\tau}\psi\vec{\phi}. \tag{8}$$

- The form (8) is manifestly invariant under the simultaneous rotation of the nucleon doublet and meson triplet in the isospin space.

1938–1947: decade of uncertainty

- Since about 1934 it had been known that cosmic rays contained two components: the soft, mostly electrons and photons, producing showers, and one, which penetrates matter much more easily than as expected for electrons on the basis of the theoretical calculations of **Bethe and Heitler**.
- Dilemma: either there are new particles in cosmic rays or the theory of electron bremsstrahlung breaks down at high energies.
- 1937: **Anderson and Neddermeyer** – distribution of energy losses clearly prefers the former option. Based on this observation, they had concluded that:

  "..there exist particles of unit charge but with mass (which may not have a unique value) larger than that of a normal free electron and much smaller than that of a proton".
- It took a decade to determine the mass of the "mesotron", to show that there is just one such particle with the mass around 100 MeV and prove that the mesotron interacted only very weakly with nuclear matter. ⇒ It could not be identified with the particle predicted by Yukawa to mediate strong interactions.

1938–1947: decade of uncertainty

- The real Yukawa particles, charged pions $\pi^{\pm}$ had been found in 1947 by **Powell** and collaborators by analyzing the tracks left by cosmic rays in a specially manufactured nuclear emulsion.
- π^0, was found only in 1950 in the collisions of photons with protons at Berkeley (first unstable particle to be discovered using an accelerator).
- Although further development had shown that Yukawa theory failed to describe strong interactions of hadrons quantitatively, by introducing the concept of isospin it paved the way to unitary symmetry, quark model and eventually Quantum Chromodynamics.

1947–1955: strange discovery and its consequences

- As we have seen on two previous occasions (Curies, Rutherford), observing a completely new phenomenon is one thing and its proper interpretation quite another. This was also the case with the discovery of strange particles. It is very likely that the first strange particle was observed by **Leprince-Ringuet** in Summer 1943, four years before the real discovery, in his cloud chamber exposed to cosmic rays in Pyreneen.
- 1947 – **Butler and Rochester** reported two events recorded in their magnetic lead plate cloud chamber exposed to cosmic rays.
  - One of their pictures showed the first "V^0-particle", i.e. neutral particle produced in the lead plate by cosmic rays and decaying into a pair of oppositely charged particles.
  - The second showed "kink" on the charged particle coming from above that was interpreted as the decay of positively charged particle.
- Kinematical analysis of both decays under the assumption that the decay particles were pions gave for the masses of unknown particles values in the region 440 ± 100 MeV and 540 ± 100 MeV. What they saw were almost certainly the decays of K^0 and K^+ mesons.

1947–1955: strange discovery and its consequences

- 1950–1952: there are actually two V^0-particles.
  One with $m \approx 500$ MeV decaying into $\pi^+\pi^-$.
  The other with $m \approx 1100$ MeV decaying into the π^-p pair.
- New particles behaved "strangely" (Hence the name given to them by Gell-Mann in 1955): they were produced in collisions of cosmic rays with nuclei at rates comparable to those of pions, but decayed many orders of magnitude slower than as expected for decay mediated by strong interaction.
- N.B. The pion (lightest strongly interacting particles) also decays slowly but as the long lifetime was understood as the decay went via weak interactions. But why could not V_1^0, meson with the mass of around 500 MeV, decay into two charged pions with lifetime of the order 10^{-23}s as expected for decays mediated by strong interactions?
- The same problem concerned the decay of baryonic V_2^0 with mass around 1100 MeV: what prevents this baryon to decay fast into the π^-p pair?

1947–1955: strange discovery and its consequences

- The situation with charged new particles was much more complicated and it took 5 years, and essential contribution from experiments at the new generation of accelerators, to clarify it.
- 1952: Discovery of the cascade hyperon Ξ^- (then called V_2^-), in a magnetic cloud chamber exposed to cosmic rays at Pic du Midi. The particle was firmly established on the basis of just a few events, because of its decay mode $\Xi^- \to \Lambda\pi^-$: kink on the negative charged track accompanied by the nearby decay of $\Lambda \to \pi^- \mathrm{p}$.
- In Summer 1953 the situation thus looked as follows:
  - there was reasonably well established decay modes of
    - two neutral V^0-particles: $V_1^0 \to \pi^+\pi^-$, $V_2^0 \to \pi^- \mathrm{p}$,
    - negatively charged baryon V_2^- (Ξ^- today) $\to \pi^- V_2^0$,
  - first signals of positively charged baryon V_2^+, decaying into the proton and some neutral particles,
  - several events showing decays of positively charged mesons, sometimes lumped together as "V_1^+", into various combinations of pions and muons,
  - no signs of a negative strange meson.

1947–1955: strange discovery and its consequences

	mode	%
K^+	$\mu^+\nu_\mu$	63.51
	$\pi^+\pi^0$	21.16
	$\pi^+\pi^+\pi^-$	5.89
	$\pi^+\pi^0\pi^0$	1.73
	$\pi^0\mu^+\nu_\mu$	3.18
	$\pi^0 e^+\nu_e$	4.82
K_S^0	$\pi^+\pi^-$	68.61
	$\pi^0\pi^0$	31.39
Λ	$\pi^- p$	63.9
	$\pi^0 n$	35.8
Σ^+	$\pi^0 p$	51.57
	$\pi^+ n$	48.31
Σ^0	$\Lambda\gamma$	100
Σ^-	$\pi^- n$	99.85
Ξ^-	$\Lambda\pi^-$	99.89
Ξ^0	$\Lambda\pi^0$	99.54

Table: Main decay channels of some of strange mesons and baryons.

1947–1955: strange discovery and its consequences

- In this situation **Gell-Mann** and shortly later **Nakano and Nishijima** suggested solution to the puzzle of new particle decays.
- Solution amounted to a particular assignment of isospin to the new "strange" particles that prevented them from decaying into the observed decay modes via strong interactions, but allowed them to proceed via weak interactions, which explained their long lifetime.
- Gell-Man assumed that the observed mesons V_1^0 and V_1^+ form an isospin doublet and the observed baryons V_2^0 and $V_2^\pm$ an isospin triplet.
- N.B. this assignment went against common wisdom set by nucleons and pions, which form isospin doublet and triplet respectively.
- Assigning strange mesons V_1^+ and V_1^0 to isospin doublet $\Rightarrow$ the antiparticle to V_1^0 was not identical with V_1^0 as is the case of π^0 meson!
- Two years later Gell-Mann and Pais suggested treatment of neutral mesons that are not eigenstates under the transformation particle→antiparticle. The above assignment was designed with the sole purpose of preventing the observed decays like $K_S^0 \to \pi^+\pi^-$ and $\Lambda \to \pi^- \mathrm{p}$ to proceed via strong interaction.

1947–1955: strange discovery and its consequences

- Brookhaven 1953: **associated production of strangeness**. Direct consequence of strangeness conservation: that strange particles are produced by strong interaction always in pairs of opposite strangeness.
- Crucial test was the event π^-p$\rightarrow K^+\Sigma^-$. This decay conserves third component of the isospin $(-1+1/2=1/2-1)$, and can thus proceed via strong interactions, but opposite charge combination $K^-\Sigma^+$ does not!
- 1954: Nishijima reformulated his and Gell-Mann's peculiar isospin assignment in terms of a new quantum number, which is conserved in strong interactions, but violated by weak force. In modern notation he wrote:

  $$Q = T_3 + \frac{B+S}{2}. \tag{9}$$

  i.e. the relation between T_3, the third component of isospin, the **hypercharge** $Y \equiv (B+S)$ and electric charge Q. (Presently called "Gell-Mann-Nishijima relation").
- In SU(3) symmetry isospin conservation is equivalent to strangeness conservation ⇒ (9) does not carry any new restriction on possible strong decays. Nevertheless, the introduction of strangeness was crucial because it opened the way to unitary symmetry and finally the quark model where it's

1956–1960: paving the eightfold way

- 1955–9: important experimental discoveries at Brookhaven and Berkeley. Discovery **antiproton**, **antineutron** and **Σ^0 and Ξ^0 hyperons** (bubble chambers).

- On the theoretical side the field theory seemed unable to provide the framework for successful theory based on standard perturbative methods applied to Yukawa theory.
- The QFT fell from favor as a result of the failure of the program of **Landau** and his collaborators to give renormalization of QED good mathematical as well as physical meaning.
- 1954: **Robert Mills and Chen Ning Yang** generalized the concept of gauge invariance of **Hermann Weyl**, who used it to derive QED, to strong interactions between nucleons. This paper became the milestone on the way to our current understanding of the fundamental forces acting in the microworld.

The analytic S-matrix

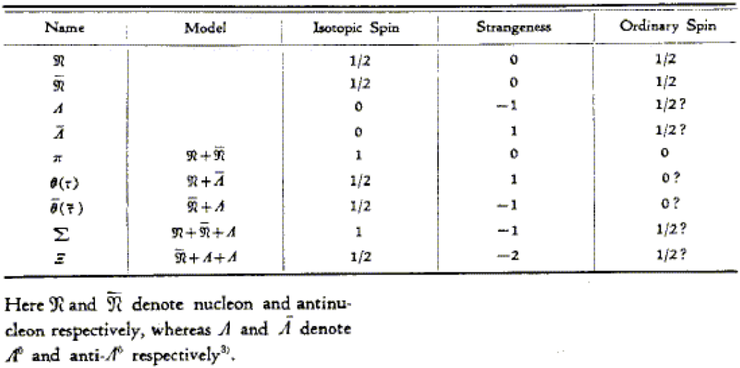
- Instead of QFT theorists concentrated on the exploitation of the rather subtle properties of the scattering matrix previously derived from quantum field theory, but which in this novel approach were simply postulated.
- The most ambitious approach within this rather widely defined program was the so called *bootstrap* model, based on the idea of "nuclear democracy" invented and pursued by **G. Chew**. It assumed that combining the analytical properties of the S-matrix, which were related to particle spectrum, with the requirements following from conservation laws,unitarity and self-consistency will in the end lead to unique determination of the S-matrix itself.
- The analytic S-matrix was considered as the best theoretical framework for formulation of the theory of strong interactions until the discovery of asymptotic freedom in 1973. This, almost overnight, changed the situation: quantum field theory was resurrected and the S-matrix returned to where it belongs, i.e. at the end of calculations based on quantum field theory.

Fermi-Yang model

- 1948: **Fermi and Yang** did not considered pions as an elementary particles. Instead they postulated them to be bound states of nucleon-antinucleon pairs of appropriate charge combination. To produce pions with mass about 140 MeV from nucleons with 940 MeV, they had to assume a very strong attractive force in $N\overline{N}$ states, but no such force in other ones.
- F–Y model was in principle, though not in practice, in conflict with the Yukawa theory of strong interactions, as in the latter pions play a fundamental role of force carriers. According to Fermi and Yang, the virtual $N\overline{N}$ states created in the vicinity of baryons *"have a tendency to pair formation of nucleons antinucleons, which will be predominantly formed in the bound states, i.e. as π-mesons.*
- Their model was precursor of all subsequent models of hadron structure, but has never become more than a qualitative framework of thinking about this question.

Sakata model

- 1956: **Sakata** extended F–Y model to strange particles by adding the Λ-baryon as third fundamental baryon and $\overline{\Lambda}$ as third antibaryon.



Name	Model	Isotopic Spin	Strangeness	Ordinary Spin
$\mathfrak{N}$		1/2	0	1/2
$\bar{\mathfrak{N}}$		1/2	0	1/2
Λ		0	−1	1/2 ?
$\bar{\Lambda}$		0	1	1/2 ?
π	$\mathfrak{N}+\bar{\mathfrak{N}}$	1	0	0
$\theta(\tau)$	$\mathfrak{N}+\bar{\Lambda}$	1/2	1	0 ?
$\bar{\theta}(\bar{\tau})$	$\bar{\mathfrak{N}}+\Lambda$	1/2	−1	0 ?
Σ	$\mathfrak{N}+\bar{\mathfrak{N}}+\Lambda$	1	−1	1/2 ?
Ξ	$\bar{\mathfrak{N}}+\Lambda+\Lambda$	1/2	−2	1/2 ?

Here $\mathfrak{N}$ and $\bar{\mathfrak{N}}$ denote nucleon and antinucleon respectively, whereas Λ and $\bar{\Lambda}$ denote Λ^0 and anti-Λ^0 respectively[3].

Figure: Composition of mesons and baryons according to Sakata.

- This model was an important step forward, as it reduced the problem of strange particles to that of the Λ hyperon.

- On the other hand, it singled out three particles, proton, neutron and the Λ, and their antiparticles, as fundamental building blocks, although

Ne'eman model

- 1961: **Yuval Ne'eman** derived the theory of strong interactions from gauge invariance. Exploiting Yang-Mills idea to use the requirement of local gauge invariance he assigned the role of gauge bosons to vector mesons (not discovered experimentally, yet!) to mediate strong interactions between all other strongly interacting particles, like pseudoscalar mesons and baryons.
- Based on the experimental evidence then available, he assigned the observed mesons to an octet (calling yet undiscovered η meson $\pi^{0,}$) and wrote, following Y–M, the interaction term, which contained just one coupling constant and which described, beside the coupling of vector mesons to baryons and pseudoscalar mesons, also the self-coupling of vector mesons.
- Selecting the symmetry group and representations occupied by baryons and pseudoscalar mesons he got a unique theory – **a direct predecessor of Quantum Chromodynamics**. The underlying symmetry group is SU(3)and the force acting between particles is generated from the gauge invariance.
- The role of the charge was played by the flavor quantum number (*Quantum Flavordynamics*). Gauge bosons of his theory, the vector mesons, carry flavor and do therefore change the flavor or baryons and pseudoscalar mesons. Moreover, as they carry flavor, they do couple locally to each other as well!

Gell-Mann models

- 1961: **Gell-Mann** wrote a preprint called *The Eightfold way: a theory of strong interaction*, which made an had enormous influence on further development of the unitary symmetry.
- Similarly to Ne'eman it is also based on the SU(3) nonabelian gauge theory. Vector mesons are introduced as gauge bosons and various phenomenologically interesting processes and decays are calculated.
- It goes to much greater detail than the paper of Ne'eman, but for reasons that are difficult to understand and have to do with Gell-Mann's complicated personality, this masterpice has never been published! It was submitted to the Physical Review but then withdrawn and rewritten. In its published version it does not even mention the idea of gauge theories which appeared in the first submitted version.

Gell-Mann models

- Gell-Mann took up Sakata's basic assumption that hadrons are made out of triplets of some basic fields but dropped the other assumption that p, n and Λ are elementary. In his modification all hadrons are composed of some "hidden" objects and are thus treated on the same footing.
- The nontrivial consequence of this approach, following from the decomposition:

$$\mathbf{3} \otimes \overline{\mathbf{3}} \otimes \mathbf{3} = \mathbf{15} \oplus \overline{\mathbf{6}} \oplus \mathbf{3} \oplus \mathbf{3} \tag{10}$$

  is that physical states of baryons may occupy any of the representations appearing on the r.h.s. of (10).
- For instance, the nucleon doublet and the triplet of Σ may be part of the same anti-sextet $\overline{\mathbf{6}}$, together with some so far unknown baryon isosinglet, but without the nucleon and Ξ doublets. Alternatively, Σ triplet may occupy, together with the Ξ doublet but without the nucleon one, the pentuplet **15**. The answer which of these options is realized in nature could not be answered by purely theoretical arguments, but had to be left to experiments. The physical states of mesons occupy, as in original Sakata model, the octet.

Gell–Mann models

- Gell–Mann instead suggested: *. . . as an alternative to the symmetrical Sakata model, another scheme with the same group, which we call "eightfold way". Here the baryons, as well as mesons, can form octets and singlets, and the baryons N, Λ, Σ and Ξ are supposed to constitute an approximately degenerate octet.*

  This suggestions relies on the relation

  $$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}. \tag{11}$$

- Note that that this scheme can be easily distinguished from the one based on (10) as is predicts quite different multiplet structure. Most importantly, the baryons N, Λ, Σ and Ξ form just one multiplet.
- *Nowhere does our work conflict with the program of the Chew et al. of dynamical calculation of the S-matrix from strong interactions using dispersion relations. If something like Sakata model is correct, then most of the mesons are dynamical bound states or resonances ... If there are no fundamental fields and no CDD poles, all baryons and mesons being bound or resonant states of one another, models like Sakata will fail; the symmetry properties we have abstracted can still be correct, however.*

1961–1964: from resonances to quarks

- The first half of sixties was marked by a proliferation of experimental discoveries, some of them spurious, of the so called *resonances* accompanied by a surge of related theoretical research.
- "resonance" $\approx$ hadrons that can decay by strong interaction and have therefore very short lifetime, of the order 10^{-23}s. This lifetime is so short that resonances do not leave any measurable tracks and their existence can be ascertained only by observing the above mentioned peaks with the width of around 100 MeV.
- The first indication of such resonances was found by Fermi and collaborators back in 1952 using the π^- beams from old Chicago proton synchrotron.
- In 1955 **S. Lindenbaum and C. Yuan** showed, using the π^+ and π^- beams of energies up to 750 MeV provided by the the Brookhaven Cosmotron, that the resonance observed by Fermi exists in all four possible πN channels and thus has isospin 3/2. As discussed below, this particle later played crucial role in the formulation of the quark model and introduction of the concept of color.

1961–1964: from resonances to quarks

- Next decisive moment on the path to the formulation of the quark model was prediction of the existence and mass of Ω^-, the last baryon resonance missing in the baryon decuplet (Gell-Mann and Ne'eman).
- Prediction was immediately addressed in several experiments in which Ω^- was looked for in one of the most likely channel

$$K^- \mathrm{p} \to K^+ K^0 \Omega^-, \tag{12}$$

with the expected decay modes $\Omega^- \to \Lambda K^-$, $\Omega^- \to \Xi^0 \pi^-$ and $\Omega^- \to \Xi^- \pi^0$.

- On January 31st 1964 **Nicholas Samios** (BNL) found the event, which was rather unambiguously interpreted as Ω^-.
- The last member of baryon decuplet was found and the *Eightfold way* triumphed. For his prediction Gell-Mann was awarded the Nobel prize for physics in 1969.

1961–1964: from resonances to quarks

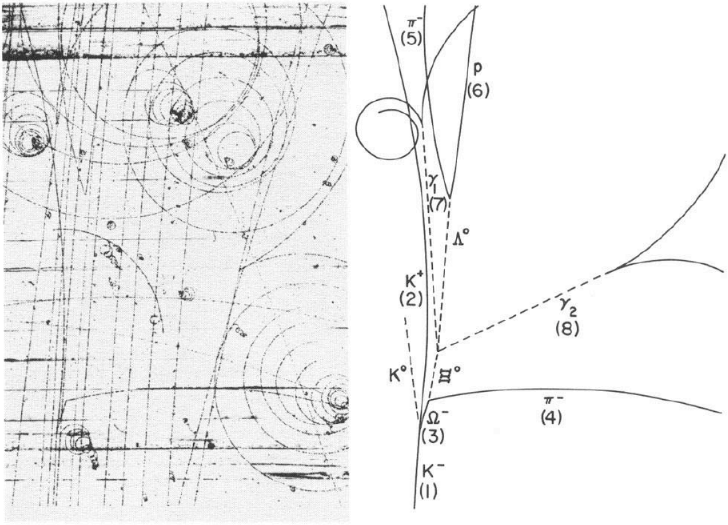


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

Figure: The first Ω^- observed in bubble chamber experiment at Brookhaven on 31.1.1964.