PERCORSI

FIFTY YEARS AGO. THE QUARK MODEL

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Fifty years ago, two U.S. physicists, Murray Gell-Mann at Caltech and George Zweig at CERN on leave from Caltech, independently advanced the hypothesis that all the hadrons, both mesons and baryons, are composed of a triplet of spin-1/2 fields of fractional charge. They where called "quarks" by Gell-Mann and "aces" by Zweig. It took several years to establish that aces/quarks are not purely mathematical but physical objects. The origin and the rise of the quark model was indeed a complicated historical process, which did not follow straight routes, faced experimental and theoretical wrong results, recovered and finally lead to the construction of the Standard Model of the fundamental interactions. In the following the main steps of its history are summarised in a non-technical language.

1 Too many to be elementary

Back in 1935 H. Yukawa [1], then at Osaka, theoretically explained the interaction between nucleons with the exchange of a new particle, the meson. The meson, was discovered by G. Occhialini, C. Powel and collaborators [2], working at Bristol, in 1947. They exposed nuclear emulsions stacks to cosmic rays at high altitudes in the mountains, up to 5500 m in the Andes. The discovery confirmed the Yukawa theory.

It was called π-meson or pion. It has isospin $I = 1$ and three different charge states: π^+, π^0, π^-. Nobody had foreseen, however, that much more mesons exist. Indeed, already in 1944, L. Leprince-Ringuet and M. L'Héritier [3] had published the observation of a particle of about 500 MeV mass. They found it, working at high altitude on the Alps with a triggered cloud chamber exposed to cosmic rays. In the following years several new particles were observed, always in the cosmic rays, both neutral and charged. All were metastable, decaying into lighter particles. They were called mesons if their mass was between those of the pion and the nucleon, hyperons if it was larger than for the latter. Nucleons, hyperons and mesons were later collectively called hadrons, meaning particles with strong interactions.

In 1947, G. Rochester and C. Butler [4] published the observation of the associated production of a pair of such unstable particles. It was soon experimentally proven that they were always produced in pair, a meson and a hyperon. Another strange behaviour was that their production was "fast", namely through strong interaction, but their decay was "slow", through weak interaction. They were called "strange particles".

The explanation was given in 1953 independently by T. Nakato and K. Nishijima [5] and by M. Gell-Mann [6]. They introduced a new (additive) quantum number S, the "strangeness". Strangeness is conserved by the strong but not by the weak interactions. The "old" hadrons, nucleons and pions, have $S = 0$, the hyperons have $S = -1$. The strange mesons, the K-mesons, have $S = +1$. The production by strong interactions from an initial state with $S = 0$ can happen only if two particles of opposite strangeness are produced. The lowest-mass strange particles can decay, for energetic reasons, only into non-strange final states; therefore, they cannot decay strongly.

Many more hadrons were discovered when accelerators of high enough energy entered in operation. If the mass of a hadron is large enough, it can decay through strong interactions without violating any selection rule. The lifetime is then extremely short, of the order of 10^{-24} s. In practice, they decay at the same point where they are produced and do not leave an observable track. We observe them as "resonances".

The first resonance was discovered by E. Fermi and collaborators in 1952 [7] observing a bump in the pion-proton cross sections. The pions were produced by the 450 MeV Chicago synchrocyclotron. Unfortunately, the energies were not sufficient to explore all the resonance curve, but Fermi correctly interpreted the observation as an excited state of the nucleon, of spin $J = 3/2$ and isospin $I = 3/2$. The doubly charged state, now called Δ^{++}, will be very important in the following story, as we shall see.

Higher energy proton accelerators became operational in the following years. The Cosmotron at BNL reached 3 GeV kinetic energy in 1953, the Bevatron at Berkeley next year reached 6 GeV. The 30 GeV energy was reached almost contemporarily in 1959 at CERN with the PS and at BNL with the AGS. Dozens of resonances, both mesons and baryons, both strange and non-strange were discovered. Their properties, mass, width, spin, parity and isospin were measured.

On the experimental side it was a very exciting period, with new results coming out almost in every issue of "Physical Review Letters" and lot of progress both in accelerator and detector techniques. On the theoretical side, there was confusion. The hadrons were too many to consider them all as elementary. Moreover, quantum field theories were in a crisis, plagued by infinities. Part of the community tried to understand the hadron spectrum by imposing self-consistency to the properties of the scattering matrix. G. Chew and F. Frautschi, in particular, proposed a "bootstrap model", meaning "pulling oneself up by one's bootstraps". Hadrons were surmised to be held together by forces consisting of exchanges of the particles themselves. There should not be any hierarchy but rather a "nuclear democracy".

2 Two plus one makes three

A first clarification came in 1961 with the independent proposal by M. Gell-Mann [8, 9] and Y. Ne'eman [10] that strong interactions conserve not only isospin and strangeness, but also a larger set of operators, which are the generators of the symmetry unitary group $SU(3)$. The theory was called the eightfold way by Gell-Mann.

Considering that isospin conservation corresponds to an $SU(2)$ symmetry and strangeness conservation to a $U(1)$ one, for what reasons did it take eight years to understand that 2+1=3 (out of the joke, that $SU(2)\otimes U(1)$ could be extended to $SU(3)$)? In a Symposium held in Nagoya in 2006 to celebrate the 50th anniversary of the Sakata model (see below), H. Lipkin [11], recalling those years, stated that "most of the particle physicists in the U.S. and Europe, knew no group theory at the time. Group theory was viewed as irrelevant mathematics (Die Gruppenpest) which had no use in particle physics". The isospin had been invented by Heisenberg in analogy to spin. Its multiplets are representations of the group of the rotations in three space dimensions and higher symmetries were searched as rotations in higher-dimensional spaces. It took a long time to recognise that the representations of the three-dimensional rotations and $SU(2)$ are just the same.

The hadrons were classified into $SU(3)$ multiplets: mesons in octets and singlets, spin-1/2 baryons in an octet (p, n, Δ^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0). The masses within a multiplet

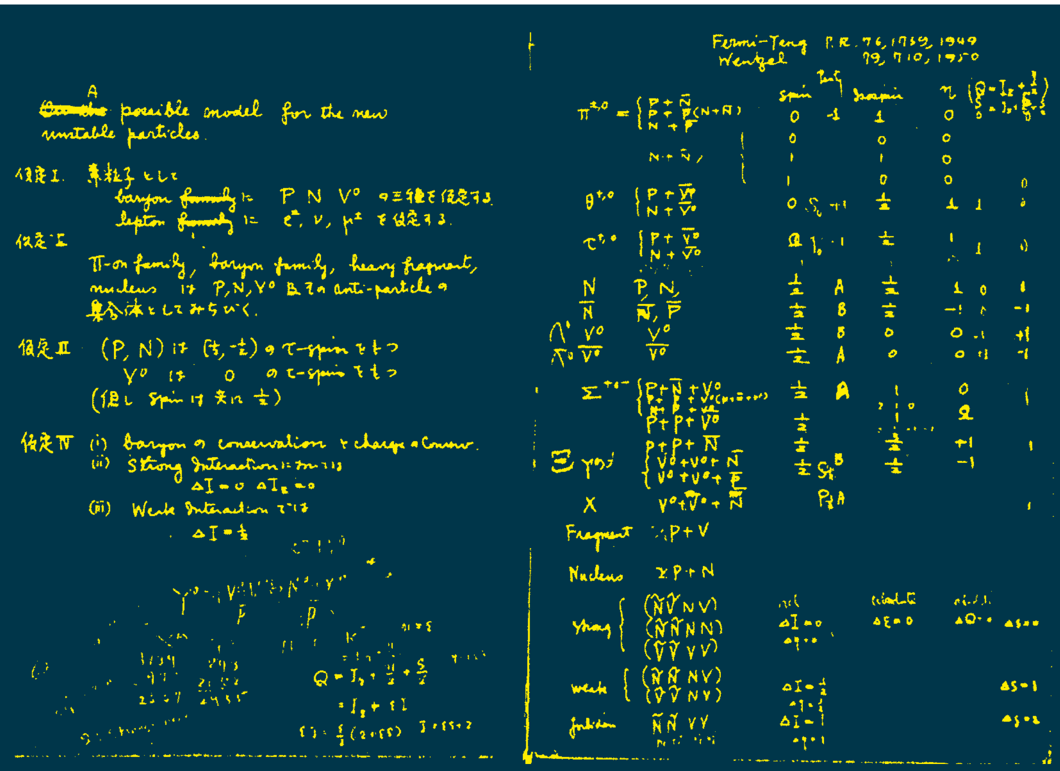

Fig. 1 Two pages of the Sakata notebook. Reproduced from Y. Ohnuki, "The Sakata Model and Birth of U (3) Symmetry: A Personal Recollection" [17] with permission of the Physical Society of Japan, © 2007.

were not equal, showing that *SU*(3) symmetry was broken. The breaking term was assumed to transform like a component of an octet. Mass formulas were obtained and positively compared with the data. At the 1962 International Conference on High Energy Physics in Geneva, the classification of the spin-3/2 resonances was discussed. Gell-Mann [12] pointed out that the absence of resonances in the KN cross section required to classify them in a decimet. The multiplet was not complete, however. A negative hyperon, now called Ω^-, with $I = 0$ and $S = -3$ was missing. The broken *SU*(3) mass formula predicted its mass around 1679 MeV. The Ω^- would have the striking property of metastability, decaying only by weak interactions into $\pi^0\Xi^-$, $\pi^-\Xi^0$, $K^-\Lambda$. Two years later Barnes *et al.* [13] discovered the Ω^- in a bubble chamber experiment at BNL with the foreseen characteristics. This marked the triumph of *SU*(3). In addition, it became clear that mere metastability is no more a criterion for elementary character for hadrons than it is for nuclei.

In the eight-fold way theory Gell-Mann [8] did not consider the states of the fundamental (**3** and $\bar{\mathbf{3}}$) representations as physical particles, but as purely mathematical entities. "We shall attach no physical significance to the "particles" out of which we have constructed the baryons".

In the theory, the interaction amplitudes are the scalar products of two currents (that can be vector or axial-vector). The amplitude of the beta decay of a neutron, for example, is the product of a hadronic current and a lepton current. The former "kills" the incoming neutron and "creates" the outgoing proton. The latter creates the outgoing electron and antineutrino. Hadronic currents obey the *SU*(3) symmetry. In 1963 N. Cabibbo [14] established that the coupling of hadronic currents in the weak interaction can be made universal by a rotation in the symmetry space, through an angle that became known as Cabibbo angle.

3 Hadron compositeness. The predecessors

E. Fermi had been first, together with C. N. Yang [15], then one of his student, to propose in 1949 that pions might not be elementary, but composite of a nucleon and an anti-nucleon (not yet discovered) bound together by a new force, different from the nuclear force.

In 1955, S. Sakata proposed at the annual meeting of the Physical Society of Japan a composite model of the hadrons. The paper was published the next year [16]. The model, which became later known as Sakata model, was based on three fundamental particles, the nucleons *n* and *p*, and one strange hyperon, the Λ, and their antiparticles. They were later called "sakatons". Sakata clearly pointed out the similarity of his model with the Heisenberg model of nuclei obeying isospin conservation.

Figure 1 reproduces two pages of the Sakata notebook, written around September 1955 [17], in which the author sketches the basic ideas of his model.

The Sakata model was developed in Japan, and in Russia by L. Okun, in the following years. In particular, the representation theory of the $U(3)$ symmetry in the frame of the model, was completed in 1959 by M. Ikeda, S. Ogawa and Y. Ohnuki [18]. Unlike the eightfold way, the evolution of the Sakata model had now a triplet of fundamental particles, $p\ n\ \Lambda$, that could physically support the symmetry.

The Sakata model was very close to the future quark model, but it was wrong. In 1962 it was found to contradict the experimental facts by C. Levinson *et al.* [19]. They showed that the reaction $\bar{p}p \to K_L^0 K_S^0$, which proceeds through an odd-parity state and had been observed, is forbidden by the model[1].

Notwithstanding this, and other problems like the non-existence of the foreseen positive $S = -2$ hyperon, the Sakata model survived, especially in Japan, for many years after the birth of the quark model.

4 Quarks and aces

The breakthrough came in 1964, when G. Zweig [20] and M. Gell-Mann [21] independently proposed a hadron model based on a fundamental triplet representation of $SU(3)$. As in the Sakata model the triplet consisted in an isospin doublet with strangeness $S = 0$ and an isospin singlet with strangeness $S = 1$. These are the u, d and s quarks, respectively. Differently from Sakata, quarks have fractional charges, +2/3, −1/3 and −1/3, respectively, and fractional baryon number =1/3. Today we speak of three different quark "flavours", which have nothing to do with the usual flavour.

The motivations of the two authors were different.

G. Zweig recalls [22] that in 1963, when he was still a PhD student of R. Feynman at Caltech, the discovery of a new vector meson, called ϕ, was published [23]. In an interview [24] in 2013 he stated: "There was a remarkable problem that required a solution, although the existence of this problem was not widely recognized. The ϕ meson was not decaying into $\rho+\pi$, which should have been its dominant mode of decay. Instead it was decaying into the kinematically unfavoured $K^+ + K^-$ mode. This suppression of $\rho+\pi$, by two orders of magnitude, had to be dynamical, since a symmetry for suppression was not available."

In Summer 1963 Zweig moved to CERN, where he fully developed his model. The puzzle could be solved assuming, similarly to Fermi and Yang, that mesons are composite of a fermion-antifermion pair. However, the fundamental, pointlike, fermions were not nucleons, like for Fermi-Yang and Sakata, but new fields he called "aces". He was thinking of a correspondence with leptons, four of which were known in 1963. In a recent conversation at the International School of Subnuclear Physics at Erice, he responded to a question of mine: "in Latin *as* is a coin but also stands for unit, or one. This was another reason for choosing the word *ace*".

As a matter of fact, the interpretation of the then known hadron spectrum required only three aces, belonging to the fundamental $SU(3)$ representation, as already recalled. In order to leave open the door to as many different aces could exist, Zweig did not use the four card suit symbols, but polygons of number of sides increasing with the mass, a circle for u, a triangle for d and a square for s. A fourth ace should be a pentagon, etc. The symbols are

[1] The argument goes as follow. We start by observing that isospin and parity conservation forbid the annihilation for odd-parity states. Indeed, the initial state has $I = 0$ and the $I = 0$ states of two pions are symmetric under the interchange of the two pions and hence have even parity. Now, in the Sakata model there is an $SU(3)$ symmetry that interchanges p with Λ everywhere. Under this transformation, charged pions, $\bar{p}n$ and $\bar{n}p$, become neutral kaons, $\bar{\Lambda}n$ and $\bar{n}\Lambda$, and the selection rule forbids the $p\bar{p} \to K^0\bar{K}^0$ annihilation in odd parity. In the octet model (and in the quark model) there is no such a selection rule, because the analogous transformation on pions and kaons interchanging u and s quarks, mixes Λ with Σ rather than Λ and p.

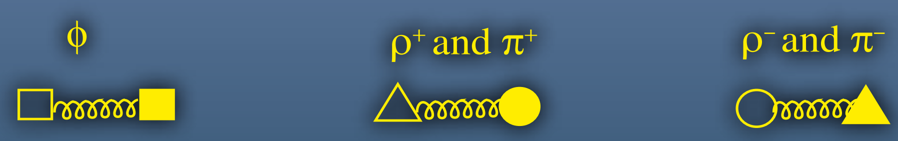

Fig. 2 Ace content of ϕ, ρ and π mesons.

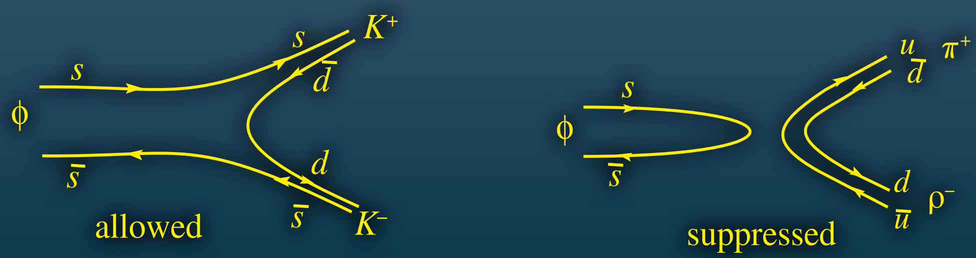

Fig. 3 A Zweig rule.

open for the aces, filled for the antiaces.

The composition of the ϕ, ρ and π mesons is shown in fig. 2.

Further hypothesis were needed beyond the broken *SU*(3) symmetry, that became know as "Zweig rule". Among them is the conservation of aces, "aces do not eat each other". Consequently, they should exist as physical, rather than purely mathematical objects. Since the ϕ consists only of s and $\bar{s}$ constituents, which are not present in ρ or π, the decay ϕ to $\rho+\pi$ is strongly suppressed. This is shown in fig. 3

A criticism was made by Feynman, when Zweig was back in Caltech in 1964, namely that nothing prevents states with the same quantum numbers, as $\rho\pi$ and $s\bar{s}$ are, from mixing. Consequently the suppression should not exist. We know now that the mixing exists but is just such that it makes ϕ contain $s\bar{s}$ only. This is not the case of the pseudoscalar mesons, for reasons that were not known at the time. Indeed, the ace model, and the quark one, were purely phenomenological. There was no theory. The theory, Quantum Chromodynamics (for an introductory level treatment see [25]), will come after many years, with all the answers.

The fundamental work of Zweig was never published. It remained in the form of a CERN Theory Division preprint [20]. Why did that happen? To my query, Zweig answered that the head of the Theory Division, L. Van Hove, blocked the publication and even cancelled the seminar that had been scheduled to present his results. Zweig told me also however that: "shortly after the CERN preprints were circulated, Linus Pauling sent me the proofs of the third edition of his "College Chemistry" [26], where he presented aces to undergraduates, for corrections. But none were necessary".

Gell-Mann's approach was completely different. Already in the eightfold way paper he had considered the field theory as a provisional instrument to abstract the symmetry relations. The latter are to be tested against the experimental evidence. In February 1964 he considered such an instrumental theory based on fields belonging to the fundamental representations of *SU*(3), the triplets 3 and $\bar{3}$. The fields had factional charges. He writes:

"[…] we assign to the triplet *t* the following properties: spin 1/2, $z = -1/3$, and baryon number 1/3. We then refer to the members $u^{+2/3}$, $d^{-1/3}$, and $s^{-1/3}$ of the triplet as "quarks" q and the members of the antitriplet as antiquarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc […].

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model […] All these relations can now be abstracted from the field theory model".

He called them quarks, inspired by *Finnegans Wake*, were

Joyce wrote the nonsense rimes

Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.

Concluding the article with:

"It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass). Since charge and baryon number are exactly conserved, one of the quarks […] would be absolutely stable. […] Ordinary matter near the earth's surface would be contaminated by stable quarks as a result of high-energy cosmic ray events throughout the earth's history, but the contamination is estimated to be so small that it would never have been detected. A search for stable quarks of charge −1/3 or +2/3 and/or stable di-quarks of charge −2/3 or +1/3 or +4/3 at the highest energy accelerators would help to reassure us of the non-existence of real quarks".

In the same year, Gell-Mann and Ne'eman published a book with the reprints of the main articles on "the eightfold way" and related topics. The introduction to the chapter on quarks reflects the thinking of the time, including Gell-Mann [27]:

"The question of which particles are "fundamental", if any, and how a detailed Lagrangian field theory model could be identified in practice are subtle ones and the whole investigation may not lead anywhere. Certainly, any attempt to describe the known hadrons dynamically as simple pairs or triads of very heavy "fundamental objects" is doomed to failure, because higher-order corrections in the field theory sense will be of greatest importance and all these dynamical effects would be largely subsumed, in the sense of dispersion theory, in the lower threshold energy channels, such as are included in approximate bootstrap calculations".

In the following years, fractional charged stable particles were searched in many experiments, both at high-energy accelerators and with Millikan-like techniques, on samples from the most different origins, including the stones brought back from the Moon by the astronauts. No quark was found, or, better, all the claims of positive evidence turned out to be wrong.

We know now that the reason for that is not that quarks do not exist, but that they cannot exist free, they are confined into the hadrons.

In the 1960s a 2-mile long linear electron accelerator (LINAC) was built at Stanford in California. Its maximum energy was 20 GeV. The laboratory, after that, was called Stanford Linear Accelerator Center (SLAC). J. Friedman, H. Kendall and collaborators at MIT and R. Taylor and collaborators at SLAC built two electron spectrometers up to 8 GeV and 20 GeV energy, respectively. The instruments accurately measured energy and direction of the outgoing electron scattered by protons or neutrons. Internal structures of size inversely proportional to the momentum transferred from the initial to the final electron can be explored. The process is very inelastic and is called deep inelastic scattering (DIS).

In 1909 the Geiger and Marsden experiment showed to Rutherford that a massive object of dimensions smaller than the resolution was sitting in the atom. In 1969, the SLAC DIS experiment gave its result [28]: protons and neutrons contain point-like objects. They were called "partons" by Feynman, who interpreted correctly the experimental observations [29]. They are just the aces or "real" quarks, as Feynman later recognised.

However, the idea of a further level of composedness was not yet accepted by all, including W. Heisenberg, who, in an interview of the first 1970s [30], answered to a specific question: "Even if quarks should be found (and I do not believe that they will be), they will not be more elementary than other particles, since a quark could be considered as consisting of two quarks and one antiquark, and so on. I think we have learned from experiments that by getting to smaller and smaller units, we do not come to fundamental units, or indivisible units, but we do come to a point where division has no meaning. This is a result of the experiments of the last twenty years, and I am afraid that some physicists simply ignore this experimental fact". The truth was just the opposite.

5 Colour and more flavours

In the quark model, the Δ^{++}, discovered by Fermi in 1952, is made of three u quarks in an S-wave and in the symmetric spin state $J = 3/2$. Consequently, the state is symmetric under permutations, in contradiction with the spin-statistics theorem of W. Pauli [31], according to which quarks, as spin-1/2 particles, obey Fermi statistics and must be in an anti-symmetric state. The same problem exists for the Δ^- (three d quarks in a symmetric state) and for the Ω^- (three s).

Theoretical developments in the 1960s lead to resolve this contradiction by allowing quarks to have a new hidden three-valued charge, which was called "colour" charge (again, nothing to do with the usual colour) in 1971 by M. Gell-Mann and H. Fritsch [32]. Quarks in a baryon in an antisymmetric configuration of the hidden degree of freedom would be in the observed symmetric configuration of space and spin.

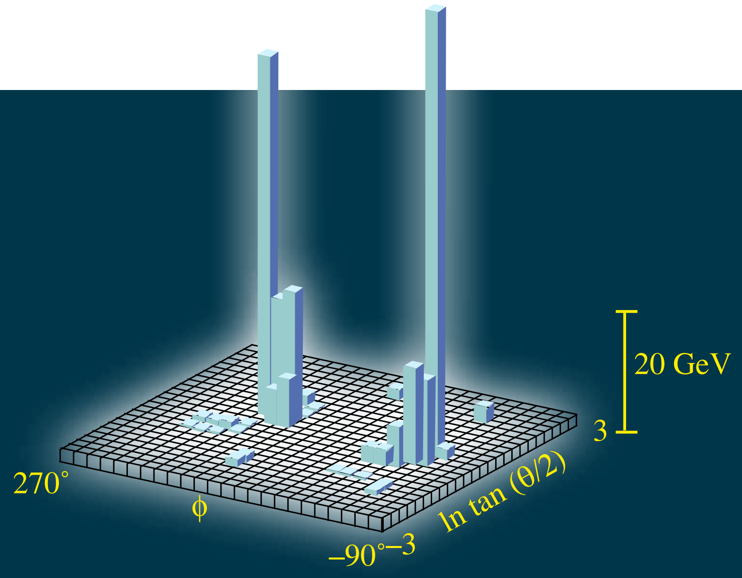

Fig. 4 Two quark jets in the calorimeters of the UA1 experiment. Elaborated from fig. 3 of Albajar *et al.* "Analysis of the highest transverse energy events seen in the UA1 detector at the SPPS collider" [37], reproduced with permission of Springer Science + Business Media, © 1987.

In 1965 Y. Nambu [33] and M. Y. Han and Y. Nambu [34] proposed a model with three quark triplets. The model has two different $SU(3)$ symmetries. One, say $SU(3)_f$, is the flavour symmetry of the quark model and the other, $SU(3)_c$, is the symmetry of the colour charge. The former is a broken symmetry, the latter is exact. The mediators of the force between quarks are an octet of vector bosons, which we now call "gluons". Differently from the photon, the gluons carry colour charges themselves. Starting from that, quantum chromodynamics (QCD), the theory of strong interactions, developed in the following years.

In 1972 G. 't Hooft in an unpublished contribution to a Conference in Marseille and in 1973 D. Polizer [35] and D. Gross and F. Wilczek [36] discovered that the colour charge decreases with decreasing distance between quarks, a property called asymptotic freedom. In a high-momentum-transfer collision quarks behave almost as free particles. However, the hit quark does not remain naked but soon it dresses with hadrons, giving origin to a "jet". The jets of hadrons are clearly observed in the laboratory. At high enough energies, above tens of GeV, we see groups of hadrons in narrow cones around the original quarks directions or as localised energy deposits in the calorimeters surrounding the interaction point. An example is shown in fig. 4. This is the way in which quarks become observable.

On the contrary, the colour force between quarks grows larger and larger as we try to take them apart increasing the distance between them. Quarks remain confined in the hadron.

A surprising outcome of the DIS experiments was that summing up the momenta carried by the quarks one obtains only 50% of the momentum of the nucleon in which they are. The reason is that hadrons are not made only of quarks, but also of gluons. The "missing" 50% of the nucleon momentum is carried by gluons.

As for the masses, we now know that those of the *u* and *d* quarks are very small, $2.3^{+0.7}_{-0.5}$ MeV and $4.8^{+0.7}_{-0.3}$ MeV, respectively. In total, only about 10 MeV of the 938 MeV proton mass is due to the quark masses, the remaining 99% is energy of the gluons, that is the energy of the colour field.

Three more quarks, heavier than the first three, were discovered in the following years.

In 1970, S. Glashow, I. Iliopoulos and L. Maiani [38] introduced a theoretical mechanism, which became known as GIM, to explain the experimentally observed suppression of the "neutral current" weak processes between quarks of different flavour that should otherwise have been faster by several orders of magnitude. This was done introducing a fourth quark *c*, with a new flavour called charm. It was discovered in cosmic rays by K. Niu *et al.* [39] in Japan in 1971 and independently at accelerators in 1974 by S. Ting *et al.* [40] and by B. Richter *et al.* [41].

In 1973, M. Kobayashi and T. Maskawa [42] showed that the observed *CP* violation in the neutral kaon system could be explained if two more flavours existed, extending to six flavours the Cabibbo mixing theory. Three, of the overall six, of them should have charge Q, three $Q-1$. The argument is valid both for integer (two more sakatons) and fractional charges (two more quarks). Indeed they are quarks, with flavours *b* for beauty, and *t* for top.

Mesons containing a $b\bar{b}$ pair were discovered in 1977 at Fermilab by L. Lederman and collaborators [43]. The sixth quark, the top, has a very large mass, 173.5 ± 1.0 GeV, and consequently had to wait eighteen years to be discovered, in 1995, by the CDF [44] Collaboration at the Fermilab Tevatron collider.

Acknowledgements

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