Chapter

Introductory Chapter: Quantum Chromodynamic

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1. Hypothesis of quarks

In the 1950s, the list of elementary particles was very long. Apart from "old" particles such as protons, neutrons, and electrons, the list contained also muons, mesons $\pi^{\pm}$, π^{0}, "heavy" mesons K, hyperon Λ, $\Sigma^{\pm}$, Σ^{0}, Ξ^{0}, Ξ^{-}. These particles decay in weak interactions. Their average lifetime was at a level of 10^{-10} s. However, some other very short-time particles were discovered (called resonances) decaying in strong interactions with the lifetime at a level of 10^{-23} s.

Among many proposals introducing some order in the elementary particle world, the most significant was the idea of Murray Gell-Mann. He proposed to introduce a new quantum number—"strangeness." This name appeared too frivolous for the Physical Review editor who demanded a more appropriate description. Finally, in the printed version of the paper, the term "unstable" was used. Gell-Mann was so disgusted that he did not publish more in Physical Review.

The English theoretician Richard Dalitz mentioned that the physics of mesons π was the most important for physicists at that time, while strange particles were treated as some type of squalidity not important in nucleus interactions. When Dalitz published a very good paper on some aspects of decay of some meson, he was warned that the development of such suspicious "theories" can be fatal for his carrier.

In 1961, Gell-Mann [1] and independently Israeli physicist Yuval Ne'eman [2] developed a classification of particles based on the SU(3) group. This symmetry is an extension of isospin symmetry introduced in 1932 by Heisenberg who noticed that proton and neutron can be treated as two different states of the same particle: nucleon. They differ only by the electric charge. In the world without the electromagnetic interactions, proton and neutron were indistinguishable.

In the SU(3) symmetry differs between themselves not only by electric charge but also by the strangeness. This formalism allowed Gell-Mann to predict the existence of the hyperon with a triple strangeness denoted as Ω^{-}. In 1964, this particle was discovered and its features were exactly as predicted by SU(3) formalism.

In 1964, Gell-Mann introduced a very brave hypothesis that all hadrons are built from sub-elementary components called "quarks" [3]. Simultaneously, a similar idea was proposed Georg Zweig. But his idea was published in the internal CERN bulletin and did not get a wide popularity. Gell-Mann assumed that three types of quarks exist in nature: "up," "down," and "strange." They would be fermions with the baryon number ⅓. The electric chargé of u-quark was + ⅔, and both d and s quarks were electric chargé −⅓. Simultaneously with quarks, anti-quarks should exist. Hadrons would consist of 3 quarks, mesons from a pair quark-antiquark. A majority of physicists in that time considered Gell-Mann idea as ridiculous and nonsensical. A society's prejudice was so strong that scientific promotions were blocked for scientists developing such nonsenses. Nevertheless, the quark model slowly became step by step more successful. It explains in a very simple way that the cross section between nucleon-nucleon interactions is 1.5 times bigger than the cross section between pions and nucleons. It was fast noticed that the introduction of the new quantum number is needed to remain the Pauli exclusion principle. For example, according to the Gell-Mann scheme Hyperon Ω^- should be built from three "s" quarks in the same state. Oscar Greenberg [4], Moo-Young Han, and Yoichiro Nambu [5] introduced in 1964 an idea of color charge (shortly a color). This idea removed difficulties with the Pauli principle.

From the time of introduction of quarks as hypothetic components of hadrons, the important problem was for an explanation whether hadrons crashing for very high energies can free quarks and we can see them as free particles. A matter ionization is proportional to the electric charge. Traces in cloud chambers remaining by free quarks should correspond to 1/9 and 4/9 in comparison with free electrons. Many research centers have looking for such traces and even some centers reported these investigations as successful; however, all appeared false. When any attempts of free quarks finding failed and theoretical assumptions were considered as doubtful, quarks started to be treated as fiction and a singularity. Even the author of quarks Murray Gell-Mann certified in 1972 that "it is possible to build the hadron theory based on quarks as fiction objects."

The best tools for studying the nucleon structure are point particles, for example, electrons. In 1933, we knew that nucleons have some structure because they have much bigger magnetic moment than calculated from Dirac equations for the point particle.

In 1953, Robert Hofstadter marked out a density distribution of the electric charge for many nucleuses and in 1954, also for proton and neutron giving their "electric radius" (squared averaged radius their charge density distribution ~0.74×10^{-15} m). Results showed that nucleons have some continuous structure.

In 1967, Jerome Friedman, Henry Kendall, and Richard Taylor started experiments at Stanford with a deep inelastic scattering of electrons on protons. Results were difficult to understand. Theoretical speculations suggested that some point structures can exist inside nucleons. At the same time, Richard Feynman and James Bjorken try to explain the Stanford results. Feynman developed the parton model, which has been confirmed in the next experiments and is used up today. Parton can be identified with quarks.

In 1974, the so-called "November revolution" significantly concurred to acceptance of the quark model. Two experimental teams from Stanford (conducted by Burton Richter) and Brookhaven (conducted by Samuel Ting) published simultaneously [6, 7] on a discovery of a new particle with a mass three times bigger than a proton. Teams used quite different methods and did not know each other on the "concurrent" experiment. The features of a newly discovered particle can be explained only by an assumption that it consists of a quark of a new type. The existing of the fourth quark was considered earlier, now this was an irrefutable proof. Symbols proposed for a new particle were different and neither Stanford nor Brookhaven teams were convinced to use a unified symbol. The particle is known as J/ψ. The fourth quark was called as "charmed."

Soon, proofs on the existence of new two quarks were obtained. Leon Liederman's team from Fermilab discover the fifth quark (denoted as "beauty" or "bottom"). In 1995, the sixth quark (denoted as "true" or "top") was discovered. At present, we accept the existence of three quark doublets: (u,d), (c,s), and (b,t). We are almost sure that the third family is the last and the fourth generation of quarks does not exist.

The only experimental results were not enough for the physics society. A theory explaining quarks interactions was expected.

2. The road toward the Standard model

In 1971, Gerardus t'Hooft [8, 9] proved that the gauge theories (introduced in 1954 by Chen-Ning Yang and Robert Mills [10]) can be renormalized as quantum electrodynamic. In 1973, David Gross and Frank Wilczek [11] from Princeton and independently David Politzer [12] from Harvard discovered quark asymptotic freedom. An interaction force between quarks increases with a distance between them and vanishes when quarks approach each other. Quarks on very small distances can be treated as almost free. The theory explained the problem of quark confinement. Quarks, as a component of hadrons, must be confined inside hadrons.

Several months later, Murray Gell-Mann, Harald Fritsch, and Heinrich Leutwyler [13] introduced carriers of quark interactions—the octet with the colored charge. This was the beginning of Quantum Chromodynamics—QCD [14].

One of the very important parts of the QCD is the theory of electro-weak interactions developed by Sheldon Glashow [15], Abdus Salam [16], and Steven Weinberg [17] known as the Standard model. This theory unified the electromagnetic interactions carrying by photons with the weak interactions carrying by intermediate bosons $W^{\pm}$ and Z^0. The last bosons were considered as an intermediary in neutral currents. In 1973, the expected neutral currents and in 1983 charged bosons W^+ and W^- and neutral Z^0 were discovered.

In QCD virtual gluons "anti-screen" color charge in a vacuum and this effect dominates on screening of electric charge by quarks. It means that the color charge, which in a big distance is large, has the source in a weak charge on small distances and aims to zero where distances between quarks also aim to zero. The force between quarks increases together with a distance between them.

The Standard Model agrees with experiments with a high precision. However, it is not a final version because it contains some free parameters that have to be taken from experimental results. Nevertheless, it is a fantastic tool describing the micro-world.

Missing elements of the Standard Model is a mechanism of mass generation by particles. Peter Higgs [18] in 1964 proposed a mechanism assuming the existence of super-heavy particle (H boson). On July 4, 2012 two experiments ATLAS and CMS announced a discovery of the Higgs boson in LHC experiments in CERN. The mass is 125.3 ± 0.4 GeV/c^2. It is a massive scalar boson with zero spin, no electric charge, and no color charge. It is also very unstable, decaying into other particles almost immediately.

In 1974, Howard Georgi and Shelton Glashow [19] proposed a first Grand Unified Theory (GUT) based on the simple Lie group SU(5). The motivation of GUT is the fact that the electric charge of electrons and protons is the same with extremely high precision but this feature is not explained by the Standard Model.

The strong and weak interactions in the Standard Model are based on gauge SU(3) and SU(2) symmetries, respectively. The weak hypercharge interaction is described by an Abelian symmetry U(1). The strong and weak interactions might be unified in one Grand Unified interaction described by a single, larger simple symmetry group containing also the Standard Model. This would automatically predict the quantized nature and values of all elementary particle charges.

The simplest group containing SU(3) × SU(2) as a candidate for the GUT is SU(5). The GUT symmetries allow a reinterpretation of known particles, like the photon, W and Z bosons, and gluon, as different states of a single particle field. The next simple Lie group that contains the standard model is SO(10). However, there are several difficulties in comparing theories with the experimental data. Model scenarios for sources of Ultra High-Energy Cosmic Rays (UHECRs), in which the observed particles are produced by the decay of other particles (top-down models), lead to large secondary fluxes of photons and neutrinos. In contrast, models in which the production of photons and neutrinos originates from secondaries generated by the propagation in the cosmic background (GZK effect) lead to much lower fluxes. The current flux limits rule out, or strongly disfavor, that top-down models can account for a significant part of the observed UHECR flux.

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