Quantum chromodynamics

G. 't Hooft

Spinoza Institut, P.O. Box 80.195, NL-3508 TD Utrecht
Netherlands
G.tHooft@phys.uu.nl

Received 18 Sep. 2000, accepted 10 Oct. 2000 by C. Thomsen

Abstract only

The strong interactions were the last of the fundamental forces in the twentieth century to be fully understood in terms of basic and fundamental equations. Shortly after the discovery of the renormalizable non-Abelian gauge theories that unified the electro-weak forces, it was realized that the strong force had to be described by such a gauge theory as well, but the mechanisms that determine the properties of physical particles sensitive to this force turned out to be considerably more difficult to understand.

The theory states that fundamental fermionic particles called "quarks" are held together by non-Abelian gauge forces associated to the group SU(3). These forces differ in an essential way from the electro-weak ones. In the latter, the gauge symmetry is affected by what we call the "Higgs-mechanism", which turns massless particle species into heavy, massive particles. The strong interaction gauge fields do not undergo the Higgs mechanism; something that could be called the diametrically opposite happens.

Whereas a step-by-step approximation procedure, called the perturbation expansion, proved to be quite effective for the electromagnetic and the weak forces, this procedure fails when one attempts to apply it for the strong force. Its "non-perturbative" features often dominate.

A number of mathematical procedures were invoked to address this situation, many of which were unsuccessful. The 'renormalization group' could be applied to obtain some idea of what might happen, and this resulted in the first good formulation of the theory, in the early '70s. The breakthrough here came with the realization that the theory is 'asymptotically free', which means that the interactions can be weak at short distances yet at the same time strong when particles are separated at larger distance from each other, exactly as had been deduced from experimental observations.

Yet how this force manages to keep the quarks completely trapped, in such a way that isolated quarks are a physical impossibility, remained a mystery, until it was realized that this could be explained if a non-perturbative version of the Higgs mechanism acts not in the electric sector, as in the electro-weak case, but rather in the magnetic sector. Purely color-magnetic charges (color-magnetic monopoles) undergo Bose condensation, but this cannot be understood using conventional perturbation expansions.

A parallel development was that the theory could be analysed further by replacing space-time by a rectangular lattice. On such a lattice, a novel perturbative technique, a large-coupling expansion, also reproduced absolute quark confinement. The two pictures could be reconciled, which was further confirmed when computers became sufficiently powerful to allow for numerical analysis based on Monte-Carlo simulations on a four-dimensional space-time lattice.

Other, complementary, instruments were: 1/N expansions if [SU(3) is replaced by SU(N)], an illustrative solvable toy model in one space- one time dimension, and computations of the consequences of topologically twisted gauge-field configurations called 'instantons'. Perturbative techniques supplemented by adding the (non-perturbative) effects due to instantons often give results that compare quite well with experimental observations. In particular, instantons provide for the unique explication of an apparently bizarre symmetry breaking pattern in the observed low-mass pseudomeson spectrum. Finally, supersymmetric and superstring techniques brought further insights.

The theory of Quantum Chromodynamics is by no means completed. Quite a few mysteries remain to be resolved. We do believe that we have the exact equations and that they can be checked against experiment numerically, but the convergence of extensive computer calculations is slow, and new analytical methods are urgently needed, in order to allow more precise comparisons with experiment to enable us to obtain more precise understanding of the physical properties of the hadronic particles, and, not to forget, to *prove* that the theory has a sound mathematical basis.

Indeed, the assignment to mathematicians to prove the existence of a mass gap — which is believed to be true by all physicists – using nothing but the mathematical axioms as a starting point, has been issued as a Prize Problem. Last but not least, it will be important to learn how to deal with the experimental data to be expected from future accelerators such as LHC concerning quark-gluon plasmas.