Background information on the 1999 Nobel Prize in Physics

Particle physics deals with the properties of the basic constituents of matter and the interactions between them. Up to now, the most successful "language" in this branch of physics has been that of relativistic quantum field theory. In this framework elementary particles are represented by (second quantized) fields, these being functions of space and time that include creation and annihilation operators for particles. For example light, the photon, is represented by such a field. These fields are thus the building blocks of theories that attempt to describe elementary particles and their interactions.

A highly successful theory of this kind is Quantum Electrodynamics, commonly known as QED. QED describes, to a very high degree of accuracy, the interactions of electrons, positrons and light at low energies. It also enjoys a great deal of success in many other applications, for example when it is used to describe the interaction of light with atoms. However, the development of QED and understanding its quantum structure did not come easily but took several decades. The theory was to be used perturbatively. In other words, taking into account higher order corrections was expected to improve the accuracy of its predictions. But instead some of these corrections were found to be infinitely large. Many scientists contributed to elucidating and solving the problems of QED, among them R. P. Feynman, J. Schwinger and S.-I. Tomonaga who shared the 1965 Nobel Prize in Physics for "their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles". Through these heroic efforts QED became a predictive theory. Employing perturbation theory, prescriptions were given as to how to compute theoretical values of measurable quantities. These could then be compared with experimental findings. Pictorial diagrams, invented by Feynman and named after him, helped a great deal in systematizing and facilitating the theoretical computations. In this approach the previously mentioned infinite quantum corrections appear in the diagrams as closed loops. High precision measurements have established that QED is an excellent theory.

The theory of weak interactions of elementary particles posed new and even more challenging difficulties. These interactions play a paramount role in nature. For example, the sun would not have shone had there been no weak interactions. A relativistic quantum field theory of weak interactions was proposed already in the 1930's by E. Fermi. This theory provided a great leap forward in the understanding of weak interactions because it systematized and described a large number of phenomena rather well. However, it encountered two major problems. One was that in the framework of perturbation theory, where it was to be used, quantum corrections to the rate of any weak process were infinitely large because of closed loops. Moreover, these infinities were far more "vicious" than those encountered earlier in QED. The second difficulty, referred to as the unitarity problem, was that the theoretical expressions for cross sections, obtained even at the lowest order of perturbation theory, looked absurd. At high energies they violated the probability interpretation of quantum mechanics. Furthermore, the methods developed earlier to cure the problems encountered in QED were not applicable for solving the difficulties of Fermi's theory.

An attractive possibility was to modify Fermi's theory by introducing two charged spin-one particles (charged vector bosons also referred to as intermediate vector bosons). The theory did then resemble QED, with the photon replaced by its massive charged counterparts. There was an additional bonus as these vector bosons could easily explain the observed "universality" of weak interactions. In spite of these good features the above two problems persisted.

The great merit of this year's Laureates, Gerardus 't Hooft and Martinus Veltman, is that they made a decisive contribution to solving the difficulties inflicting theories of weak interactions by investigating them in an extended framework called nonabelian gauge theories or Yang-Mills theories, where the concept of symmetry plays the leading role.

In 1954 C. N. Yang and R. L. Mills constructed the first example of a nonabelian gauge theory. These physicists examined what would happen if the isospin symmetry (introduced by W. Heisenberg in 1932 in order to explain certain similarities of protons and neutrons) were a "local", i.e., space-time dependent symmetry. They discovered that such a requirement would entail the existence of a trio of massless self-interacting vector bosons, with electric charges +1, 0 and –1, in units of the proton charge. In spite of the fact that no such massless particles exist in nature, this way of thinking constituted the basis on which the Standard Model of particle physics was built (see below). The quantum structure of the "massless Yang-Mills theory" was studied by several authors. Among those who at an early stage made significant contributions in this domain were R. P. Feynman, B. S. DeWitt, L. D. Faddeev and V. N. Popov.

At present the weak interactions are described, together with electromagnetic interactions, by the Standard Electroweak Model which is a nonabelian gauge theory appended by a QED-like structure. In this Model there are three families of quarks and leptons and four vector bosons. Two of the vector bosons carry electric charge and are heavy (the W+ and the W- bosons), one is heavy and neutral (the Z boson) and the fourth one is the photon. The masses are introduced via the so-called Higgs mechanism. The Model predicts the existence of a spin-zero particle, called the Higgs Boson, which remains to be discovered. Furthermore, Fermi's theory emerges as the low-energy limit of the Electroweak Model taking into account only interactions mediated by the W+ and the W- bosons. In 1979 S. L. Glashow, A. Salam and S. Weinberg received the Nobel Prize in Physics "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current." The actual discovery of the massive vector bosons was honored by the 1984 Nobel Prize in Physics to C. Rubbia and S. van der Meer.

The contributions of 't Hooft and Veltman have had an enormous impact on the development of particle physics. They showed that the nonabelian quantum field theories could make sense and provided a method for computing quantum corrections in these theories. This was a pathbreaking discovery that made it possible to compute quantum corrections to many processes and compare the results with experimental observations or to make predictions. For example, the mass of the top quark could be predicted, using high precision data from the accelerator LEP (Large Electron Positron) at the Laboratory CERN, Switzerland, several years before it was discovered, in 1995 at the Fermi National Laboratory in USA. The top quark, in spite of being too heavy to be produced at the LEP accelerator, contributed through quantum corrections by a measurable amount to several quantities that could be measured at LEP. Similarly, comparison of theoretical values of quantum corrections involving the Higgs Boson with precision measurements at LEP gives information on the mass of this as yet undiscovered particle.

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References

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