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Elementary Particle Physics

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The two classical branches of elementary particle physics are the experimental and the theoretical one. Experimental particle physics started more than a hundred years ago with the discovery of the electron. The constituents of the atomic nuclei, protons and neutrons followed, but more and more new and exotic elementary particles were discovered in the course of time. The analysis of their behaviour revealed three different kinds of fundamental forces between the particles: first the electromagnetic interactions, which include the electric and magnetic phenomena, and are most important in everyday life, secondly the weak interactions, which are responsible for certain types of radioactivity and nuclear reactions, and thirdly the strong nuclear interactions, which bind the constituents of atomic nuclei together. In addition, there is the familiar gravitational force, which, however, does not play an important role in the physics of elementary particles.

The first complete theory of elementary particles was Quantum Electrodynamics, QED, the theory of electrons of photons. It describes the electromagnetic interactions of charged particles in a way consistent with both quantum theory and the special theory of relativity. It originates in the early work of Jordan, Pauli, Heisenberg, Dirac and others and was brought to maturity in the 1940s by Feynman, Schwinger, Dyson and Tomonaga. In QED the electromagnetic interactions are mediated by photons, the particles of light. The duality of matter and waves finds its full expression in QED: the quantized electromagnetic field can equivalently be considered as an ensemble of photons.

QED was not only a complete but also a perfect theory. It led to predictions, whose experimental examinations belong to the tests of physics with the highest precision. The necessary calculations do not rely on electronic computers, they are based on series expansions. The physical quantities of interest are expanded in powers of the electromagnetic coupling, the finestructure constant $\alpha = e^2/4\pi\epsilon_0\hbar c$, whose numerical value is approximately 1/137.036. It is the smallness of this number which allows such precise predictions to be made in QED.

The situation is different for the case of the strong interactions, where the coupling strength is by no means small. Methods analogous to the series expansions of QED soon came to an end, and much effort was spent to find suitable calculation schemes in the theory of strong interactions. In the early 1970s an ingenious proposal for a theory of the strong interactions was made, namely Quantum Chromodynamics, QCD. It describes the constituents of all nuclear matter, the quarks, and their mutual interactions via the exchange of so-called gluons. However, it was difficult to arrive at concrete numerical predictions from it.

A breakthrough was initiated by Ken Wilson's formulation of QCD on a space-time lattice. The replacement of the space-time continuum by a four-dimensional lattice allowed the application of a great variety of new methods, some of them coming from statistical mechanics of lattice systems. One of these methods was introduced to the field of elementary particle physics by Creutz, Jacobs, Rebbi and by Wilson himself, namely the numerical simulation of theories on a lattice by means of Monte Carlo algorithms. It turned out to become one of the most powerful tools for obtaining predictions from QCD and other models of elementary particle physics.

The simulation of a model is different from the traditional theoretical approaches. It is more of a numerical experiment, performed on a computer, with unknown outcome. The result is afflicted with systematical and statistical errors, like in real experiments. Because of its intermediate character, we can call it a computer experiment.

With increasing computer power, the results from numerical simulations of QCD and other models have become better and better. The major field of application within elementary particle physics is still QCD. The articles of Lippert, Orth and Schilling from Wuppertal, and of Sommer and Wittig for the ALPHA collaboration give an introduction to the basic ingredients of QCD and its Monte Carlo simulation. They discuss how problems like the calculation of the spectrum of bound states and the determination of fundamental parameters of QCD can be solved by performing computer experiments. Other quantities of great interest for the phenomenology of particles include the structure functions and form factors of nucleons, which are discussed in the article of Schierholz for the QCDSF collaboration.

In the early history of the universe and in different astrophysical objects like neutron stars, matter is under extreme conditions, i.e. at very high temperatures or densities. For the theoretical study of nuclear matter in such situations Monte Carlo simulations are an indispensible tool. Research in this field is described in the articles by Karsch et al. from Bielefeld, and by Montvay, Hands et al. from DESY, Hamburg, and Swansea.

Although numerical simulations of models of particle physics have been performed for more than 20 years now, there is still progress in the development of algorithms and lattice formulations of theories. The article of Jansen et al. discusses obstacles and their removal for the realization of an important symmetry, chiral symmetry of quarks, on the lattice.

QCD is part of the so-called Standard Model of elementary particle physics. Despite the great success of this model, it has some short-comings, and physicists try to go beyond the Standard Model. The most popular attempts in this direction involve supersymmetry, an extended concept of symmetry. The study of supersymmetric theories with the help of numerical simulations is the subject of the article of Montvay, Münster et al. from the DESY-Münster-Roma collaboration.

Finally, the article of Jansen shows, how sources of systematic errors in computer experiments, namely the finite lattice spacing and the finite volume of the lattice, can be dealt with and can even be exploited to gain physical information.