Chapter 1

Introduction

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Since old ages it has been one of the noble aspirations of humankind to understand the world in which we are living. In addition to our immediate environment, planet earth, two more remote frontiers have attracted interest: the infinitely small and the infinitely large. A flood of new experimental and theoretical results obtained during the past decades has provided a completely new picture of the micro- and macrocosm and surprisingly intimate relations have been discovered between the two. It turned out that the understanding of elementary particles and the forces acting between them is extremely relevant for our perception of the cosmological development. Quite often scientific research is supported because it is the basis for technical progress and for the material well-being of humans. The exploration of the microcosm and the universe contributes to this goal only indirectly by the development of better instruments and new techniques. However, it tries to answer some fundamental questions which are essential to understand the origins, the environment and the conditions for the existence of humankind and thus is an essential part of the cultural heritage.

One of the fundamental questions concerns the nature of matter, the substance of which the stars, the planets and living creatures are made, or to put it in another way—can the many phenomena which we observe in nature be explained on the basis of a few elementary building blocks and forces which act between them. The first attempts go back 2000 years when the Greek philosophers speculated about

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indestructible atoms, like Democritus, or the four elements and the regular bodies of Plato.

Since Newton who introduced infinitely hard smooth balls as constituents of matter¹ and who described gravitation as the first force acting between them, the concept of understanding nature in terms of ‘eternal’ building blocks hold together by forces has not changed during the past 200 years. What has changed was the nature of the elementary building blocks and new forces were discovered. The chemists discovered the atoms of the 92 elements which, however, contrary to their name, were found to be divisible consisting of a nucleus surrounded by an electron cloud. Then it was found that the atomic nuclei contain protons and neutrons. Around 1930 the world appeared simple with everything consisting of these three particles: protons, neutrons and electrons.

Then came the ‘annus mirabilis’ 1931 with the discovery of the positron as the first representative of antimatter and the mysterious neutrino in nuclear beta-decay indicating a new force, the weak interaction. In the following decades the ‘particle zoo’ with all its newly discovered mesons, pions and ‘strange’ particles was leading to great confusion. Simplicity was restored when all these hundreds of ‘elementary’ particles could be understood in terms of a new kind of elementary particles, the quarks and their antiquarks. The systematics of these particles is mainly determined by the strong nuclear force, well described today by the quantum chromodynamics QCD. Whether quarks and gluons (the binding particles of the strong interaction) exist only inside the atomic nuclei or whether a phase transition into a quark-gluon plasma is possible, is one the intriguing questions which still needs an answer.

Impressive progress was made in another domain, in the understanding of the weak nuclear force responsible for radioactive beta-decay and the energy production in the sun. Three kinds of neutrinos (with their associated antiparticles) were found and recently it could be shown that the neutrinos are not massless as had been originally assumed. The mechanism of the weak interaction could be clarified to a large extent by the discovery of its carriers, the W- and Z-particles. All the experimental results obtained so far will be summarized in this volume and the beautiful theoretical developments will be presented. The climax is the establishment of the ‘Standard Model of Particle Physics’ SM which has been shown to be a renormalizable gauge theory mainly by the LEP precision experiments. The LEP experiments have also shown that there are only three families of quarks and leptons (electron, muon, tau-particle and associated neutrinos), a fact not yet understood.

All the attempts to find experimental deviations from the SM have failed so far. However, the SM cannot be the final theory for the understanding of the microcosm. Its main fault is that it has too many arbitrary parameters (e.g. masses of the particles, values of the coupling constants of the forces, number of quark and lepton families) which have to be determined empirically by experiment. An underlying theory based on first principles is still missing and possible ways into the future will be discussed below.

¹Isaac Newton, *Optics*, Query 31, London 1718.

Returning to the ‘naïve’ point of ultimate building blocks one might ask whether the quarks and leptons are fundamental indivisible particles or whether they have a substructure. Here we are running into a dilemma which was recognised already by the philosopher Immanuel Kant.² Either ultimate building blocks are mathematical points and cannot be divided, but then it is difficult to understand how they can have a mass and carry charges and spin. Alternatively, the building blocks might have spatial extension, but then it is hard to understand why they could not be divided into smaller parts. Whenever one meets such a paradox in science it is usually resolved by recognising that a wrong question was asked.

Indeed the recent developments of particle physics indicate that the naïve concept of ultimate building blocks of matter has to be abandoned. The smaller the ‘building blocks’ are, the higher energies are necessary to break them up. This is simply a consequence of the Heisenberg uncertainty principle of quantum mechanics. In the case of quarks their binding energies become so strong that any energy applied to break them apart is used to produce new quark-antiquark pairs.³ The existence of antimatter implies also that matter does not have an ‘eternal’ existence. When matter meets antimatter the two annihilate by being converted into ‘pure’ energy and in the reverse mode matter can be produced⁴ from energy in the form of particle-antiparticle pairs.

One of the most exciting development of physics or in science in general is a change of paradigms. Instead of using building blocks and forces acting between them, it was progressively recognised that symmetry principles are at the basis of our understanding of nature. It seems obvious that laws of nature should be invariant against certain transformations since ‘nature does not know’ how we observe it. When we make experiments we have to choose the origin of the coordinate system, its orientation in space and the moment in time when we start the observation. These choices are arbitrary and the laws deduced from the observations should not depend on them. It is known since a long time that the invariance of laws of nature against the continuous transformations, i.e. translations and rotations in space and time, give rise to the conservation of momentum, angular momentum and energy, the most basic laws of classical physics.⁵ The mirror transitions (i.e. spatial reflection, particle-antiparticle exchange and time reversal) lead to the conservation of parity P , charge parity C and detailed balance rules in reactions, all of which are essential ingredients of quantum mechanics.

The detection of complete parity violation in weak interactions in 1957 was one of the most surprising observations. Many eminent physicists, including Wolfgang

²Immanuel Kant, *Kritik der reinen Vernunft*, 1781, see, e.g., Meiner Verlag, Hamburg 1998, or translation by N.K. Smith, London, MacMillan 1929.

³The binding energies are comparable to mc^2 , where m is the rest mass of a quark and c is the velocity of light.

⁴When Pope Paul John II visited CERN and I explained to him that we can ‘create’ matter his response was: you can ‘produce’ matter, but ‘creation’ is my business.

⁵Emmy Noether, *Nachr. d. königl. Gesellschaft d. Wissenschaften zu Göttingen*, 1918, page 235.

Pauli, thought that this symmetry could not be violated. Such a belief indeed goes back to Emanuel Kant² who claimed that certain ‘a priori’ concepts have to be valid so that we would be able to explore nature. Since it seemed obvious that nature does not know whether we observe it directly or through a mirror a violation of mirror symmetry seemed unacceptable. This phenomenon is still not understood, although the fact that also C conservation is completely violated and the combined symmetry PC seemed to hold has reduced somewhat the original surprise. The whole situation has become more complicated by the detection that PC is also violated, although very little. A deep understanding of the violation of these ‘classical’ symmetries is still missing. So far experiments show that the combined symmetry PCT still holds as is required by a very general theorem.

In field theories another class of more abstract symmetries has become important—the gauge symmetries. As is well known from Maxwell’s equations the electrodynamic fields are fully determined by the condition that gauge symmetry holds, which means that the electric and magnetic fields are independent against gauge transformations of their potentials. It was discovered that analogous gauge symmetries determine the fields of the strong and weak interactions in which case the (spontaneous) breaking of the symmetries plays a crucial role.

In summary, we have abandoned the description of nature in terms of hard indestructible spheres in favour of abstract ideas—the symmetries and their breaking. From a philosophical point of view one might, in an over-simplistic way, characterize the development as moving away from Democritus to Plato.

Finally, it should be mentioned that in particle physics progress was only possible by an intimate cooperation between theory and experiments. The field has become so complex that by chance discoveries are extremely rare. The guidance by theory is necessary to be able to put reasonable questions to nature. This does not exclude great surprises since many theoretical predictions turned out to be wrong. Indeed most progress could be made by verifying or disproving theories.

Although the Standard Model of Particle Physics SM (with some extensions, e.g. allowing for masses of neutrinos) has achieved a certain maturity by being able to reproduce all experimental results obtained so far, it leaves open many fundamental questions. One particular problem one has gotten accustomed to, concerns P and C violations which are put into the SM ‘by hand’. And as has been mentioned above the SM leaves open many other questions which indicate that it cannot be a final theory.

In 2008 I wrote the concluding paragraph of this introduction as “Many arguments indicate that a breakthrough in the understanding of the microcosm will happen when the results of LHC at CERN will become available. LHC will start operation in 2008, but it will probably take several years before the experiments will have sufficient data and one will be able to analyse the complicated events before a major change of our picture will occur, although surprises are not excluded. Hence it seems to be an appropriate time to review the present situation of our

understanding of the microcosm". Meanwhile, more than 10 years later, and with the Higgs boson discovered in 2014 at the LHC, the extended SM has been confirmed with unprecedented precision yet the outstanding questions, in particular which path to follow beyond the SM, have remained with us.

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