Beyond the Nanoworld

Quarks, Leptons, and Gauge Bosons

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Wellesley, Massachusetts

Editorial, Sales, and Customer Service Office

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888 Worcester Street, Suite 230
Wellesley, MA 02482
www.akpeters.com

Library of Congress Cataloging-in-Publication Data

Dosch, Hans Günter.
[Jenseits der Nanowelt. English]
Beyond the nanoworld : quarks, leptons, and gauge bosons / Hans Günter Dosch.
p. cm.
Includes index.
ISBN 978-1-56881-345-5 (alk. paper)
1. Particles (Nuclear physics) --History-- 20th century. I. Title.

QC793.16D6713 2007
539.7′20904--dc22

2007041605

Front cover images, left to right: ALICE muon spectrometer; ATLAS cavern; TCP Time Projection Chamber; ALICE muon spectrometer. ALICE Collaboration, CERN Document Server. ©CERN.

Back cover image: Gluon discovery in 1979. DESY, Hamburg, Germany.

Printed in the United States of America
12 11 10 09 08 10 9 8 7 6 5 4 3 2 1

In memory of *J. H. D. Jensen*

For *Simon, Linus, Jonas, and Philipp*

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Contents

1

The Heroic Time

The foundations of modern physics—in contrast to those of classical physics—were laid in the first half of the twentieth century. In theoretical physics, the decisive developments were the establishment of relativity and quantum physics, while experimental physics contributed a secure knowledge of the atomic structure of matter as well as the internal structure of atoms. Nearly all fields of modern science, from astrophysics to medical diagnostics, have been strongly influenced by the methods and concepts developed during this period.

1.1 Introduction

The study of the science of elementary particles goes back to ancient times. In ancient Greek natural philosophy, we already find the hope that by exploring the fundamental constituents of matter, one might reduce sensory experiences —such as sweet and bitter, warm and cold—to these basic components. The idea of using the certainty of mathematics to this end is also traceable to that era. More than 2,000 years ago, this was attempted by Plato, who described his theory of the world in his dialogue *Timaeus*. He made use of the mathematical result that there are only five regular solid figures. He assigned four of these Platonic solids to the four elements of ancient science (see Figure 1.1). To earth he assigned the cube, since "the earth is of the four kinds the most immovable and under the bodies the most plastic." To fire he assigned the tetrahedron, since it has the "least areas and is in all directions the most movable, the most acute and the sharpest." Using similar reasoning, he assigned the icosahedron to water and the octahedron to air. He assigned the remaining dodecahedron,

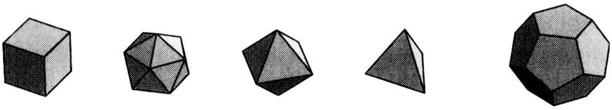

Figure 1.1. The assignment of the five Platonic solids to the four natural elements and to the universe as a whole.

which is the most similar to the sphere, to the All (the universe). Plato is scientifically very restrained in presenting his theory, indeed more cautious than Galileo would be almost 2,000 years later. Plato claims only that his theory is plausible, not that it is certain.

In his book *The Part and the Whole,* Werner Heisenberg writes that as a college student he found Plato's theory very speculative, but more convincing than the atoms of his schoolbooks with their hooks and eyes.

Ancient atomism was described by Lucretius in the six books of his poem *On the Nature of Things.* Of course, there are essential differences between ancient natural philosophy and modern particle physics, but they have some fundamental ideas, and even some methodological approaches, in common. This is apparent when one looks at the great influence of ancient ideas on modern thought. Plato's influence on Galileo and Kepler is well known. The Scottish physicist Lord Kelvin proposed a very abstract and strikingly modern topological model of the atom as a vortex in the ether in 1886, not long after Hermann Helmholtz had shown that such vortices were stable in an ideal liquid. Therefore, to Lord Kelvin these vortices seemed to furnish a very plausible model for—as he writes—Lucretian atoms.

The first theorists of elementary particles in the modern sense of the term were chemists. In chemistry, the fundamental particles are the constituents of the basic chemical elements. They were called atoms, since they were believed to be indivisible. Important quantitative conclusions were drawn from that atomic theory. With the discovery of the electron, however, it became clear that there are particles that are even simpler than the atoms studied by chemists.

I do not intend to describe the complete history of atomism; I will start with the discovery of the electron at the end of the nineteenth century (1899). From that time on, the name *elementary particle* has been used for a host of different objects. Until 1935, the study of particle physics was rather uncomplicated. The well-established elementary particles were the *proton* and the *neutron,* which were the components of the atomic nucleus, the *electron,* which formed the atomic cloud around the nucleus, and the *photon*, which was the quantum of electromagnetic radiation. In the late 1930s the *mesotron* and the *neutrino* joined the club. The mesotron was introduced in order to explain nuclear forces, while the existence of the neutrino was postulated in order to explain certain types of radioactive decay.

From 1950 onward the situation became more complex. More and more particles were discovered, all of which could with equal justification be called elementary. Moreover, the theoretical description of these particles using the older methods no longer appeared to be meaningful. This led to the era of "nuclear democracy," which posited the existence of many particles of equal status, with the existence of any one of them including the existence of the others. However, this theoretical framework was soon seen to be insufficient and possibly inconsistent. Slowly, a theoretical model was developed according to which nuclear constituents such as the proton, the neutron, and many of the newly discovered particles of the nuclear democracy were taken to be composed of simpler constituents, *quarks.* This model was soon developed into a consistent theory, called *quantum chromodynamics.* The development of this "particle zoo" is displayed graphically in Figure 6.15 at the end of the book.

Forty years later, the question about which particles are truly elementary seems easier to answer, and at the same time, the goals are more ambitious. Today, one wants not only to explain the properties of matter starting from the basic properties of elementary particles, but also to deduce the properties of elementary particles themselves from elementary principles. This is the subject of *Dreams of a Final Theory: The Scientist's Search for the Ultimate Laws of Nature,* written in 1992 by the Nobel Prize winner Steven Weinberg. It seems, however, that we now are further away from discovering the "final theory" than we were when Weinberg had his dream.

In the first half of the twentieth century, theory played the leading role, but in the second half of that century, progress was largely initiated by new experimental techniques. The basis for these techniques was also established in the first half of the century, but the enormous development since that time can easily be seen from the increase in the size of research instruments, illustrated in Figure 1.2: The "large" accelerator built by E. O. Lawrence in 1939 had a diameter of 37 inches. The Large Hadron Collider (LHC), under construction at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, with its diameter of more than five miles, exceeds the limits of the canton of Geneva. There are plans—still to be financed—to construct a linear accelerator (TESLA) with a length of more than 20 miles.

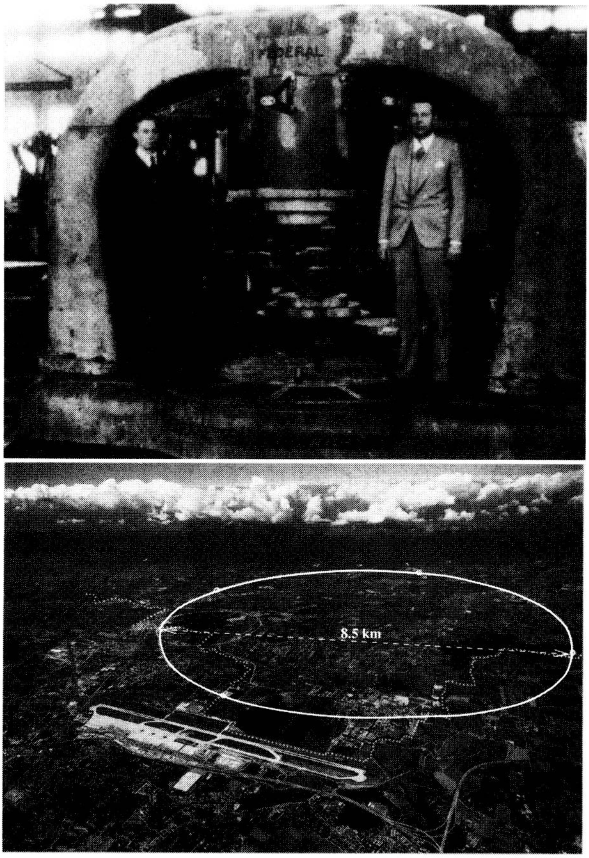

Figure 1.2. Magnet for 37-inch cyclotron (top) and Large Hadron Collider (bottom) depicts how accelerators have increased in size. The top photograph shows Lawrence, on the right, and a collaborator, in the yoke of the magnet for the 37-inch cyclotron. The magnet was obtained at a bargain price from the Federal Telegraph Company because its application in radio transmission had been made obsolete by the development of vacuum tubes. The bottom photograph shows the ring of the Large Hadron Collider (LHC) at CERN in Geneva.

Detectors that were originally the size of cigar boxes, are today as big as houses. The quantity of data flowing from a typical measurement is impressive even to communications specialists. It is no wonder that the Internet was developed at CERN. As a result of such growing complexity, ever larger numbers of scientists are involved in a single experiment. In 1933, C. D. Anderson proved the existence of antimatter. His article in *Physical Review Letters* was four pages long. By contrast, the discovery of the top quark in 1995 resulted from research undertaken by two large groups of scientists. When this discovery was described in print, the list of authors and institutions alone filled nearly four pages.

Modern particle physics began around 1950. Since that time, accelerators have played a dominant role in its development. Now, theory is once again ahead of experimental physics; there are many serious theoretical speculations that that have yet to be verified.

Today, with the standard model of particle physics, we have the means to explain the essential features of the dynamics of elementary particles. Many physicists, in fact, are more worried about the theory being too good, leaving them with no new physics to discover, than about potential problems with the standard model. It is generally agreed that further essential progress can be made only if gravity can be incorporated into the quantum field theory of elementary particle physics. There are fascinating links between the physics of the small and of the large: particle physics and cosmology. Knowledge gained from the study of particle physics is essential for explaining the early history of the universe, and some hypotheses in particle physics can at the moment only be tested by examining their cosmological consequences.

We will meet two constants of nature again and again: the speed of light in a vacuum, denoted generally by the letter c, and the elementary quantum of action, Planck's constant h. The speed of light was first measured in 1676 by the Danish astronomer Olaf Römer, but its overwhelming importance was not realized until much later, when Einstein incorporated it into his special theory of relativity. The speed of light has the same value for all observers, independent of the observer's velocity with respect to the source of the light. No particle can move faster than light, and in particular, no signal can be transmitted faster than light. One of the consequences of this is that time is relative. The same process can have different durations for different observers. This sounds incredible, but it has been well tested empirically. The speed of light is very large compared to our everyday experience: 186,000 miles per second (300,000 km/s). Though Einstein's theory of relativity is valid in general, deviations from our intuitive expectations and experience only become apparent if we consider systems whose speeds are comparable to that of light. Then the laws of Newtonian physics have to be replaced by those of special relativity.

In particle physics, the speed of light in a vacuum is the natural unit for measuring velocities. In this context,"slow" describes moving at a velocity that is much less than the speed of light, while "fast" describes moving at a velocity comparable to that of light.

Planck's constant was introduced in 1900 in order to describe the phenomenon of heat radiation. It is an essential constant for all the processes that occur at the atomic scale and below. It is the fundamental quantum of action, where "action" has special meaning in physics as the product of energy and time. The numerical value of Planck's constant is very tiny when expressed in units of everyday life: it is approximately $6.626 \times 10^{-34} = 0.000\ldots0006626\ \mathrm{J \cdot sec}$ (joule seconds), where the notation indicates that there are 33 zeros after the decimal point. It is highly probable that quantum physics is also valid for macroscopic processes, but if the action is large compared to Planck's constant, one can approximate the constant by zero, and one is returned to classical physics. Angular momentum has the same units as action, and therefore Planck's constant is the natural unit for expressing angular momentum on the quantum scale. For practical reasons, one usually uses the *reduced Planck constant* $\hbar = h/(2\pi) \approx 1.05 \times 10^{-34}\ \mathrm{J \cdot sec}$.

A unit of energy in particle physics is usually expressed as an electron volt, which is the energy gained by an electron when it passes through an electrostatic potential difference of one volt. For practical reasons, electron volts usually are stated using the measure of mega electron volts and giga electron volts. The mega electron volt (MeV) is equal to one million electron volts, and the giga electron volt (GeV)is equal to one billion electron volts. GeV is expressed as BeV in the older literature.

The customary unit of mass is the mega electron volt divided by the square of the speed of light in a vacuum, MeV/c^2, or the giga electron volt divided by the speed of light, in a vacuum GeV/c^2; more details are given in Appendix B. The appendix also includes a glossary of the most important and widely used terms in this book together with references to the sections in which they are introduced.

1.2 Brave Old World

I begin by describing the history of the discovery of the elementary particles that occur naturally and by explaining the structure of matter under normal circumstances.

The proton. It is impossible to determine exactly when the proton, one of the most important building blocks of matter, was discovered. Today, we know that a single proton forms the nucleus of hydrogen, the lightest chemical element. However, when hydrogen was discovered by Henry Cavendish in 1766, it was by no means clear what a chemical element was, much less what constituted an atom. Most remarkable, however, is the hypothesis that was advanced by William Prout in 1815. Based on the atomic weights that were known at the time, Prout hypothesized that all elements are formed from hydrogen. This hypothesis was very fruitful, even if it turned out later not to be fully tenable.

The electric charge of the proton is sometimes called an *elementary charge.* If one speaks of a particle with an (elementary) charge of -1, one means that it has a charge that is opposite to that of a proton. The mass of the proton is 1.672×10^{-27} kilogram, or in the standard units of particle physics, 938.2720 MeV/c^2. Reference to other important properties of the proton will be made later on, in connection with the other building block of the nucleus, the neutron.

The electron. The electron is the first elementary particle about which one can speak of a clear discovery, and it has maintained its status as an elementary particle to this day.

The discovery of the electron was made possible by advances in vacuum technology. The mechanic and glassblower H. Geissler constructed air pumps and discharge tubes that were so well sealed that the air pressure in the tubes was stable at about one ten-thousandth of atmospheric pressure. With these tubes, Julius Plücker, best known as a mathematician, made a thorough investigation of electric discharges. He found that from the negative pole, the cathode, radiation was emitted that resulted in a green glow at the opposite wall of the tube. This effect is still used today, for example, on radar screens and—in a more refined form—in color television.

Heinrich Hertz, the discoverer of radio waves, found that this radiation could penetrate thin aluminum foils, and that led his student, Philipp Lenard, to extract the radiation through such a foil making it easy to experiment with these *cathode rays.* The nature of the rays was obscure. Most British physicists believed them to be beams of particles, while in Germany the idea that they related to the ether was more popular.

If one accepted the concept of a particle beam, one could determine the ratio of the electric charge to the mass by observing the beam's deflection in a combined electric and magnetic field. In January 1897, Emil Wiechert in Königsberg estimated this ratio of charge to mass on the basis of his experiments to be 200 to 4,000 times that of the hydrogen ion. Assuming the same value of the charge, he concluded that there existed a particle that was 200 to 4,000 times lighter than the hydrogen atom.

That same year, W. Kaufmann, in Berlin, and J. J. Thomson, in Cambridge, England, also measured this ratio. Kaufmann obtained the value 1,000, while Thomson obtained the value 770. However, the two researchers reached completely different conclusions. Kaufmann argued that his result was probably irreconcilable with a particle interpretation, since there were no known particles with such a small mass. Thomson, however, concluded that the beam consisted of particles that have either a much smaller mass or a much greater charge (or both) than the hydrogen ion. The final breakthrough came in 1899 when Thomson employed a newly developed instrument, the cloud chamber, which was invented by his student, C. T. R. Wilson. (We will explore the cloud chamber in more detail in Section 1.3.) By counting the droplets in the chamber, Thomson could estimate the electric charge of the particles in the cathode rays, and he obtained a value for the charge that allowed him to conclude that the particles were at least 60 times lighter than hydrogen ions. In fact, the correct number is 1,836 instead of 60. Although Thomson greatly overestimated the mass of the particles, he firmly established the existence of a particle much lighter than the simplest atom—the electron had been discovered. The electric charge and mass of the electron are now known with great accuracy: the charge is exactly one negative elementary charge, and the mass is 0.51099899 MeV/c^2.

At the time of the discovery of the electron, attention was focused on two properties—charge and mass. With the development of quantum mechanics in the 1920s, another property turned out to be essential—the *spin*. This property is only partially accessible to our intuition, which is, of course, formed by our experience from everyday life. Nonetheless, spin has many properties in common with classical angular momentum, and the formal treatment in quantum mechanics is the same. In some respects, one can consider spin as the angular momentum caused by a classical rotation of the particle. The classical model of a spinning particle can indeed explain some properties, but in other respects this paradigm falls short. The numerical value of the electron spin is exactly half of the reduced Planck constant, $\frac{1}{2}\hbar$. We will return to the topic of spin in more detail in Section 1.5.2.

The electron acts like a small magnet; its dipole moment is—to great accuracy—the value of the spin times the ratio of charge to mass. If the spin were a normal angular momentum, one would expect only half that value.

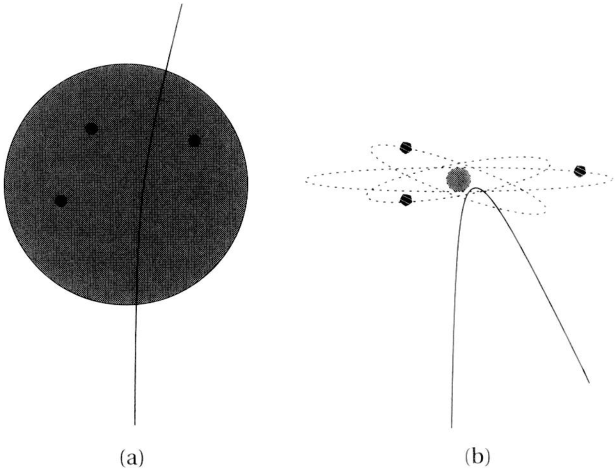

Figure 1.3. (a) Thomson's model of the atom. In Thomson's model, the electrons (black) swim in the extended, positively charged atom (gray) like "plums in a pudding." (b) Rutherford's model of the atom. In the model of Rutherford and Bohr, the electrons revolve around a small nucleus like the planets around the sun. The solid line is the trajectory of a particle hitting the atom. (The figure is not to scale.)

Models of the atom. After the discovery of the electron, J. J. Thomson developed a model of the atom in which the electrons are distributed like plums in a pudding; see Figure 1.3(a). This model explained some important properties of matter quite well, such as the optical index of refraction. The model became untenable, however, after Ernest Rutherford's interpretation of the experiments of Hans Geiger and Ernest Marsden disproved the model.

Although these experiments did not lead to the detection of new elementary particles, the experiments are important in the history of particle physics. Rutherford's interpretation led to a new branch of physics—nuclear physics, which is the precursor of modern particle physics. In addition, Rutherford's technique of particle scattering was essential in the investigation of the structure of matter, from elementary particle physics to the physics of condensed matter.

Rutherford had investigated the scattering of alpha particles on thin gold foil. An *alpha particle* (α-particle) is the nucleus of a helium atom emitted from a radioactive nucleus. Geiger, who worked at Rutherford's institute in Manchester, continued these experiments and confirmed that alpha particles are only weakly deflected by the gold atoms. This was to be expected, since the fields in