Chapter 1
Hors d'œuvre

Nicht allein in Rechnungssachen
Soll der Mensch sich Mühe machen;
Sondern auch der Weisheit Lehren
Muß man mit Vergnügen hören.

Wilhelm Busch
Max und Moritz (4. Streich)

1.1 Fundamental Constituents of Matter

In their search for the fundamental building blocks of matter, physicists have found smaller and smaller constituents that have proven to be themselves composite systems. By the end of the nineteenth century, it was known that all matter is composed of atoms. However, the existence of close to 100 elements showing periodically recurring properties was a clear indication that atoms themselves have an internal structure, and are not indivisible.

The modern concept of the atom emerged at the beginning of the twentieth century, in particular as a result of the experiments by Rutherford and co-workers. An atom is composed of a dense nucleus surrounded by an electron cloud. The nucleus itself can be decomposed into smaller particles. After the discovery of the neutron in 1932, there was no longer any doubt that the building blocks of nuclei are protons and neutrons (collectively called nucleons). The electron, neutron and proton were later joined by a fourth particle, the neutrino, which was postulated in 1930 in order to reconcile the description of β-decay with the fundamental laws of conservation of energy, momentum and angular momentum.

Thus, by the mid-thirties, these four particles could describe all the then known phenomena of atomic and nuclear physics. Today, these particles are still considered to be the main constituents of matter. But this simple, closed picture turned out in fact to be incapable of describing other phenomena.

Experiments at particle accelerators in the 1950s and 1960s showed that protons and neutrons are merely representatives of a large family of particles now called *hadrons*. More than 200 hadrons, sometimes called the "hadronic zoo", have thus far been detected. These hadrons, like atoms, can be classified in groups with similar properties. It was therefore assumed that they cannot be understood as fundamental

B. Povh et al., *Particles and Nuclei*, Graduate Texts in Physics,
DOI 10.1007/978-3-662-46321-5_1

constituents of matter. In the late 1960s, the quark model established order in the hadronic zoo. All known hadrons could be described as combinations of two or three quarks.

Figure 1.1 shows different scales in the hierarchy of the structure of matter. As we probe the atom with increasing magnification, smaller and smaller structures become visible: the nucleus, the nucleons, and finally the quarks.

Leptons and quarks The two fundamental types of building blocks are the *leptons*, which include the electron and the neutrino, and the *quarks*. In scattering experiments, these were found to be smaller than 10^{-18} m. They are possibly point-like particles. For comparison, protons are as large as $\approx 10^{-15}$ m. Leptons and quarks have spin $1/2$, i.e., they are fermions. In contrast to atoms, nuclei and hadrons, no excited states of quarks or leptons have so far been observed. Thus, they appear to be elementary particles.

Today, however, we know of six leptons and six quarks as well as their antiparticles. These can be grouped into so-called "generations" or "families", according to certain characteristics. Thus, the number of leptons and quarks is relatively large;

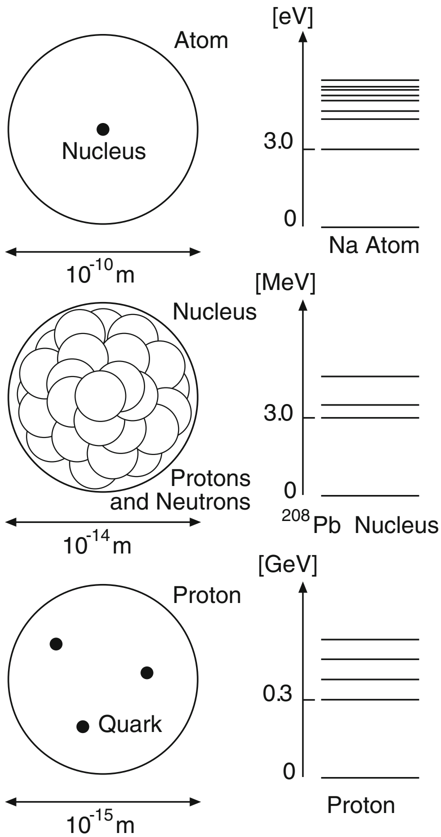

Fig. 1.1 Length scales and structural hierarchy in atomic structure. To the right, typical excitation energies and spectra are shown. Smaller bound systems possess larger excitation energies

furthermore, their properties recur in each generation. Some physicists believe these two facts are a hint that leptons and quarks are not elementary building blocks of matter. Only experiment will teach us the truth.

1.2 Fundamental Interactions

Together with our changing conception of elementary particles, our understanding of the basic forces of nature and so of the fundamental interactions between elementary particles has evolved. Around the year 1800, four forces were considered to be basic: *gravitation, electricity, magnetism* and the barely comprehended forces between atoms and molecules. By the end of the nineteenth century, electricity and magnetism were understood to be manifestations of the same force: *electromagnetism*. Later it was shown that atoms have a structure and are composed of a positively charged nucleus and an electron cloud; the whole held together by the electromagnetic interaction. Overall, atoms are electrically neutral. At short distances, however, the electric fields between atoms do not cancel out completely, and neighbouring atoms and molecules influence each other. The different kinds of "chemical forces" (e.g., the Van der Waals force) are thus expressions of the electromagnetic force.

When nuclear physics developed, two new short-ranged forces joined the ranks. These are the *nuclear force*, which acts between nucleons, and the *weak force*, which manifests itself in nuclear β-decay. Today, we know that the nuclear force is not fundamental. In analogy to the forces acting between atoms being effects of the electromagnetic interaction, the nuclear force is a result of the *strong force* binding quarks to form protons and neutrons. These strong and weak forces lead to the corresponding fundamental interactions between the elementary particles.

Intermediate bosons The four fundamental interactions on which all physical phenomena are based are gravitation, the electromagnetic interaction, the strong interaction and the weak interaction.

Gravitation is important for the existence of stars, galaxies, and planetary systems (and for our daily life), it is of no significance in subatomic physics, being far too weak to noticeably influence the interaction between elementary particles. We mention it only for completeness.

According to today's conceptions, interactions are mediated by the exchange of vector bosons, i.e., particles with spin 1. These are *photons* in electromagnetic interactions, *gluons* in strong interactions and the W^+, W^- and Z^0 bosons in weak interactions. The diagrams in Fig. 1.2 show examples of interactions between two particles by the exchange of vector bosons: In our diagrams we depict leptons and quarks by straight lines, photons by wavy lines, gluons by spirals, and $W^\pm$ and Z^0 bosons by dashed lines.

Each of these three interactions is associated with a charge: electric charge, weak charge and strong charge. The strong charge is also called *colour charge* or

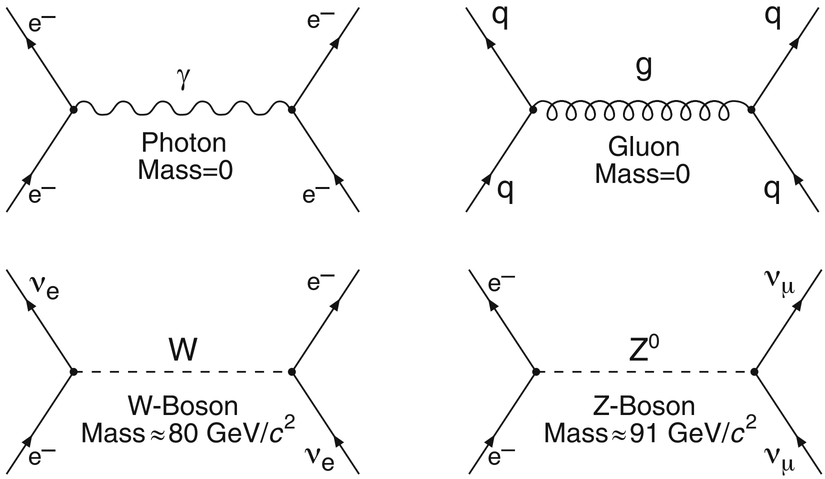

Fig. 1.2 Diagrams for fundamental interactions between particles by the exchange of vector bosons

colour for short. A particle is subject to an interaction if and only if it carries the corresponding charge:

– Leptons and quarks carry weak charge.
– Quarks are electrically charged, so are some of the leptons (e.g., electrons).
– Colour charge is only carried by quarks (not by leptons).

The W and Z bosons, masses $M_\mathrm{W} \approx 80\ \mathrm{GeV}/c^2$ and $M_\mathrm{Z} \approx 91\ \mathrm{GeV}/c^2$, are very heavy particles. According to the Heisenberg uncertainty principle, they can only be produced as virtual, intermediate particles in scattering processes for extremely short times. Therefore, the weak interaction is of very short range. The rest mass of the photon is zero. Therefore, the range of the electromagnetic interaction is infinite.

The gluons, like the photons, have zero rest mass. Whereas photons, however, have no electrical charge, gluons carry colour charge. Hence they can interact with each other. As we will see, this causes the strong interaction to be also very short ranged.

1.3 Symmetries and Conservation Laws

Symmetries are of great importance in physics. The conservation laws of classical physics (energy, momentum, angular momentum) are a consequence of the fact that the interactions are invariant with respect to their canonically conjugate quantities (time, space, angles). In other words, physical laws are independent of the time, the location and the orientation in space under which they take place.

An additional important property in non-relativistic quantum mechanics is reflection symmetry.[1] Depending on whether the sign of the wave function changes under reflection or not, the system is said to have negative or positive *parity* (P), respectively. For example, the spatial wave function of a bound system with angular momentum $\ell\hbar$ has parity $P = (-1)^\ell$. For those laws of nature with left-right symmetry, i.e., invariant under a reflection in space $\mathcal{P}$, the parity quantum number P of the system is conserved. Conservation of parity leads, e.g., in atomic physics to selection rules for electromagnetic transitions.

The concept of parity has been generalised in relativistic quantum mechanics. One has to ascribe an *intrinsic parity* P to particles and antiparticles. Bosons and antibosons have the same intrinsic parity, fermions and antifermions have opposite parities. An additional important symmetry relates particles and antiparticles. An operator $\mathcal{C}$ is introduced which changes particles into antiparticles and vice versa. Since the charge reverses its sign under this operation, it is called *charge conjugation*. Eigenstates of $\mathcal{C}$ have a quantum number *C-parity* which is conserved whenever the interaction is symmetric with respect to $\mathcal{C}$.

Another symmetry derives from the fact that certain groups ("multiplets") of particles behave practically identically with respect to the strong or the weak interaction. Particles belonging to such a multiplet may be described as different states of the same particle. These states are characterised by a quantum number referred to as strong or weak *isospin*. Conservation laws are also applicable to these quantities.

1.4 Experiments

Experiments in nuclear and elementary particle physics have, with very few exceptions, to be carried out using particle accelerators. The development and construction of accelerators with ever greater energies and beam intensities has made it possible to discover more and more elementary particles. A short description of the most important types of accelerators can be found in the appendix. The experiments can be classified as *scattering* or *spectroscopic* experiments.

Scattering In scattering experiments, a beam of particles with known energy and momentum is directed towards the object to be studied (the *target*). The beam particles then interact with the object. From the changes in the kinematical quantities caused by this process, we may learn about the properties both of the target and of the interaction.

Consider, as an example, elastic electron scattering which has proven to be a reliable method for measuring radii in nuclear physics. The structure of the target

[1] As is well known, reflection around a point is equivalent to reflection in a plane with simultaneous rotation about an axis perpendicular to that plane.

becomes visible via diffraction only when the de Broglie wavelength $\lambda = h/p$ of the electron is comparable to the target's size. The resulting diffraction pattern of the scattered particles yields the size of the nucleus rather precisely.

Figure 1.1 shows the geometrical dimensions of various targets. To determine the size of an atom, X-rays with an energy of $\approx 10^4$ eV suffice. Nuclear radii are measured with electron beams of about 10^8 eV, proton radii with electron beams of some 10^8–10^9 eV. Even with today's energies, 10^{11} eV for electrons and $4 \cdot 10^{12}$ eV for protons, there is no sign of a substructure in either quarks or leptons.

Spectroscopy The term "spectroscopy" is used to describe those experiments which determine the decay products of excited states. In this way, one can study the properties of the excited states as well as the interactions between the constituents.

From Fig. 1.1 we see that the excitation energies of a system increase as its size decreases. To produce these excited states high energy particles are needed. Scattering experiments to determine the size of a system and to produce excited states require similar beam energies.

Detectors Charged particles interact with gases, liquids, amorphous solids, and crystals. These interactions produce electrical or optical signals in these materials which betray the passage of the particles. Neutral particles are detected indirectly through secondary particles: photons produce free electrons or electron-positron pairs, by the photoelectric or Compton effects, and pair production, respectively. Neutrons and neutrinos produce charged particles through reactions with nuclei.

Particle detectors can be divided into the following categories:

- Scintillators provide fast time information, but have only moderate spatial resolution.
- Gaseous counters covering large areas (wire chambers) provide good spatial resolution, and are used in combination with magnetic fields to measure momentum.
- Semiconductor counters have a very good energy and spatial resolution.
- Cherenkov counters and counters based on transition radiation are used for particle identification.
- Calorimeters measure the total energy at very high energies.

The basic types of counters for the detection of charged particles are compiled in Appendix A.2.

1.5 Units

The common units for length and energy in nuclear and elementary particle physics are the *femtometre* (fm, or *Fermi*) and the *electron volt* (eV). The Fermi is a standard SI-unit, defined as 10^{-15} m, and corresponds approximately to the size of a proton.

An electron volt is the energy gained by a particle with charge $1e$ by traversing a potential difference of 1 V:

$$1\ \text{eV} = 1.602 \cdot 10^{-19}\ \text{J}\,. \tag{1.1}$$

For the decimal multiples of this unit, the usual prefixes are employed: keV, MeV, GeV, etc. Usually, one uses units of MeV/c^2 or GeV/c^2 for particle masses, according to the mass-energy equivalence $E = mc^2$.

Length and energy scales are connected in subatomic physics by the uncertainty principle. The Planck constant is especially easily remembered in the form

$$\hbar \cdot c \;\approx\; 200\ \text{MeV} \cdot \text{fm}\,. \tag{1.2}$$

Another quantity which will be used frequently is the coupling constant for electromagnetic interactions. It is defined by:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137}\,. \tag{1.3}$$

For historical reasons, it is also called the *fine structure constant*.

A system of physical quantities which is frequently used in elementary particle physics has identical dimensions for mass, momentum, energy, inverse length and inverse time. In this system, the units may be chosen such that $\hbar = c = 1$. In atomic physics, it is common to define $4\pi\varepsilon_0 = 1$ and therefore $\alpha = e^2$ (Gauss system). In particle physics, $\varepsilon_0 = 1$ and $\alpha = e^2/4\pi$ is more commonly used (Heavyside-Lorentz system). However, we will utilise the SI-system [1] used in all other fields of physics and so retain the constants everywhere.

Reference

1. S.U.N. Commission, Symbols, units and nomenclature in physics. Physica **93A**, 1 (1978)