Chapter 13
The Standard Model

Se non è vero, è ben trovato.

Giordano Bruno
Gli eroici furori

Die Wissenschaft hat ewig Grenzen,
aber keine ewigen Grenzen.

P. du Bois-Reymond
Über die Grenzen
des Naturerkennens

The *standard model* of elementary particle physics comprises the unified theory of the electroweak interaction and quantum chromodynamics. In the following, we will once more summarise what we have learnt in previous chapters about the different particles and interactions.

– As well as gravitation, we know of three elementary interactions which have very similar structures. Each of them is mediated by the exchange of vector bosons.

Interaction	Couples to	Exchange particle(s)	Mass (GeV/c^2)	J^P
Strong	Colour charge	8 gluons (g)	0	1^-
Electromagnetic	Electric charge	Photon (γ)	0	1^-
Weak	Weak charge	$W^{\pm}$, Z^0	$\approx 10^2$	1

Gluons carry colour and therefore interact with each other. The bosons of the weak interaction themselves carry weak charge and couple with each other as well.

– As well as the exchange bosons, the known fundamental particles are the quarks and the leptons. They are fermions with spin-1/2. They are grouped, according to their masses, into three "families", or "generations".

B. Povh et al., *Particles and Nuclei*, Graduate Texts in Physics,
DOI 10.1007/978-3-662-46321-5_13

Fermions	Family			Electr. charge	Colour	Weak Isospin		Spin
	1	2	3			Left-hd.	Right-hd.	
Leptons	ν_e	ν_μ	ν_τ	0	–	1/2	–	1/2
	e	μ	τ	−1			0	
Quarks	u	c	t	+2/3	r, b, g	1/2	0	1/2
	d	s	b	−1/3			0	

Each fermion has an associated antifermion. It has the same mass as the fermion, but opposite electric charge, colour and third component of weak isospin.

From the measured width of the Z^0 resonance, one can deduce that no further (fourth) light neutrino exists. Thus, the existence of a fourth generation of fermions (at least one with a light neutrino) can be excluded.

– In the standard model neutrinos are predicted as massless. The observation of neutrino oscillations, however, showed that they have to possess a mass (see Chap. 11). The resulting lepton mixing can be described in analogy to the mixing in the quark sector without having to give up the standard model.
– Quarks can change their flavour. They prefer transitions within one family, transitions from the first to the second family are suppressed by one order of magnitude, from the first to the third by two. Transitions of leptons do not display such a hierarchy, but are almost generation independent.
– The consistency of the standard model necessitates the existence of a neutral spin-0 particle, which couples to the other elementary particles with strength proportional to their masses. This *Higgs particle* seems to have been detected, having a mass of $126\,\text{GeV}/c^2$.
– The range of the electromagnetic interaction is infinite since photons are massless. Because of the large mass of the exchange bosons of the weak interaction, its range is limited to 10^{-3} fm. Gluons have zero rest mass. Yet, the effective range of the strong interaction is limited by the mutual interaction of the gluons. The energy of the colour field increases with increasing distance. At distances $\gtrsim 1$ fm, it is sufficiently large to produce real quark-antiquark pairs. "Free" particles always have to be colour neutral.
– The electromagnetic interaction and the weak interaction can be interpreted as two aspects of a single interaction: the electroweak interaction. The corresponding charges are related by the Weinberg angle, cf. (12.14).
– Different conservation laws apply to the different interactions:

- In all three interactions, energy (E), momentum ($\boldsymbol{p}$), angular momentum ($\boldsymbol{L}$), charge (Q), colour, baryon number (B) and the lepton number L are conserved.
- The P and C parities are conserved in the strong and in the electromagnetic interaction; but not in the weak interaction. For the charged current of the weak interaction, parity violation is maximal. The charged current only couples to left-handed fermions and right-handed antifermions. The neutral weak current is partly parity violating. It couples to left-handed and right-handed fermions

and antifermions, but with different strengths. The combined CP parity is not conserved in weak interactions.

- Only the charged current of the weak interaction transforms one type of quark into another type (quarks of a different flavour) and one type of lepton into another. Thus, the quantum numbers determining the quark flavour (third component of isospin (I_3), strangeness (S), charm (C) etc.) are conserved in all other interactions.
- The magnitude of the isospin (I) is conserved in strong interactions.

The allowed transitions within lepton families are shown in Fig. 13.1. The transitions are shown between the leptonic weak interaction eigenstates and also between leptonic mass operator eigenstates. The corresponding quark family transitions are shown in Fig. 13.2. Here the transitions between the quark eigenstates of the weak interaction are shown, as are those between quark flavours. These pictures are

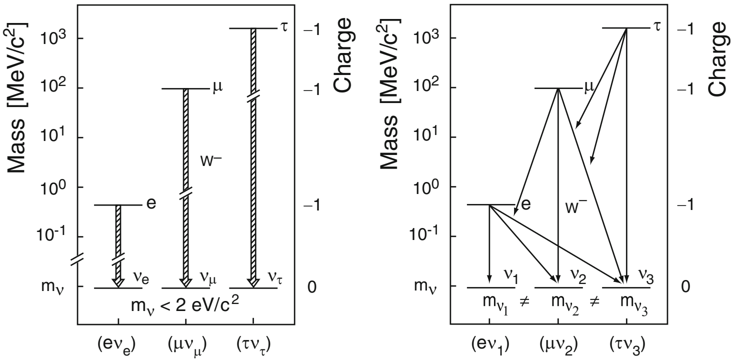

Fig. 13.1 Transitions between lepton states via charged currents. On the *left* for leptonic weak interaction eigenstates, on the *right* for mass operator eigenstates

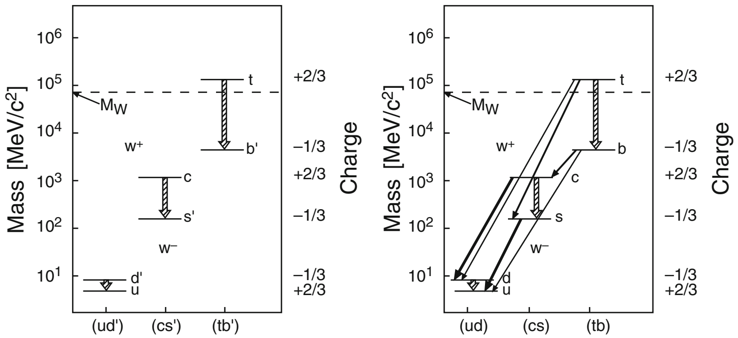

Fig. 13.2 Transitions between quark states via charged currents. On the *left* quark weak interaction eigenstates, on the *right*, mass operator eigenstates. The strength of the coupling is reflected in the width of the *arrows*. The mass of the t-quark is so large, that it decays by emission of a *real* W^+ boson

perhaps the forerunner of a new type of spectroscopy, more elementary than the atomic, nuclear or hadronic spectroscopies.

In summary, experiments are in astoundingly good quantitative agreement with the assumptions of the standard model. These include the grouping of the fermions into left-handed doublets and right-handed singlets of weak isospin, the strength of the coupling of the Z^0 to left-handed and right-handed fermions, the three-fold nature of the quark families because of colour and the ratio of the masses of the $W^{\pm}$ and Z^0. We thus possess a self-contained picture of the fundamental building blocks of matter and of their interactions.

And yet today's standard model is unsatisfactory in many respects. A large number of free parameters remain: 3 coupling constants for the interactions, 6 quark masses, 3 masses of charged leptons, 4 parameters in the CKM mixing matrix and 2 parameters that describe the properties of the Higgs boson. If one includes neutrino masses, 3 neutrino masses and 4 (or 6) parameters in the PMNS matrix are added. Those parameters do not follow from the standard model, but have to be determined experimentally. In addition, effects and observations which cannot be explained in the standard model at all are present: for instance, dark energy or dark matter, both of which dominate the evolution and the structure of the universe.

Many questions are still completely open. Why do exactly three families of fermions exist? Is it a coincidence that within every family the fermions which carry more charge (strong, electromagnetic, weak) have larger masses? Are baryon number and lepton number strictly conserved? What is the origin of CP violation? What is the origin of the mixture of lepton families, described by the Pontecorvo-Maki-Nakagawa-Sakata matrix? What is the origin of the mixture of quark families, described by the Cabibbo-Kobayashi-Maskawa matrix? What is the origin of small neutrino masses? Why are there just four interactions? What determines the magnitudes of the coupling constants of the different interactions? Is it possible to unify the strong and electroweak interactions, as one has unified the electromagnetic and weak interactions? Will it be possible to include gravitation in a complete unification?

Such questions reflect the experience physicists have gained in analysing the building blocks of matter. On their journey from solid bodies to quarks via molecules, atoms, nuclei, and hadrons, they have constantly found new, fundamental particles. The question "Why?" implicitly assumes that more fundamental reasons exist for observed phenomena – new experiments are the only way to check this assumption.

Nature has always looked like a horrible mess, but as we go along we see patterns and put theories together; a certain clarity comes and things get simpler.

Richard P. Feynman [1]

Reference

1. R.P. Feynman, *QED – The Strange Theory of Light and Matter* (Princeton University Press, Princeton, 1985)