Chapter 1

Introduction

Literature:

- Halzen/Martin [1]
- Aitchison/Hey [2] (rigorous)
- Seiden [3] (experimental, up to date)
- Nachtmann [4] (difficult to purchase)

Elementary particles are the smallest constituents of matter. Therefore the notion "elementary" changes with scientific progress (cf. Tab. 1.1).

We can define "elementary" as "having no resolvable inner structure". This also means that there can be no excited states. Elementary particles interact in a well-defined way through fundamental interactions. These are

- gravity,
- electromagnetic interaction,
- weak interaction, and
- strong interaction,

where only the last three are relevant, at the elementary particle level, at energies currently available. Range of phenomena:

- structure of matter
- stability of matter

1869	Mendeleev/Meyer	periodic system	atom
1890	J. Thomson	electron	
1910	Bequerel/Curie	radioactivity	atomic nucleus & electron
	Rutherford	scattering	
1932	Chadwick	neutron	proton, neutron, electron
	Anderson	positron	& their antiparticles
1947	Blackett/Powell	pion, muon	"particle zoo"
1956	Cowan/Reines	neutrino	
1967	Glashow/Weinberg/Salam	**electroweak theory**	
1968	SLAC	deep inelastic scattering	quarks & leptons
1972	Fritzsch/Gell-Mann/Leutwyler	**quantum chromodynamics**	
1974	SLAC/BNL	c-quark, τ-lepton	
1979	DESY	gluon	
1977	Fermilab	b-quark	
1983	CERN	W, Z bosons	
1995	Fermilab	t-quark, ν_τ	

Table 1.1: Historical outline of the concept of "elementarity"

- instability of matter, radioactivity: decay of elementary particles
- scattering of elementary particles
- production of new particles
- indirect implications
  - early history of the universe
  - fuel cycle in stars
  - astrophysical phenomena: supernovae, very high energy cosmic rays

1.1 Units

The Planck constant

$$\hbar = \frac{h}{2\pi} = 1.0546 \cdot 10^{-34}\,\mathrm{Js} \tag{1.1}$$

has dimension of action and angular momentum. Another important physical constant is the speed of light

$$c = 2.998 \cdot 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}. \tag{1.2}$$

Because we are dealing with constants, Eq. (1.1) and (1.2) establish a relationship among the units for energy, time, and length. Using so-called natural units, i. e. setting $\hbar = c = 1$, we find

$$[c] = [\text{length}] \cdot [\text{time}]^{-1} = [L][T]^{-1} \Rightarrow [L] = [T] \tag{1.3}$$
$$[\hbar] = [\text{energy}] \cdot [\text{time}] = [M][L]^2[T]^{-1} \Rightarrow [M] = [L]^{-1} \tag{1.4}$$
$$\Rightarrow [M] = [L]^{-1} = [T]^{-1} \text{ and } [E] = [M]. \tag{1.5}$$

This raises the question of a suitable fundamental unit for energy. One electron volt is the energy acquired by an electron passing a potential difference of 1 V :

$$\begin{aligned} 1\,\text{eV} &= 1.602 \cdot 10^{-19}\,\text{J} \\ \text{keV} &= 10^3\,\text{eV} \\ \text{MeV} &= 10^6\,\text{eV} \\ \text{GeV} &= 10^9\,\text{eV} \\ \text{TeV} &= 10^{12}\,\text{eV}. \end{aligned}$$

Examples of some orders of magnitude are

$$\begin{aligned} m_e &= 511\,\text{keV} \\ m_p &= 938\,\text{MeV} \\ m_n &= 939\,\text{MeV} \\ E_e(\text{LEP}) &= 104.5\,\text{GeV} \\ E_p(\text{Tevatron}) &= 980\,\text{GeV} \\ E_p(\text{LHC}) &= 7\,\text{TeV}. \end{aligned}$$

Converting the units for energy, time, and length into each other yields, in agreement with Eq. (1.5),

$$\hbar = 6.58 \cdot 10^{-25}\,\text{GeV} \cdot \text{s} \stackrel{!}{=} 1 \Rightarrow \boxed{1\,\text{GeV}^{-1} \simeq 6.58 \cdot 10^{-25}\,\text{s}}, \tag{1.6}$$

(recall lifetime $\tau = \frac{1}{\Gamma}$ with Γ the resonance width), and

$$c = 2.998 \cdot 10^8\,\frac{\text{m}}{\text{s}} \stackrel{!}{=} 1 \Rightarrow \boxed{1\,\text{fm} = 10^{-15}\,\text{m} \simeq \frac{1}{200\,\text{MeV}}}. \tag{1.7}$$

Cross sections have dimensions of area:

$$[\sigma] = [L]^2 = [M]^{-2} = \frac{1}{(\text{eV})^2}. \tag{1.8}$$

As unit we choose

$$\frac{1}{(1\,\text{GeV})^2} = 389379\,\text{nb} = 389379 \cdot 10^{-9}\,\text{b}$$

with $1\,\mathrm{b} : 1\,\mathrm{barn} = 10^{-24}\,\mathrm{cm}^2$ the typical scale of nuclear absorption.

The unit of electrical charge can be defined in different ways. The dimensionless fine structure constant α is accordingly expressed differently in terms of e in different systems of units,

$$\begin{aligned}\alpha &= \left.\frac{e^2}{4\pi\varepsilon_0\hbar c}\right|_{\mathrm{SI}} = 7.2972\cdot 10^{-3} \simeq \frac{1}{137}\\ &= \left.\frac{e^2}{\hbar c}\right|_{\mathrm{CGS}}\\ &= \left.\frac{e^2}{4\pi\hbar c}\right|_{\text{Heaviside-Lorentz}},\end{aligned}$$

and determines the strength of the electromagnetic interaction. Therefore, in Heaviside-Lorentz units, the electron charge is fixed to be

$$e = \left.\sqrt{4\pi\alpha}\right|_{\mathrm{HL}}. \tag{1.9}$$

1.2 Elementary interactions

Gravitation. Since

$$Gm_p^2 \approx 10^{-39}$$

and because of the fact that gravity's range is infinite, it is relevant for macroscopic systems (and can be neglected here).

Electromagnetic interaction. Recall that $\alpha \simeq \frac{1}{137}$. The range of the electromagnetic interaction is infinite and typical lifetimes of particles decaying through electromagnetic interactions range from $\tau_{\Sigma^0\to\Lambda^0\gamma} = 10^{-20}\,\mathrm{s}$ to $\tau_{\pi^0\to\gamma\gamma} = 10^{-16}\,\mathrm{s}$. Typical cross sections are of order $\sigma_{ep\to ep} = 1\,\mu\mathrm{b}$. QED's (quantum electrodynamics') predictions have been tested to high theoretical and experimental precision. Consider for example the anomalous magnetic moment of the electron:

$$\begin{aligned}\mu_e^{\mathrm{QED}} &= \frac{e}{2m_e}\frac{g}{2} = \frac{e}{2m_e}\Bigg\{\underbrace{1}_{\text{Dirac}} + \underbrace{\frac{1}{2}\frac{\alpha}{\pi}}_{\text{Schwinger}} \underbrace{-0.388\frac{\alpha^2}{\pi^2}}_{\text{Petermann}} + \underbrace{1.18\frac{\alpha^3}{\pi^3}}_{\text{Laporta/Remiddi}}\Bigg\}\\ &= \frac{e}{2m_e}\big\{1.0011596521465(270)\big\}\\ \mu_e^{\mathrm{exp.}} &= \frac{e}{2m_e}\big\{1.0011596521883(42)\big\},\end{aligned}$$

where the experimental value was obtained by Van Dyck, Schwinberg and Dehmelt.

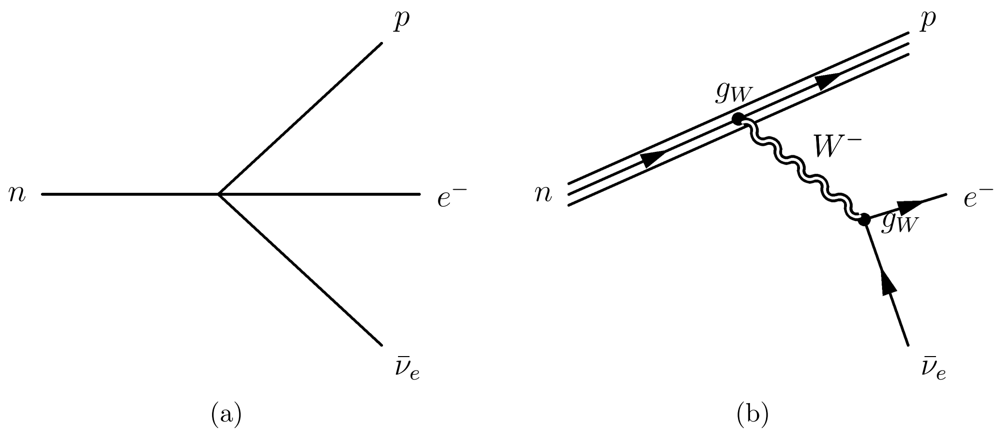

Figure 1.1: *Beta decay of neutron.* Depicted as a point like process, as described by Fermi's constant (a) and via W^- boson exchange (b).

Weak interaction. As an example for weak interactions consider β decay: $n \to pe\bar{\nu}_e$: see Fig. 1.1(a). The range is about 1 fm and for the coupling we have

$$G_F m_p^2 \approx 10^{-5}.$$

The lifetimes go from 10^{-10} s to 10^3 s and cross sections are of order $\sigma \approx 1$ fb. Theoretically, the process is explained by W^- boson exchange, see Fig. 1.1(b), which yields for Fermi's constant $G_F = \frac{g_{\mathrm{w}}^2}{8M_W^2}$.

Strong interaction. At the nuclear level, the Yukawa theory of pion exchange (see figures 1.2(a) and 1.2(b)) is still used. It explains the bonding of protons and neutrons by exchange of massive pions: $m_\pi = 130\,\mathrm{MeV} \Rightarrow$ range $\simeq \frac{1}{m_\pi} = \frac{1}{130\,\mathrm{MeV}} \simeq 1.4\,\mathrm{fm}$. QCD (quantum chromodynamics) states that particles like p, n, and π consist of quarks which interact through gluons. Gluons (in contrast to photons) carry themselves the charges they are coupling to which influences the strong interaction's potential, see fig.1.3. The QCD coupling constant is approximately given by $\alpha_s \simeq 0.12$.

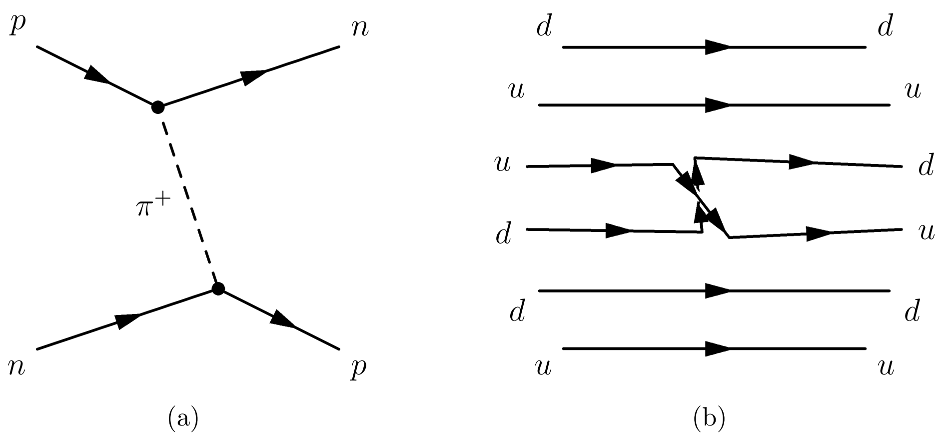

Figure 1.2: *Yukawa theory.* Interaction by pion exchange (a) and exchange of quark and anti-quark (b).

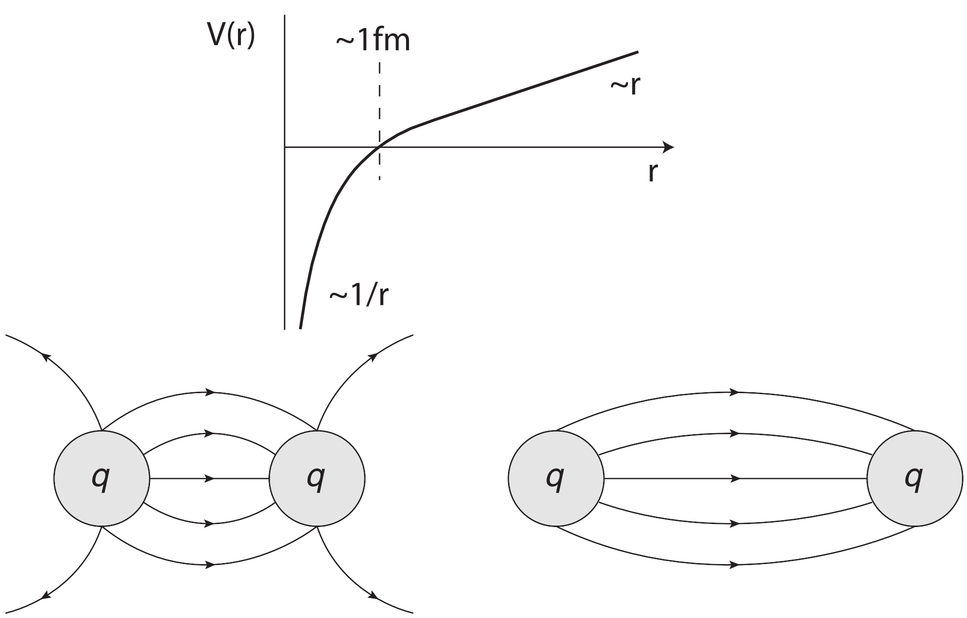

Figure 1.3: *Potential of the strong interaction.*