6. Semi-Leptonic Interactions of Hadrons

6.1 The World of Hadrons

All strongly interacting particles are called hadrons. One distinguishes baryons (baryon number $B = \pm 1$), which are fermions and carry spin $\frac{1}{2}, \frac{3}{2}, \ldots$, and mesons (baryon number $B = 0$), which always have integer spin. The lightest hadrons, with equal spin (and equal parity), can be arranged in simple multiplets, where two further quantum numbers serve as order criteria: the isospin $I$, and its third component $I_3$, and the strangeness $S$, or alternatively the so-called strong hypercharge $Y = B + S$. These quantum numbers are characterized by the fact that they are exactly conserved under strong interactions. Conservation of strangeness is broken by weak interactions, which leads to decays of, for example, the $\Lambda$ particle. The most important multiplets\(^1\) are depicted in Figs. 6.1–4.

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For each baryonic multiplet there exists a corresponding multiplet of antiparticles, which is obtained from the former by reflection at the origin. These multiplets are just the eigenvalues belonging to the simple representations of the group SU(3). Gell-Mann and Zweig therefore postulated\(^2\) that the particles belonging to the two fundamental representations (triplet, antitriplet) should also exist; these were called \textit{quarks}. Their charges are \(q_u = \frac{2}{3}e\), \(q_d = q_s = -\frac{1}{3}e\) (Fig. 6.5). The \(u\), \(d\), and \(s\) quarks have baryon number \(B = \frac{1}{3}\), and the corresponding antiquarks have \(B = -\frac{1}{3}\). By using \(Y = B + S\), one readily verifies that the \(u\), \(d\), \(\bar{u}\), and \(\bar{d}\) quarks carry zero strangeness, the \(s\) quark has \(S = -1\), and \(\bar{s}\) has \(S = +1\).

One readily observes that all hadrons can be made up of either three quarks (baryons) or a quark–antiquark pair (mesons). Some examples are:

\[
\begin{align*}
p &= (uud) \quad & n &= (udd) \\
\Lambda &= (uds) \quad & \Xi &= (dss) \\
\Delta^{++} &= (uuu) \quad & \Omega^- &= (sss) \\
\pi^+ &= (u\bar{d}) \quad & K^+ &= (u\bar{s}) \\
K^0 &= (d\bar{s}) \quad & \bar{K}^0 &= (s\bar{d}) \\
\rho^0, \omega &= (u\bar{u}, d\bar{d}) \quad & \phi &= (s\bar{s})
\end{align*}
\]

Hence hadrons are made of quarks just as an atomic nucleus is made of protons and neutrons. The strangeness of a hadron is simply given by the number of \(\bar{s}\) quarks minus the number of \(s\) quarks within the hadron. Although quarks have never been observed as free particles, their existence inside hadrons must be considered firmly established. We list a few arguments.\(^3\)

1. The hadronic mass spectrum can be explained with the help of just a few parameters, if one regards quarks as (nearly) freely moving particles which are enclosed in a small space volume of about \(1\, \text{fm}\) radius ("the bag model", see Fig. 6.6).

2. High-energy deep-inelastic electron–nucleon scattering can only be interpreted by assuming that the electrons scatter off point-like constituents, the so-called \textit{partons}, inside the hadrons (Fig. 6.7).

The radius of these partons must be smaller than \(10^{-16}\, \text{cm}\). Their charges can be determined from the measured cross sections and are in good agreement with the quark model. For the proton we have, for example,

\[
\sum_p q_i^2 = e^2 \left( 2q_u^2 + q_d^2 \right) = e^2 \left( 2 \times \frac{4}{9} + \frac{1}{9} \right) = e^2 ,
\]

and for the neutron

\[
\sum_n q_i^2 = e^2 \left( q_u^2 + 2q_d^2 \right) = e^2 \left( \frac{4}{9} + 2 \times \frac{1}{9} \right) = \frac{2}{3}e^2 .
\]

\(^2\) M. Gell-Mann: Phys. Lett. 8, 214 (1964); G. Zweig, CERN Report No. 8182/TH 401. (This latter work could not be published in a scientific journal, which shows that sometimes strong resistance has to be overcome before a new idea gains common acceptance.)