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Introduction

1.1 STRONG, ELECTROMAGNETIC AND WEAK INTERACTIONS

One of the main objectives of physics is to find out what, if any, are the basic constituents of matter and to understand the nature of the forces by which they interact. Fundamental particles appear, at present, to be of two distinct types. The first group consists of *quarks* and *leptons*. These are spin $\frac{1}{2}$ particles obeying Fermi–Dirac statistics (*fermions*). The second group consists of the so-called *gauge bosons*. These are integral spin particles obeying Bose–Einstein statistics (*bosons*). The gauge bosons appear to be responsible for mediating the interaction forces between quarks and leptons. Existing results show clear evidence for four types of interactions in nature. These are the strong, electromagnetic, weak and gravitational interactions. Our knowledge of these interactions stems, to a great extent, from our understanding of the underlying symmetries which appear to exist in nature and in the way in which they appear to be broken.

The world is made up of ninety-two naturally occurring chemical elements. The properties of a given isotope of an element do not, as far as we know, depend on its origin. These elements are composed of electrons and nuclei, which are in turn composed of protons and neutrons. The electrons are fermions and obey the Pauli exclusion principle. This leads to an elaborate shell structure and important differences in the chemical properties of the elements. Prior to the development of particle accelerators, studies in particle physics were limited to indirect means. These consisted of using either the low energy particles produced in the radioactive decays of nuclei or the higher energy protons, nuclei and other particles which make up cosmic radiation.

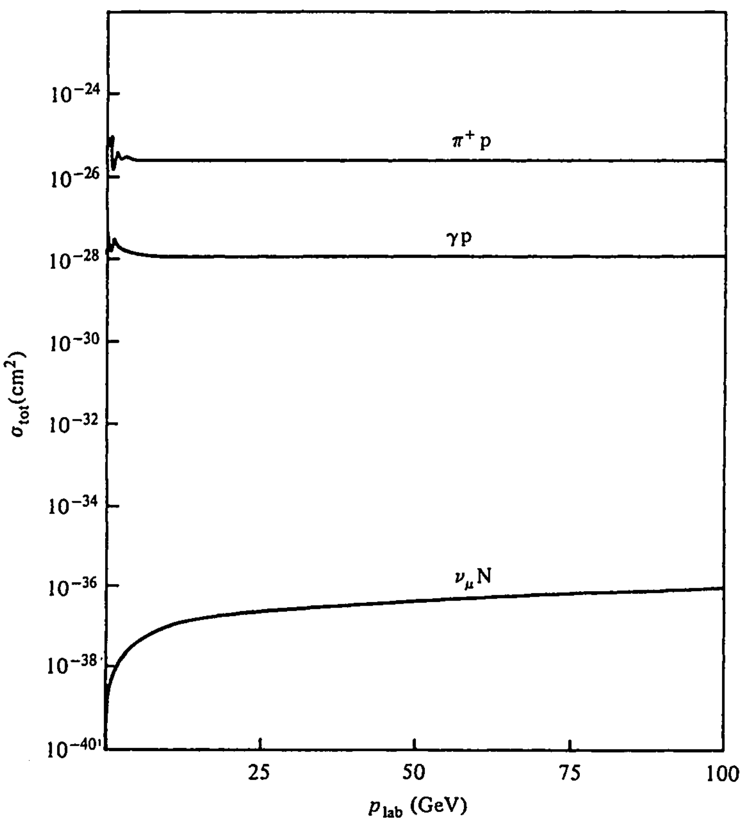
Direct study of the interactions of particles at high energy physics laboratories is made essentially by two methods. In the first, the interactions of beams of high energy particles on a stationary (fixed) target are studied. The target particle is either an atomic electron or, more likely, a nucleus. Hydrogen and deuterium targets are used if nuclear effects, such as Fermi motion, are to be avoided. The beam or projectile particle is obtained by first accelerating to high energy either protons (e.g. CERN 450 GeV, Fermi National Accelerator Lab, FNAL, 1 TeV) or electrons (e.g. Stanford Linear Accelerator Center, SLAC, 20 GeV). In the case of proton accelerators, the extracted protons can also be used to make secondary beams of $\pi^{\pm}$, $K^{\pm}$, K^0, $\bar{K}^0$ (*mesons*) or $\bar{p}$, n, $\bar{n}$, Λ, Σ, Ξ, Ω^- (*baryons*) by suitably collecting the decay products from the primary proton interactions. Beams are restricted to those *hadrons* (a class consisting of mesons and baryons) which are both sufficiently long-lived to give a reasonable flight path and light enough to be produced copiously. Beams of $e^{\pm}$, $\mu^{\pm}$, ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ (*leptons*) are produced either by starting with atomic electrons or allowing mesons to decay.

The second method of study is that of the collisions of two high energy beams of particles. Particles which are essentially stable must be used, so studies with this technique are restricted to pp, $\bar{p}p$ (e.g. CERN Collider, up to 450 + 450 GeV) and e^+e^- (e.g. DESY, 25 + 25 GeV). Beams of heavy ions can also be considered for colliding beam machines. Since the collisions take place in the centre-of-mass (cms) system, high values of the cms energy can be reached. For example, in the CERN Collider the cms energy for 270 GeV beams is 540 GeV, whereas the cms energy of a 270 GeV proton collision with a stationary proton is only 27.5 GeV. However, this gain is at the expense of effective luminosity (luminosity = reaction rate/cross-section). The most recent and planned future accelerators are mainly of this type and include machines at FNAL ($\bar{p}p$ 1 + 1 TeV), TRISTAN in Japan (e^+e^- 30 + 30 GeV), the Stanford Linear Collider (SLC) at SLAC (e^+e^- 50 + 50 GeV), LEP at CERN (e^+e^- phase I 55 + 55 GeV, 1989; phase II 95 + 95 GeV, 1993), HERA at DESY (e^-p 30 + 820 GeV, 1990), UNK in the Soviet Union (pp 3 + 3 TeV, 1993?) and possibly the Superconducting Super Collider (SSC) in the USA (pp 20 + 20 TeV, 1995?). Note that for the HERA Collider the protons are much more energetic than the electrons, and hence the collisions are not in the ep cms.

Hadrons (from the Greek hadros = strong) all have *strong* interactions. The total cross-section for π^+p collisions, as a function of the lab momentum of the π^+ meson (p_{lab}) is shown in Fig. 1.1. For $p_{lab} \sim 10$ GeV, the total cross-section is about 25 mb. The leptons (from Greek meaning light, small) do not feel the strong force and their interaction cross-sections are significantly less than those of hadrons. The total cross-section for the process $e^+e^- \to \mu^+\mu^-$ as a function of $(s)^{1/2}$, the cms energy of the e^+e^-

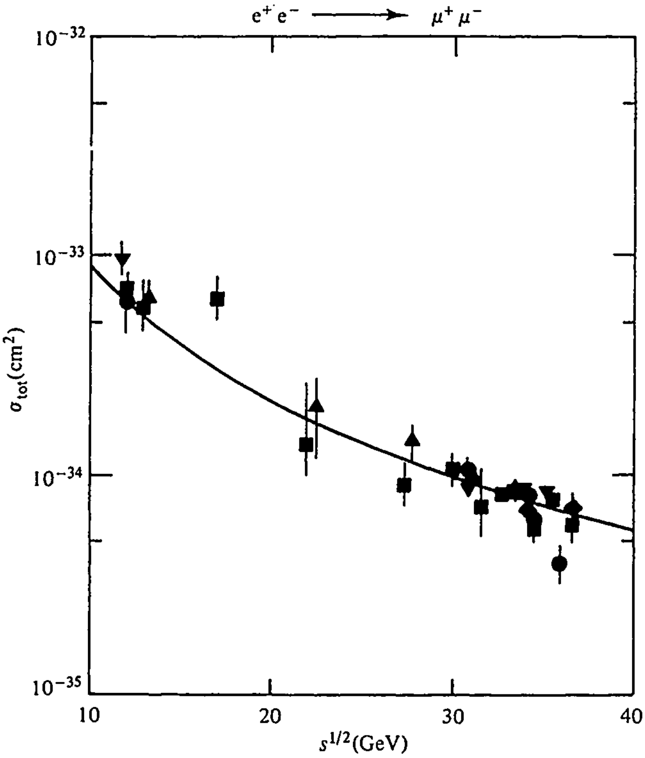
system, is shown in Fig. 1.2. Photon beams can also be produced at proton accelerators and the γp cross-section, as a function of the laboratory (lab) energy of the photon, is shown in Fig. 1.1. Charged leptons and photons interact by the *electromagnetic* interaction. The main contribution to the cross-section shown in Fig. 1.2 is from this interaction. The cross-sections for neutral leptons (ν and $\bar{\nu}$) are many orders of magnitude less than those for charged leptons. The total cross-section for ν_μ interactions as a function of the lab neutrino energy E_ν is shown in Fig. 1.1. This is an example of a *weak* interaction and the cross-section shows an approximately linear increase with E_ν. For $E_\nu \sim 10$ GeV the cross-section is about 11 orders of magnitude less than for 10 GeV π^+p (strong) interactions.

Fig. 1.1 Sketch of the total cross-sections, as a function of laboratory momentum p_{lab}, for π^+p, γp and ν_μN interactions. For ν_μ the results are the cross-section per nucleon (average of proton and neutron), obtained from heavy nuclear targets (e.g. iron).



The decay rates, or equivalently the lifetimes, of particles also span an enormous range, as shown in Fig. 1.3. The typical width Γ of a resonance decaying by the strong interaction (e.g. $\rho \to \pi\pi$) is approximately 100 MeV. Use of the uncertainty principle $\Gamma\tau \sim \hbar = 6.6 \times 10^{-22}$ MeV s (see Appendix A) gives a corresponding lifetime $\tau \sim 10^{-23}$ s. The decay of the neutral pion $\pi^0 \to \gamma\gamma$, which is an electromagnetic interaction, has a lifetime $\tau \sim 10^{-16}$ s. The charged pion, however, decays weakly (mainly via the decay $\pi \to \mu\nu_\mu$) with a lifetime $\tau \sim 10^{-8}$ s. These are typical values; however, it can be seen from Fig. 1.3 that the range of lifetimes for a given interaction is large, in particular for the weak interaction. Part of the reason for this large spread in lifetimes is that the density of final states (or phase space) available is often small due to the small energy release in the decay. For example, the expression for the decay rate for neutron beta decay,

Fig. 1.2 Total cross-section for the interaction $e^+e^- \to \mu^+\mu^-$. The data points are from e^+e^- experiments at PETRA and have been corrected for higher order radiative effects and hence are comparable with the full line, which is the lowest order QED calculation. ■, MARK J; ●, TASSO; ▲, PLUTO; ▼, JADE; ◆, CELLO.

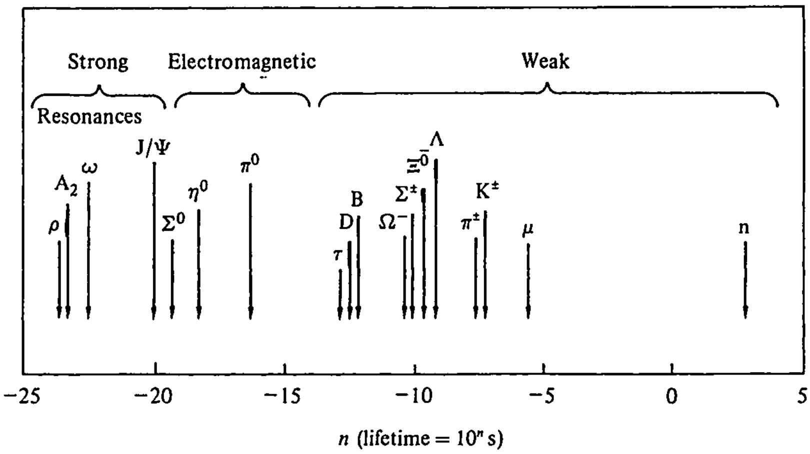


$n \to p + e^- + \bar{\nu}_e$, contains a factor Δ^5, where $\Delta = m_n - m_p = 1.3$ MeV, and this small energy release leads to a rather long lifetime ($\tau_n \simeq 900$ s).

The classification of interactions into a hierarchy of strong, electromagnetic and weak is a convenient framework. However, a particular scattering or decay process can of course have contributions from more than one of these forces. Hence this classification is most meaningful if one of these interactions dominates. For example, the contribution of the electromagnetic and weak interactions to the inelastic $\pi^+ p$ scattering cross-section for $p_{\text{lab}}^{\pi^+} \sim 10$ GeV is negligible. However, for an incident momentum of, say, 10^{15} GeV this may well not be the case. The π^0-meson decays electromagnetically into two photons, there being no competing strong decay because the pion is the lightest hadron. Weak decays become observable when both the strong and electromagnetic decays are suppressed. For example, the weak decay process $K^+ \to \pi^+ \pi^0$ is observable because potentially faster decay modes, via the strong or electromagnetic interactions, are forbidden. This is because the quantum number strangeness is conserved in these interactions and the kaon is the lightest strange particle.

As the energy of a particular scattering process increases, the classification in terms of a specific interaction becomes less distinct. For example, the e^+e^- annihilation process at a value of the cms energy squared $s \sim 10$ GeV^2 is predominantly electromagnetic, whereas at $s \sim 2000$ GeV^2 there is a sizeable interference term between the competing electromagnetic and weak processes.

Fig. 1.3 Lifetimes of various particles decaying by the strong, electromagnetic and weak forces.



From a theoretical point of view it is clearly desirable to have a single theory which describes all of the fundamental interactions in nature. Some considerable progress in this direction has been made. The *electroweak theory* of Glashow (1961), Weinberg (1967) and Salam (1968) 'unifies' the electromagnetic and weak interactions. This theory, the so-called *standard model*, and the relevant experimental data form the main subject matter of this book.

1.2 THE LIGHT LEPTONS

The discovery and interpretation of both leptons and quarks have depended upon rapid advances in both experimental methods and our theoretical understanding. The starting point was the discovery of the electron by J.J. Thomson in 1897 from a study of the electrical properties of gases at low pressure. Some 30 years later, the use of a cloud chamber in the study of cosmic radiation led to the discovery of the positron, the antiparticle of the electron (Anderson 1932, Blackett and Occhialini 1933). The possible existence of the positron had been predicted by Dirac. Similar experimental techniques led to the discovery (although not initially the correct interpretation) of the muon by Street and Stevenson (1937) and Neddermeyer and Anderson (1937). Further work in cosmic radiation led to the discovery of the π-meson (Lattes *et al.*, 1947), the K-meson (Rochester and Butler, 1947) and the Λ, Σ and Ξ hyperons.

By the early 1950s important advances in our theoretical understanding of matter and the various forces of nature had also been made. The ideas of relativity and quantum mechanics had been combined into the field theory called *quantum electrodynamics* (QED), which successfully accounts for the electromagnetic properties of electrons, muons and photons (the photon is the field quantum of the electromagnetic interaction). The success of this theory is important in that it contains the basic ideas of quantum mechanics. There are many conceptually difficult ideas in quantum mechanics which arise in attempting to explain phenomena outside the range of human experience. Ever since their introduction these ideas have caused intense debate about the validity of quantum mechanics. However, the impressive accuracy to which the predictions of QED have been experimentally verified has, to some extent, allayed worries about the statistical nature of the predictions, i.e. that it is outside the scope of the theory to predict the outcome of a specific interaction and hence, ultimately, the future.

Early attempts to understand the results from studies of radioactive beta decays led to considerable confusion. These phenomena are associated with the weak force, and interpretation of the results in terms of the then known particles (electron, proton and neutron) led to the conclusion that the hallowed laws of energy-momentum and angular-momentum conservation were violated in these decays. Pauli (1933) gave a way out of this dilemma by postulating the existence of an approximately massless neutral particle with half-integral spin, called the neutrino. Fermi (1934), assuming the existence of the neutrino, formulated a theory of beta decays. This was based, to some extent, on the ideas of QED, but with important differences. The Fermi theory postulates the weak interaction to be that of four spin-$\frac{1}{2}$ fermions at the same space-time point (point-like coupling). Thus the theory contains no equivalent of the exchanged boson of QED (i.e. the photon) to mediate the force. Any doubts about the existence of the neutrino were removed by its discovery (or, more precisely, the discovery of the antineutrino) by Reines and Cowan (1953, 1959), who used the intense flux produced by a nuclear reactor.

The advent of new accelerators, with proton energies up to about 30 GeV at Brookhaven National Laboratory and at CERN, allowed the construction of neutrino beams. The neutrinos came mainly from the decays $\pi \to \mu\nu$ and $K \to \mu\nu$. Danby *et al.* (1962) observed that the neutrinos produced in this way gave interactions containing a final state muon, but not containing a final state electron. This showed that there are (at least) two types of neutrino and that the neutrino associated with the muon (ν_μ) is different to that associated with the electron (ν_e).

These and other experimental results on leptons can be explained by assigning two additive quantum numbers defined as follows:

$$\begin{aligned} L_e &= 1\ (e^-, \nu_e), & L_\mu &= 1\ (\mu^-, \nu_\mu), \\ &\quad -1\ (e^+, \bar{\nu}_e), & &\quad -1\ (\mu^+, \bar{\nu}_\mu), \\ &\quad 0\ \text{(other particles)}, & &\quad 0\ \text{(other particles)}. \end{aligned} \tag{1.1}$$

L_e and L_μ are the lepton numbers for the electron and muon families respectively, and $\sum L_e$ and $\sum L_\mu$ appear to be separately conserved in interactions. For example, the principal decay mode of the μ^- is

$$\begin{array}{lcccc} & \mu^- \to & e^- & \bar{\nu}_e & \nu_\mu \\ L_e & 0 & 1 & -1 & 0 \\ L_\mu & 1 & 0 & 0 & 1 \end{array} \tag{1.2}$$

However, the decay $\mu^- \to e^-\gamma$, which would violate these rules, has never been seen, and has an upper limit for its branching ratio of $< 1.7 \times 10^{-10}$.

1.3 THE LIGHT QUARKS

These new proton accelerators also led to many other important discoveries. A rich spectrum of excited states of mesons (e.g. $\rho(770)\rightarrow\pi\pi$) and baryons (e.g. $\Delta(1232)\rightarrow N\pi$) was found (N stands for nucleon i.e. p or n). These states decay via the strong interaction to the experimentally observed particles.

Studies on the production of the so-called strange particles showed that they are produced in pairs (associated production) by the strong interaction. An additive quantum number *strangeness* (S) can be assigned to all particles and this is conserved by the strong interaction, e.g.

$$\begin{array}{ccccc} & \pi^- + & \mathrm{p} \rightarrow & \mathrm{K}^0 + & \Lambda^0 \\ S & 0 & 0 & +1 & -1 \end{array} \qquad (1.3)$$

Many excited states of strange mesons (e.g. $K^*(892)\rightarrow K\pi$) and strange baryons (e.g. $\Sigma(1385)\rightarrow\Lambda\pi$) exist, and these have decay widths (or equivalently lifetimes) similar to those of their non-strange counterparts. However, the lifetimes of the K^0 (which decays predominantly to two pions) and the Λ (mainly to $N\pi$) are both about 10^{-10} s. These decays are examples of the weak interaction. In these weak decays strangeness is not conserved.

The baryon quantum number B, like strangeness, is additive. However, it appears that the total baryon number is conserved to good accuracy in the strong, electromagnetic and weak interactions. By definition mesons have $B=0$, whereas baryons and antibaryons have $B=1$ and $B=-1$ respectively. Further, mesons have integral spin (bosons), whereas baryons have half-integral spin (fermions). Baryon states other than the proton are unstable and decay either directly or sequentially to a proton plus one or more particles, e.g.

$$\Delta^+(1232) \xrightarrow{\text{strong}} \pi^+ n \xrightarrow[\text{weak}]{} p e^- \bar{\nu}_e \qquad (1.4)$$

$$\pi^+ \xrightarrow[\text{weak}]{} \mu^+ \nu_\mu$$

$$\mu^+ \xrightarrow[\text{weak}]{} e^+ \nu_e \bar{\nu}_\mu$$

The lifetime of the proton is in excess of 10^{30} yr and is thus effectively stable. Thus the particles produced in a particular interaction eventually decay to 'stable' particles, i.e. p, $\bar{p}$, e^-, e^+, ν, $\bar{\nu}$, γ. The photon is the end product of an electromagnetic decay sequence, e.g. $\eta(548)\rightarrow 3\pi^0\rightarrow 6\gamma$.

The observed spectrum of hadrons contains both particles and antiparticles. By definition, the charge conjugation operator (C) changes a particle to its antiparticle. This operation changes the charge, magnetic moment, baryon number and lepton number of the particle, leaving the space-time coordinates and momenta unchanged. Hence the spin $\boldsymbol{\sigma}$ is unchanged under C, since one can write $\boldsymbol{\sigma} = \mathbf{r} \times \mathbf{p}$. Some examples of the effects of the operator C are $C(\mathrm{p}) = \bar{\mathrm{p}}$, $C(\mathrm{e}^-) = \mathrm{e}^+$, and $C(\pi^+) = \pi^-$. In these cases the particle and its antiparticle are separate entities. However, neutral non-strange particles which have lepton and baryon number zero, such as the photon and π^0, do not have distinct antiparticles. These particles are eigenstates of C with eigenvalues $C = \pm 1$. The photon has $C = -1$; this follows, since the electromagnetic field produced, say, by an electron changes sign under C. A system of n photons has $C = (-1)^n$. Hence, since the π^0-meson decays predominantly to two photons, $C(\pi^0) = 1$. The other two members of the isospin triplet of pions are not eigenvalues of C, since $C(\pi^+) = \pi^-$. If we define R_2 to be a rotation of 180° around the isospin axis I_2, such that $I_3 \to -I_3$, then $R_2(\pi^-) = \pi^+$. In general, one can write $R_2 = (-1)^I$. This expression is analogous to that for parity, $P = (-1)^l$, in terms of the orbital angular momentum l. Thus, all three members of the pion isotriplet are eigenstates of the combined operation $G = CR_2$. The eigenvalues of G are ± 1. For the pion G is negative since $C(\pi^0) = 1$ and $R_2 = -1$. For a system of $n\pi$, $G = (-1)^n$. A fermion–antifermion system (e.g. $\mathrm{p}\bar{\mathrm{p}}$, $\mathrm{e}^+\mathrm{e}^-$, $\mathrm{q}\bar{\mathrm{q}}$) is also an eigenstate of C with eigenvalues, $C = (-1)^{l+s}$, where l and s are the relative orbital angular momentum and spin of the pair respectively.

The observed spectrum of hadron states could be neatly classified by the quark model of Gell-Mann (1964) and Zweig (1964) in terms of three fractionally charged spin-$\frac{1}{2}$ quarks, called u (up), d (down) and s (strange) – see Table 1.1. The various types of quarks are referred to as *flavours*. In the quark model mesons are bound states of a quark and antiquark ($\mathrm{q}\bar{\mathrm{q}}$) whereas baryons and antibaryons are composed of three quarks (qqq) and three antiquarks ($\bar{\mathrm{q}}\bar{\mathrm{q}}\bar{\mathrm{q}}$) respectively.

The approximate symmetry of the strong interaction with respect to transformations of u and d quarks can be specified in terms of *isospin*. The u and d quarks have $I = \frac{1}{2}$ with third components $I = \frac{1}{2}$ and $-\frac{1}{2}$ respectively. The inclusion of the strange quark necessitates the introduction of a further quantum number, the hypercharge $Y = B + S$. The approximate invariance of the strong interaction under transformations of u, d and s quarks is expressed using the unitary symmetry group SU(3). This group consists of rotations in the three-dimensional coordinate system corresponding to u, d and s quarks with the 'special' condition

Table 1.1. *Quantum numbers of the quarks.* For antiquarks the quantum numbers have the opposite sign.

Flavour	Constituent mass (GeV)	Baryon number B	Charge (units of e)	U	D	S	C'	B'	T'
u	0.35	$\frac{1}{3}$	$\frac{2}{3}$	1	0	0	0	0	0
d	0.35	$\frac{1}{3}$	$-\frac{1}{3}$	0	-1	0	0	0	0
s	0.5	$\frac{1}{3}$	$-\frac{1}{3}$	0	0	-1	0	0	0
c	1.5	$\frac{1}{3}$	$\frac{2}{3}$	0	0	0	1	0	0
b	5	$\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0	-1	0
t	?	$\frac{1}{3}$	$\frac{2}{3}$	0	0	0	0	0	1

The symbols C', B' and T' are used to denote quark flavour numbers, in order to distinguish these from charge conjugation (C), baryon number (B) and time reversal (T).

that the length of a rotated vector is conserved (Chapter 2). This leads to multiplets of particles of a given spin and parity, which would be degenerate in mass if the symmetry were exact and if the electromagnetic effects could be 'switched off'. The quark compositions of the lightest multiplets of mesons and baryons are given in Tables 1.2 and 1.3 respectively. Associated with a particular hadron one can define an intrinsic parity, e.g. for the π-meson $P_\pi = -1$. The various spin-parity states of the multiplets correspond to specific configurations of the quarks' spins and relative orbital angular momenta. This latter separation is, however, non-relativistic and such a simplification is not, in all cases, justifiable.

A reasonable understanding of the mass spectrum of these hadrons can be obtained by assuming that the quarks are relatively light. The mass attributed to the quarks in this context is called the *constituent* mass and is about 0.35 GeV for the u and d quarks. The d quark is slightly heavier than the u quark. The mass difference, $m_d - m_u \sim 3$ MeV, can be determined from the neutron (udd) and proton (uud) mass difference. The mass assigned to the strange quark is somewhat larger (about 0.5 GeV). The mass spectrum of the spin parity $J^P = \frac{1}{2}^+$ baryon octet (p, n, Λ^0, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-) gives a relatively clear demonstration of the relative mass assignments. These topics are discussed in detail by Flamm and Schöberl (1982).

A more explicit demonstration that the nucleon is composed of quarks came from the pioneering experiments performed using the high energy electron beam (up to 20 GeV) at the two-mile-long linear accelerator at