3

Nucleons and the strong interaction

We turn now to the hadrons, bound systems of quarks which interact by the *strong interaction*, as well as by the weak and electromagnetic interactions. In particular we shall describe the *nucleons*, that is to say, the *proton* and the *neutron*, the forces between nucleons, and the effect of the weak interaction on the stability of nucleons.

3.1 Properties of the proton and the neutron

Nucleons, like leptons, are fermions with spin $\frac{1}{2}$. The mass of the neutron is 0.14% greater than that of the proton:

$$\begin{aligned} m_{\mathrm{n}} &= 939.566\ \mathrm{MeV}/c^2, \\ m_{\mathrm{p}} &= 938.272\ \mathrm{MeV}/c^2. \end{aligned} \tag{3.1}$$

Thus the mass difference $m_{\mathrm{n}} - m_{\mathrm{p}} = 1.29\ \mathrm{MeV}/c^2$ (≈ 2 electron masses).

The neutron has no net electric charge. The proton has the opposite charge to the electron: protons are responsible for exactly cancelling the charge of the electrons in electrically neutral atoms.

The electric charge on a proton is not concentrated at a point, but is symmetrically distributed about the centre of the proton. By the experimental methods to be discussed in Chapter 4, the mean radius R_{p} of this charge distribution is found to be $R_{\mathrm{p}} \approx 0.8$ fm. An extended charge distribution is also found in the neutron, positive charge in the central region being cancelled by negative charge at greater distances. The matter distribution in nucleons also extends to a distance of about R_{p}.

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Both the proton and the neutron have a magnetic dipole moment, aligned with their spin:

$$\begin{aligned}\mu_p &= 2.792\,85(e\hbar/2m_p),\\ \mu_n &= -1.913\ 04(e\hbar/2m_p).\end{aligned} \tag{3.2}$$

Clearly neither magnetic moment is simply related to the value $e\hbar/[2(\text{nucleon mass})]$ expected from a simple Dirac equation, and this is a clear indication that the nucleons are not themselves fundamental particles.

Compelling evidence that the nucleons are the ground states of a composite system is given by data of which that in Fig. 3.1 is an example.

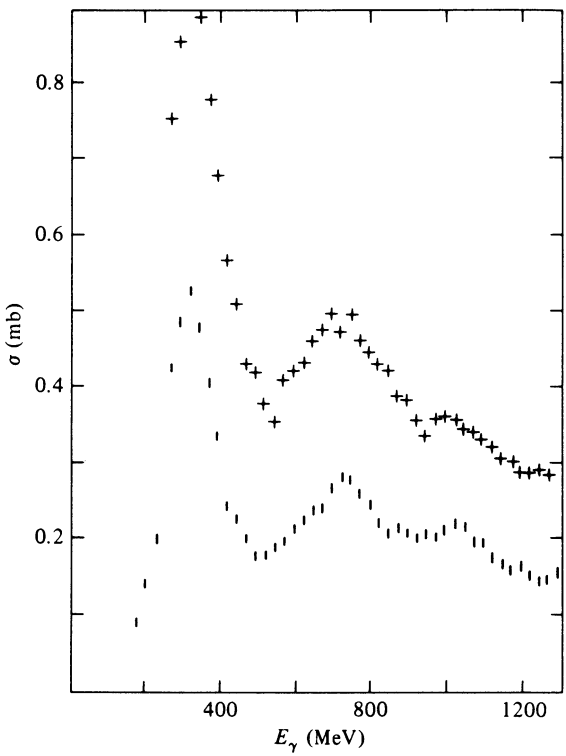


Fig. 3.1 The total photon cross-section for hadron production on protons (dashes) and deuterons (crosses). The difference between these cross-sections is approximately the cross-section on neutrons. (After Armstrong, T. A. *et al.* (1972), *Phys. Rev.* **D5**, 1640; *Nucl. Phys.* **B41**, 445.)

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This shows the cross-section for absorption of photons by protons and by deuterons (see §3.3), as a function of photon energy up to 1300 MeV. The cross-sections vary rapidly with energy. A precise definition of cross-section is given in Appendix A, but for our immediate purpose it is sufficient to remark that the peaks are due to photons being preferentially absorbed to create an excited state when the photon energy matches the excitation energy of that state. Perhaps a more familiar example of photons being absorbed by a composite system is that of atomic absorption. Similar peaks in atomic absorption cross-sections, but at energies of a few electron volts, correspond to the excitation of the atom to higher energy states. The nucleon peaks have a similar interpretation, albeit on a very different energy scale. The first peak in the proton cross-section is at a photon energy of about 294 MeV, and corresponds to the formation of a state called the Δ^+. The Δ^+ is a fermion with mass of about $(938 + 294)$ MeV ≈ 1232 MeV; its spin has been determined to be $\frac{3}{2}$.

Data for the neutron show that it has a sequence of excited states of the same spins and almost identical energies as has the proton. The electrical energies associated with the charge distributions of the proton and neutron are of order of magnitude $e^2/(4\pi\varepsilon_0 R_\mathrm{p}) \approx 2$ MeV (taking $R_\mathrm{p} = 0.8$ fm), which is small compared with the nucleon rest mass energies and excitation energies. We shall see that, in all strong interactions, protons and neutrons behave in the same way to a good approximation. The near independence of the strong interaction on nucleon type is an important fact for our understanding of the properties of the nucleus.

3.2 The quark model of nucleons

Any composite system with spin $\frac{1}{2}$ must contain an odd number of fermion constituents. (An even number would give integral spin.) The highly successful quark model postulates that nucleons contain three fundamental fermions called *quarks*. We cannot here present the particle physics which establishes the validity of the quark model, but since particle physics does have implications for the concepts of nuclear physics we give – without attempting justification – some of the most relevant results.

As is the case with the elementary leptons, there are several types of quark, with a curious and so far unexplained mass hierarchy. For nucleons and nuclear physics only the two least-massive quarks are involved, the up quark u and the down quark d. The proton basically contains two up quarks and a down quark (uud) and the neutron two downs and one up (ddu). These quarks are bound by the fundamental

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strong interaction field, called by particle physicists the *gluon* field. The fact that the strong interactions of neutrons are almost the same as those of protons is explained by the gluon field having the same coupling to all quarks, independent of their type.

What are the properties of these quarks? They have mass, but the mass of a particle is generally determined by isolating it and measuring its acceleration in response to a known force. Because a single quark has never been isolated, this procedure has not been possible, and our knowledge of the quark masses is indirect. The consensus is that much of the nucleon mass resides in the gluon force fields that bind the quarks, and only a few MeV/c^2 need be assigned to the u and d quark masses. It is well established that the d quark is heavier than the u quark, since in all cases where two particles differ only in that a d quark is substituted for a u quark, the particle with the d quark is heavier. The principal example of this is the difference in mass between the neutron and proton. The mass, $\sim 2\ \mathrm{MeV}/c^2$, associated with the electrical energy of the charged proton is far greater than that associated with the (overall neutral) charge distribution of the neutron, so that one might expect the proton to be heavier. However, the extra d quark in the neutron more than compensates for this, and makes the neutron heavier than the proton.

The electric charges carried by quarks are well verified by measurements of the electromagnetic transitions between the nucleon ground states and excited states. The u has charge $\frac{2}{3}e$ and the d has charge $-\frac{1}{3}e$. Thus the proton (uud) has net charge e and the neutron (ddu) has net charge zero. Again, since a quark has never been isolated, the evidence for these assignments is all indirect.

The differences between neutrons and protons, other than their electric and weak charges, are due to the u–d mass difference. This has only a small effect on the basic strong interactions, so that the resulting strong interaction between nucleons is almost independent of nucleon type. This independence may be expressed mathematically by introducing the concept of 'isotopic spin symmetry', but for our purposes this elaboration is unnecessary.

3.3 The nucleon–nucleon interaction: the phenomenological description

We shall see in later chapters that the kinetic energies and potential energies of nucleons bound together in a nucleus are an order of magnitude smaller than the energies (~ 290 MeV) required to excite the quarks

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in an individual nucleon. It is, therefore, reasonable to regard a nucleus as an assembly of nucleons interacting with each other, but basically remaining in their ground states. To understand the physics of nuclei it is therefore important to be able to describe the interactions between nucleons. Since nucleons are composite particles, we can anticipate that their interactions with each other will not be simple. In fact they are rather complicated. Nevertheless, after 70 years of experimental and theoretical effort a great deal is known empirically about the forces between two nucleons, especially at the low energies relevant to nuclear physics.

The empirical approach is to construct a possible potential which incorporates our limited theoretical knowledge (which we shall discuss in §3.4) and has adjustable features, mainly to do with the short-range part of the interaction. The Schrödinger equation for two nucleons interacting through this potential is then solved numerically and the adjustable features are varied to fit the experimental facts, namely the properties of the *deuteron* and the low-energy scattering data.

The deuteron is a neutron–proton bound state with:

$$\begin{aligned} &\text{binding energy} = 2.2245\ \text{MeV},\\ &\text{angular momentum } j = 1,\\ &\text{magnetic moment} = 0.8574(e\hbar/2m_{\text{p}}),\\ &\text{electric quadrupole moment} = 0.286\ \text{fm}^2. \end{aligned} \tag{3.3}$$

Neither proton–proton nor neutron–neutron bound states exist.

The scattering data provide much more information. Nucleons have spin $\frac{1}{2}$, which may be 'flipped' in the scattering. It can be shown that there are five independent differential cross-sections for spin-polarised proton–proton and a further five for proton–neutron scattering which can, in principle, be measured. Neutron–neutron cross-sections have never been measured directly because there are no targets of free neutrons.

As has been explained, the strong neutron–neutron interaction should be almost the same as the strong proton–proton interaction, and both these should be almost the same as the proton–neutron interaction for the same states of relative motion. However, we must remember here the Pauli exclusion principle: the neutron and proton can exist together in states which are not allowed for two protons or two neutrons. This is why the neutron and proton can have a bound state, whereas two protons or two neutrons do not bind, without any contradiction of the principle that the strong interaction is almost independent of nucleon type.

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A large amount of careful and accurate data has been accumulated, and the most sophisticated and accurate empirical potential has been constructed by a group of scientists working in Paris. Two expressions are needed: one for the (anti-symmetric) states allowed for two protons or two neutrons, as well as a proton and a neutron, and one for symmetric states accessible only to the neutron–proton system. For both cases, when the spins of the two nucleons are coupled to give a total spin $S = 0$ (see Appendix C) the nucleons only experience a central potential.

In Fig. 3.2, the central potential for the anti-symmetric states with $S = 0$ is denoted by V_{C0}. The central potential for symmetric states differs from this, and is not shown.

When the spins couple to $S = 1$ there are four contributions to these potentials, which are then each of the form

$$V(r) = V_{C1}(r) + V_T(r)\Omega_T + V_{SO}(r)\Omega_{SO} + V_{SO2}(r)\Omega_{SO2},$$

where

$$\begin{aligned} \Omega_T &= 3\frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{r})(\boldsymbol{\sigma}_2 \cdot \mathbf{r})}{r^2} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \\ \hbar\Omega_{SO} &= (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \mathbf{L} \\ \hbar^2\Omega_{SO2} &= (\boldsymbol{\sigma}_1 \cdot \mathbf{L})(\boldsymbol{\sigma}_2 \cdot \mathbf{L}) + (\boldsymbol{\sigma}_2 \cdot \mathbf{L})(\boldsymbol{\sigma}_1 \cdot \mathbf{L}). \end{aligned} \tag{3.4}$$

In these expressions $\boldsymbol{\sigma}(\hbar/2)$ is the nucleon spin operator, $\mathbf{L}$ is the orbital angular momentum operator of the nucleon pair, and the subscripts 1 and 2 refer to the two nucleons present.

Again, the radial factors differ in the two cases of symmetric and anti-symmetric states. In Fig. 3.2, V_{C1}, V_{SO} and V_T correspond to symmetric states.

V_{C1} is essentially an ordinary central potential. $V_T\Omega_T$ is called the tensor potential. It has the same angular structure as the potential between two magnetic dipoles and it is also interesting because it is the only part of the potential which does not commute with $\mathbf{L}^2$, so that l is not a good quantum number. $V_{SO}\Omega_{SO}$ and $V_{SO2}\Omega_{SO2}$ give rise to different terms for the different couplings of spin and orbital angular momenta. Spin–orbit coupling is well known in atomic physics, where it is due to magnetic interactions. However, these terms in the nuclear potential, which are of major importance, arise out of the strong interaction.

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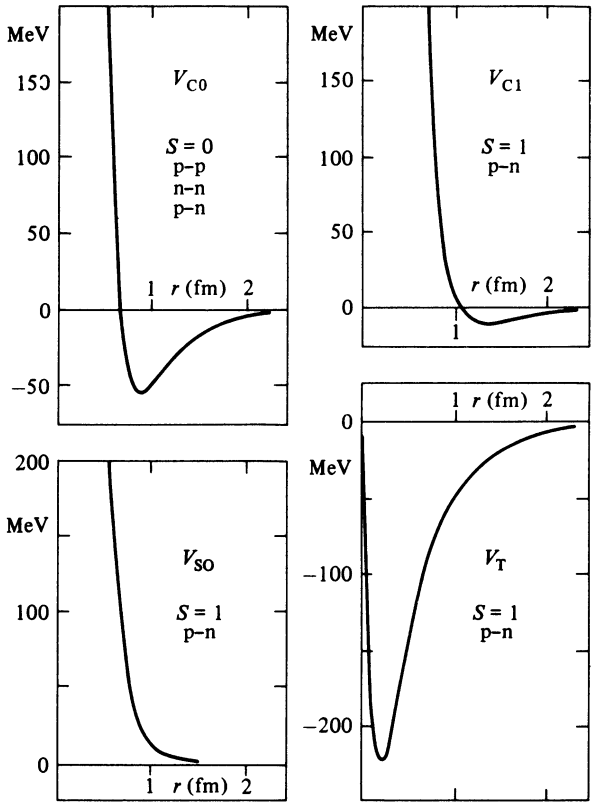


Fig. 3.2 The most important components of the 'Paris potential'. (After Lacombe, M. *et al.* (1980), *Phys. Rev.* **C21**, 861.)

In Fig. 3.2 we show the four potentials that are most important at low energies of interaction (< 100 MeV) and in particular are important for nucleons in nuclei.

The potential $V_{CO}(r)$ is appropriate for low-energy proton–proton and neutron–neutron interactions. The attractive tail is not, however, sufficiently deep to bind two nucleons. The potentials $V_{C1}(r)$, $V_{SO}(r)$ and $V_T(r)$ are responsible for binding the deuteron: note the deeply attractive part of $V_T(r)$, which is associated also with the large electric quadrupole moment of the deuteron.

The tensor potential is particularly important for binding the deuteron, but since it is zero on averaging over all directions it becomes less important in heavier nuclei. This last remark presupposes that the poten-

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tial established for the interaction of two nucleons in isolation is relevant when many nucleons are interacting in an atomic nucleus. We shall discuss this assumption further in Chapter 4.

For the moment, we simply note the similarity between the central potentials and the well-known Lennard-Jones pair potential between neutral atoms, which also has a repulsive core and attractive tail, and (albeit on a different scale) binds the atoms together in condensed matter.

3.4 Mesons and the nucleon–nucleon interaction

Like all fermions, quarks have corresponding anti-particles. Anti-protons and anti-neutrons can exist, made up of anti-quarks, ($\bar{u}\bar{u}\bar{d}$) and ($\bar{d}\bar{d}\bar{u}$); the excited states of nucleons have images of identical mass but opposite charge in anti-quark matter. In fact the electromagnetic and strong interactions of anti-matter seem to be identical to those of matter. It is possible to contemplate the existence of stable anti-atoms, and macroscopic bodies, made up of anti-matter, but as electrons annihilate with positrons, so do nucleons annihilate with anti-nucleons; matter and anti-matter, though stable in isolation, cannot coexist. To study anti-particles we must create them in laboratories.

As well as binding three quarks or three anti-quarks together to make nucleons and anti-nucleons, the strong gluon field can bind a quark and an anti-quark together to form a short-lived particle called a *meson*. Like nucleons, such bound pairs have a sequence of excited states.

Of most importance for nuclear physics are the π mesons. The electrically charged π^+ and π^- are made up of ($u\bar{d}$) and ($d\bar{u}$) pairs respectively, and the neutral π^0 is a superposition $(u\bar{u} - d\bar{d})/\sqrt{2}$ of quark anti-quark pairs. (The orthogonal combination $(u\bar{u} + d\bar{d})/\sqrt{2}$ belongs to a meson called the η.)

The masses of the π mesons are:

$$\begin{aligned} &\text{mass of } \pi^+ = \text{mass of } \pi^- = 139.57 \text{ MeV}/c^2, \\ &\text{mass of } \pi^0 = 134.9 \text{ MeV}/c^2. \end{aligned} \tag{3.5}$$

(The η has mass $\approx 547\,\text{MeV}/c^2$.)

The quark–anti-quark pairs in these mesons have orbital angular momentum zero and intrinsic spins coupled to give total angular momentum zero. The first excited states also have orbital angular momentum zero, but the intrinsic spins are coupled to give a total spin with quantum

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number $S = 1$. These states are called the ρ^+, ρ^- and ρ^0 mesons; they have masses $\sim 770\ \mathrm{MeV}/c^2$.

Quarks are sources of the gluon field, and in a nucleon they are confined by this field to lie within the nucleon. At distances ≥ 1 fm the force between nucleons is not mediated by the basic gluon field, but rather by the exchange of mesons. Mesons have integral spin and are bosons, as are the photons which mediate the electromagnetic interaction and the $W^{\pm}$ and Z particles which mediate the weak interaction.

Although mesons are composite particles, their motion as a whole is still described by a wave-function $\Phi(\mathbf{r}, t)$, obeying in free space the wave-equation for massive particles:

$$\left[\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \left(\frac{mc}{\hbar}\right)^2\right]\Phi(\mathbf{r}, t) = 0, \tag{3.6}$$

where m is the mass of the particle (cf. equations (2.10)–(2.12)).

One solution of this equation describes the π meson field associated with a nucleon having operator spin $\boldsymbol{\sigma}_1(\hbar/2)$ at $\mathbf{r}_1$:

$$\Phi(\mathbf{r}, t) = g_\pi(\boldsymbol{\sigma}_1 \cdot \nabla_1)\frac{\mathrm{e}^{-mc|\mathbf{r}-\mathbf{r}_1|/\hbar}}{|\mathbf{r}-\mathbf{r}_1|}, \tag{3.7}$$

where g_π is a measure of the meson source strength of the nucleon. The gradient operator ∇_1 acts only on $\mathbf{r}_1$, so that (3.7) is evidently a solution of (3.6) (cf. (2.11)).

The field (3.7) changes sign under reflection in the origin (see §2.6) and is said to be a *pseudo-scalar* field. It is the simplest such field we can construct which satisfies the wave-equation. The 'dipole-like' nature of the field is well understood by particle physicists, and the interaction energy between two nucleons associated with it is of 'dipole–dipole' form:

$$U_{12} \propto g_\pi^2(\boldsymbol{\sigma}_2 \cdot \nabla_2)(\boldsymbol{\sigma}_1 \cdot \nabla_1)\frac{\mathrm{e}^{-mc|\mathbf{r}_2-\mathbf{r}_1|/\hbar}}{|\mathbf{r}_2-\mathbf{r}_1|}. \tag{3.8}$$

The π mesons are the mesons of smallest mass and hence give the largest contribution to the interaction at large distances. The appropriate length scale, from the exponential in (3.7), is

$$\hbar/mc \approx 1.4\ \mathrm{fm}.$$

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Explicit differentiation shows that (3.8) includes a potential of the tensor form $V_T(\mathbf{r})\Omega_T$. It is well established that π meson exchange is responsible for most of the tensor potential (3.4), and is the dominant contribution to the whole potential at distances $|\mathbf{r}_2 - \mathbf{r}_1| > 1.4$ fm. At smaller distances other meson exchange processes become important, including the exchange of ρ mesons. However, the potentials at distances < 0.8 fm and, in particular, the short-range repulsion, are empirical and so far have no established explanation.

3.5 The weak interaction: β-decay

Hadrons are subject to the weak interaction as well as to the electromagnetic and strong interactions, and it is through the weak interaction that quarks, like leptons, are coupled to the W and Z bosons. For example, one quark can change to another by emitting or absorbing a virtual W boson. The phenomena of β-decay, in which a neutron becomes a proton or a proton becomes a neutron, proceed in this way.

In free space, the proton is the only stable three-quark system.The neutron in free space has enough excess mass over the proton to decay to it by the process shown in Fig. 3.3.

The mean life of the neutron in free space is 886.7 s $\approx$ 15 minutes. However, a neutron bound in a nucleus will be stable if the nuclear binding energies make decay energetically forbidden. Conversely, a proton bound in a nucleus may change into a neutron

$$p \rightarrow n + e^+ + \nu_e,$$

if the nuclear binding energies involved allow the process to occur. The energetics of β-decay will be dealt with in detail in Chapter 4, and a more quantitative theory of β-decay will be given in Chapter 12.

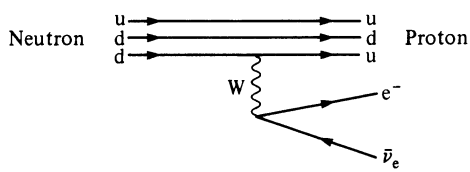


Fig. 3.3 The decay $n \rightarrow p + e^- + \bar{\nu}_e$. As with muon decay, parity is not conserved in this weak interaction.

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Table 3.1. *Properties of quarks*

Quark	Approximate mass	Electric charge (e)
Down d	3–9 MeV/c^2	$-\frac{1}{3}$
Up u	1.5–5 MeV/c^2	$\frac{2}{3}$
Strange s	60–170 MeV/c^2	$-\frac{1}{3}$
Charm c	1.1–1.4 GeV/c^2	$\frac{2}{3}$
Bottom b	4.1–4.4 GeV/c^2	$-\frac{1}{3}$
Top t	174 GeV/c^2	$\frac{2}{3}$

3.6 More quarks

The u and d quarks are merely the two least massive of a sequence of types, or 'flavours' of quark, and to set the discussion of β-decay above into this wider context we list in Table 3.1 all the presently known flavours.

The existence of the more massive quarks in this table is revealed by the observation of states similar to the nucleon states and meson states we have already discussed, but which are apparently formed by substituting any of the 'new' quarks for the u or d quarks. Thus, for example, substituting an s quark for a d quark, there exists a K^+ meson ($u\bar{s}$) (mass 493.68 MeV/c^2) like the π^+ meson ($u\bar{d}$) but heavier, and a Σ^0 baryon (uds) (mass 1193 MeV/c^2) like the neutron (udd) but heavier. *Baryon* and *anti-baryon* are the generic names for particles essentially made up of three quarks or three anti-quarks. Again, since no quark has ever been isolated, the masses given in Table 3.1 are effective masses and have no precise significance.

Were it not for the weak interaction a heavy quark would be stable and there would be more absolute conservation laws, for example, the conservation of strangeness and the conservation of charm. Such laws hold for processes involving only the electromagnetic and strong interactions, but are not absolute since all quarks couple to the $W^{\pm}$ and Z weak interaction fields, and a quark changes its flavour (but remains a quark!) when it emits or absorbs a virtual $W^{\pm}$ boson. Thus, for example, the s quark in the Σ^- baryon can decay through processes like those shown in Fig. 3.4. We shall see that nuclear binding energies are not sufficiently large to make a baryon containing a heavy quark stable even in a nucleus.

The weak interaction makes *all* mesons unstable. Mesons containing a heavy quark can decay by the heavy quark changing into a lighter

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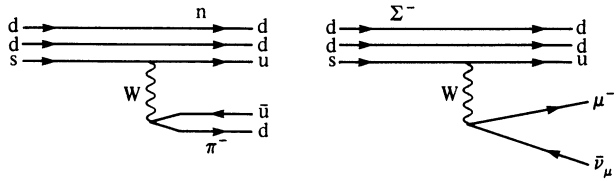


Fig. 3.4 The decays $\Sigma^- \rightarrow n + \pi^-$, $\Sigma^- \rightarrow n + \mu^- + \bar{\nu}_\mu$.

quark. Another possible process is illustrated in Fig. 3.5, in which a quark and an anti-quark annihilate through the weak interaction into an anti-muon and a muon neutrino. This latter process is the predominant type of decay of the charged pions. The mean life of charged pions is 2.60×10^{-8} s.

The π^0 usually decays into two photons by the direct annihilation of the quarks with their own anti-quarks, in a way rather similar to the decay of positronium (an electron–positron pair e^+e^- in a bound state). Such a decay (Fig. 3.6) takes place through the electromagnetic interaction, and is therefore much quicker: the mean life of the π^0 is 0.84×10^{-16} s.

All the available experimental evidence is consistent with there being a law of '*conservation of baryon number*': the total number of baryons (anti-baryons being counted negatively) is conserved in all interactions, so that a baryon and an anti-baryon are always created or destroyed

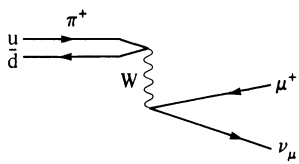


Fig. 3.5 The decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$. The charged pion was discovered by Powell and co-workers in Bristol in 1947 by the observation of this decay.

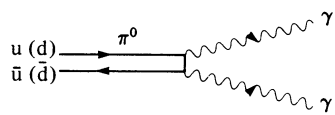


Fig. 3.6 The electromagnetic decay $\pi^0 \rightarrow \gamma + \gamma$.

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together. Indeed, it has been established that a lower limit to the mean life of an isolated proton exceeds 1.6×10^{25} years.

3.7 The Standard Model of particle physics

The electromagnetic, weak, and strong interactions of leptons and quarks are combined in the theoretical edifice known as the *Standard Model* of particle physics. This model has been remarkably successful in the interpretation of the data of particle physics. It is generally believed that the properties of nuclei, and the phenomena of nuclear physics in general, are a consequence of the established laws of particle physics. Our presentation of nuclear physics has been guided by the Standard Model, but a detailed understanding of, even, the proton within the Standard Model remains an experimental and theoretical challenge.

The concepts which are useful at the low energies we consider, were developed long before the Standard Model was established. We shall see in the following chapters that quite simple theoretical models are highly successful in elucidating the properties of nuclei.

Problems

3.1 The spins of the neutron and the proton in the deuteron are aligned. Show that the magnetic moment of the deuteron is within 3% of the sum of the neutron and proton moments. What might be the origin of the discrepancy?

3.2(*a*) Show that the magnetic interaction energy between two magnetic dipoles $\mu\boldsymbol{\sigma}_1$ and $\mu\boldsymbol{\sigma}_2$ is of the form $V_{\mathrm{T}}(r)\Omega_{\mathrm{T}}$ with $V_{\mathrm{T}}(r) = -(\mu_0/4\pi)\mu^2/r^3$. ($\mu_0$ is the permeability of the vacuum.)

(*b*) Verify that equation (3.8) includes terms in the nucleon–nucleon potential of tensor form.

3.3 The Coulomb self-energy of a hadron with charge $+e$ or $-e$ is about 1 MeV. The quark content and rest energies (in MeV) of some hadrons are:
n(udd) 940, p(uud) 938
Σ^- (dds) 1197, Σ^0(uds) 1192, Σ^+(uus) 1189
$K^0(d\bar{s})$ 498, $K^+(u\bar{s})$ 494.

The u and d quarks make different contributions to the rest energy. Estimate this difference.

3.4 Which of the following processes are allowed by the conservation laws?

(*a*) $n \rightarrow p + \gamma$,

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(*b*) $p \rightarrow e^+ + \gamma$,

(*c*) $p \rightarrow \pi^+ + \gamma$,

(*d*) $\bar{p} + n \rightarrow \pi^- + \pi^0$.

3.5 The decay of the Ξ^{*-} initiates the sequence of decays shown below:

$$\Xi^{*-} \rightarrow \begin{cases} K^- + \Sigma^0 \begin{cases} \hookrightarrow \Lambda^0 + \gamma \\ \qquad \hookrightarrow p + e^- + \bar{\nu}_e \end{cases} \\ \pi^- + \pi^0 \begin{cases} \hookrightarrow \gamma + \gamma \end{cases} \\ \mu^- + \bar{\nu}_\mu \\ \qquad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu \end{cases}$$

The quark content of the hadrons involved is:
$\Xi^{*-}(ssd)$, $\Sigma^0(sud)$, $\Lambda^0(sud)$, $p(uud)$,
$K^-(s, \bar{u})$, $\pi^-(d\bar{u})$, $\pi^0(u\bar{u} - d\bar{d})$.
Classify the decays as strong, electromagnetic, or weak.

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