QUARK MODEL AND HIGH ENERGY COLLISIONS

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PREFACE

This book treats one of the directions in elementary particle physics, namely, the application of the quark model to high energy hadron interactions. The main topics under consideration are binary processes, multiparticle production and hadron-nucleus collisions. Since we are considering a relatively restricted subject matter, we have the possibility of presenting a detailed exposition of the results as well as the required calculational techniques. We have made an effort to elucidate the material to such an extent that a novice in the field should be able to make his own calculations after the book is studied. The audience for whom the book is written is assumed to be familiar with quantum field theory, including Feynman diagrams, and also to be acquainted with the eperimental situation in high energy physics.

The subjects considered are inevitably connected with some other domains of elementary particle physics. In our effort to make our book as self-contained as possible we have discussed the necessary background material from these adjacent domains. Chapter 2 gives a concise account of the main experimental results in high energy strong interactions; the foundations of the Regge-pole phenomenology and multiperipheral dynamics are also briefly described there. In Chapter 3 the methods for treating composite systems are explained, while Chapter 4 discusses the theory of multiple rescattering at high energies. The present status of the quark model is reviewed in Chapter 5.

The material covered in Chapters 2 and 5 are described in more detail in books like

J.C. Polkinghorne, *Models of High Energy Physics*, Cambridge Univ. Press, Cambridge (1975).
P.D.B. Collins, *An Introduction to Regge Theory and High Energy Physics*, Cambridge Univ. Press, Cambridge (1975).
K. Huang, *Quarks, Leptons & Gauge Fields*, World Scientific, Singapore (1982).
F.E. Close, *An Introduction to Quarks and Partons*, Academic Press, New York (1979).

Some auxiliary material has been relegated to the Appendices and could probably aid the reader in making various explicit calculations.

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We are specially indebted to our deceased friend V.M. Shekhter. Our collaboration with him has provided much material which is being passed on in this book. This book is dedicated to his memory.

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CONTENTS

Chapter 1

INTRODUCTION

1.1 The Quark-Gluon Structure of Hadrons

It was assumed long ago that the observed elementary particles are not elementary at all. Already in the late forties Fermi and Yang[1)] suggested that the pion is a composite system of a nucleon and an antinucleon. In the early fifties the discovery of the K-mesons and hyperons gave rise to different models, in which some particles were considered as fundamental ones, others as composite systems. The best known model of this kind was that of Sakata[2)] in which the proton, the neutron and the Λ-hyperon were chosen as fundamental particles. The Sakata model and the scheme of unitary symmetry SU(3) which was built up on the basis of the fundamental p, n, Λ fields led to a proper classification of the pseudoscalar and vector mesons, but faced difficulties in the description of baryons. The Eightfold Way which was suggested by Gell-Mann[3)] and Ne'eman[4)] provided a possibility to describe both the mesons and the baryons. A splendid verification of this symmetry was the experimental discovery of the Ω^- hyperon.

The idea of the quark structure of hadrons appeared first in the papers of Gell-Mann[5)] and Zweig[6)]. It was shown, that the SU(3) octet symmetry may be realized on the basis of a fundamental triplet of some hypothetical particles, called quarks by Gell-Mann, carrying fractional electric charges. The quantum numbers of these quarks q(u,d,s) are presented in Table 1.1.

By now it is well known that u, d and s are not the only quarks: there exists also a group of heavy quarks. Experimentally two sorts (flavours) of these heavy quarks were discovered: the c-quark and the b-quark. The existence of a third quark, t, was also expected: after long unsuccessful searches it seems to have been found in recent experiments. The masses of heavy quarks are considerably larger than those of the light quarks. Because of this, dealing with soft processes (i.e. with processes with small momentum transfers) we can restrict ourselves to the consideration of the quarks (u,d,s) which realize the lowest representation of the $[SU(3)]_{flavour}$ group.

Table 1.1 Quantum numbers of light quarks

flavour	charge	isospin		strangeness	baryon charge
u	2/3		$I_3=1/2$	0	1/3
		I=1/2			
d	-1/3		$I_3=-1/2$	0	1/3
s	-1/3	I = 0		- 1	1/3

In the quark picture of hadrons, the meson consists of a quark-antiquark pair, while the baryon is a system of three quarks:

$$M = q\bar{q}, \qquad B = qqq \tag{1.1}$$

In general, one may say that in quark dynamics the only existing states are quark states with zero triality (i.e. when $|N(q) - N(\bar{q})|_{\text{mod } 3} = 0$).

In the non-relativistic quark model the light quarks realize the fundamental representation of a larger symmetry group SU(6) which acts in the space of spins and flavours:

$$q = (u^{\uparrow}, u^{\downarrow}, d^{\uparrow}, d^{\downarrow}, s^{\uparrow}, s^{\downarrow}). \tag{1.2}$$

The indices $\uparrow$ and $\downarrow$ denote the quark spin projection $s_z = \pm 1/2$ on the quantization axis. The introduction of the group

$[SU(6)]_{\text{flavour} \times \text{spin}}$ instead of the group $[SU(3)]_{\text{flavour}}$ was suggested by Gürsey and Radicati[7)] and Sakita[8)]. The analogy which motivated this step was the successful transition from $[SU(2)]_{\text{isospin}}$ to $[SU(4)]_{\text{isospin} \times \text{spin}}$ in nuclear physics, suggested by Wigner[9)].

The SU(6) symmetry might be interpreted in terms of the wave functions of the composite quark systems; in doing so, the introduction of new quark quantum numbers is required[10-12)]. The recent picture of coloured quarks was formulated by Gell-Mann[13)]. In this picture, each quark possesses a new quantum number, colour, which can have three values:

$$q_i \quad i = 1,2,3 \text{ (or red, yellow, green)} . \tag{1.3}$$

The coloured quarks realize the lowest representation of the colour group $[SU(3)]_{\text{colour}}$. Instead of the requirement of zero triality for the quark bound states here it is postulated, that the observable hadrons are singlets of the $[SU(3)]_{\text{colour}}$ group, i.e. they are white states. For the simplest mesons and baryons this means

$$M = \sum q_i \bar{q}_i$$

$$B = \sum_{i,k,\ell} \varepsilon_{ik\ell}\, q_i q_k q_\ell \quad . \tag{1.4}$$

Here the sum runs over the quark colours; $\varepsilon_{ik\ell}$ is the unit totally antisymmetric tensor. A more detailed picture of the history of the quark models is given in many review papers[14-20)].

An important step in the development of the hadron quark structure is found in the parton hypothesis[21,22)]. According to this, a fast hadron consists of point-like particles called partons. In deep inelastic collisions the photon or the weak intermediate boson interacts with the parton with large momentum transfer; hence in these processes the parton structure can be observed. There is experimental evidence showing that interacting partons are particles carrying the quantum numbers of quarks. The nucleon consists of three valence quarks-partons and a large number (a "sea") of quark-antiquark pairs and gluons. Investigating the momentum distributions one can conclude that the quark-partons carry about half of the momentum of the fast nucleon. The remaining half of the momentum is carried away by gluons which do not interact with the electro-weak field. The investigation of other hard processes such as $\mu^+\mu^-$ production in hadron collisions, hadron production with large p_T and, in particular, e^+e^- annihilation, confirmed the hypothesis of the quark-parton hadron structure and gave serious arguments in favour of the existence of gluons; besides, in these processes new heavy quarks were discovered. The existence of gluons led to three-jet events in e^+e^- annihilation: there must be gluon jets as well as quark jets. In fact such events are observed experimentally and the analysis of these events shows that there are jets which are initiated by particles with $J^P = 1^-$. (The quark-parton hypothesis and the experimental status of the hard processes are described in detail, e.g., in Refs. 23 to 27.

Our present understanding of hadrons as bound states of quarks is based on the theory of quantum chromodynamics. This is a non-Abelian gauge theory based on the theory of Yang-Mills fields[28)] (for a discussion of non-abelian gauge theory we refer, e.g., to the textbook[29)]). In QCD the interaction of quarks is due to the exchange of massless gluons just as the electromagnetic interaction arises from photon exchange. The main process in QCD is the emission of gluons, that in QED is the emission of photons, (Fig. 1.1a). In contrast to QED, where, along with the electron, one neutral photon exists, in QCD three types of quarks (three colours) are assumed and each of them can transform into another via the emission of 8 possible coloured gluons. Colour charge of gluons leads to the consequence that not only quarks emit gluons, but gluon emission by gluons and gluon-gluon scattering are also taking place (Fig. 1.1b and c). The requirement of three colours determines the theory unambiguously.

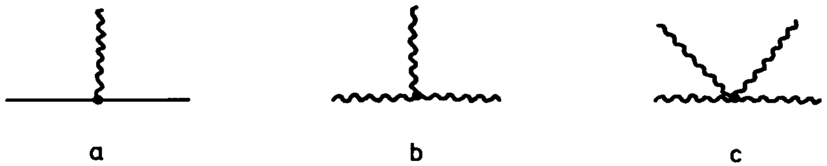

Fig. 1.1 QCD interactions vertices: gluon emission by the quark (a) or by the gluon (b); gluon-gluon scattering (c).

The most striking difference between QED and QCD is that, while electrons and photons are observed in nature, quarks and gluons are not seen as free particles. The hope that in QCD the confinement of coloured objects does take place is based on the increase of the effective charge at large distances. At the same time the decrease of the effective charge at large momenta[30-32] leads to a very important consequence, namely quarks and gluons are asymptotically free at small distances. The asymptotic freedom gives a theoretical justification of the parton model: quarks considered in QCD are quark-partons. At the same time perturbative QCD predicts some small deviations from the results of the naive parton model for hard processes. The detailed test of perturbative QCD calculations is of extreme interest; however the possibilities for the direct comparison of these calculations with the experiment are rather poor. (One can get introduced to the technique of the QCD calculations and its characteristic results in review papers, e.g. see Refs. 33 and 34.

According to our present understanding, QCD is an adequate theory of hadronic matter interactions both at small and large distances. However because of the growth of the effective charge in QCD at large distances perturbative methods cannot be applied to soft processes. A possible way out seems to be phenomenology based on QCD, which returns us to the quark model on a new level of understanding. Indeed, by stating that the colour forces allow the existence of colourless free states only, one implies that these forces are sufficiently strong.

For strong forces it would be natural to lead to a complicated structure of the hadrons as composite systems of quarks and gluons. On the other hand, many years of experimental analysis proved that hadrons can be well described as systems consisting of three quarks (baryons: $B = qqq$) or a quark and an antiquark (mesons: $M = q\bar{q}$) with a relatively small admixture of quark-antiquark pairs. Thus we see that the quarks of the quark model are rather complicated systems themselves. These constituent quarks are the objects of consideration for strong-interaction phenomenology.

1.2 Dressed Quarks

The attempts to combine the results of the quark model with the quark-parton picture have led to the assumption of double hadron structure long ago[35-38]. According to this assumption, practically all the quark-gluon matter inside the hadron is contained in two (mesons) or three (baryons) spatially separated clusters. Every cluster is a dressed (or constituent) quark; it consists of a valence QCD quark (or antiquark), surrounded by quark-antiquark pairs and gluons (see Fig. 1.2). This hypothesis of the double hadron structure states that the hadrons are built similarly to the light nuclei like deuterium or tritium, which consist of two or three nucleons. Such an analogy allows one to call this hadron structure "quasinuclear" (the name "quasinuclear" was introduced by Lipkin[39]). The underlying structure of the dressed quarks manifests itself in the deep inelastic scattering processes.

The quantum numbers of the dressed quark and that of the QCD quarks coincide (it is evident from hadron spectroscopy data — see Chap. 5); however, the other properties of these objects differ rather significantly. Let us first of all consider quark masses. The masses of QCD quarks may be estimated within the framework of current algebra with the use of the partial conservation of axial current hypothesis (PCAC). These estimates lead to comparatively low mass values of the light QCD quarks[40-43]; they are presented in Table 1.2.

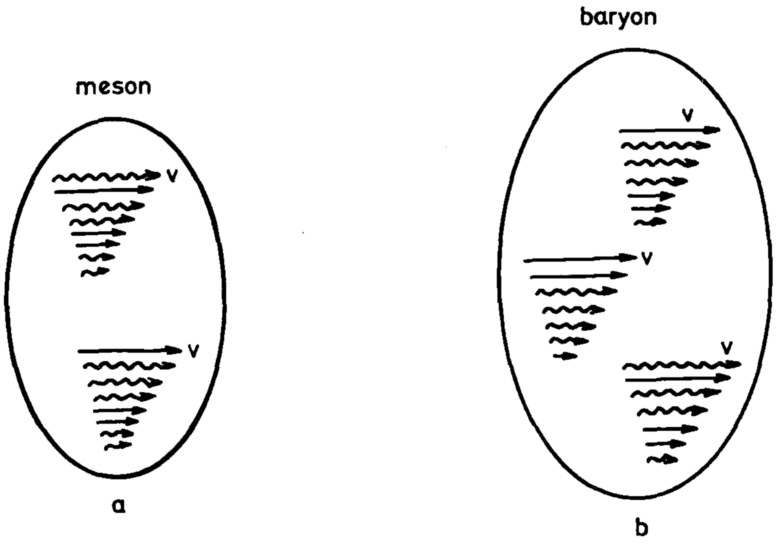

Fig. 1.2 Parton structure of the meson (a) and of the nucleon (b). Nucleon consists of three (meson of two) dressed quarks; each dressed quark (antiquark) consists of the valence quark-parton (straight arrow, marked by index V), sea gluons (wavy arrows) and sea quark-partons (straight arrows).

The masses of the dressed quarks m_q (q = u,d,s), which are estimated on the basis of hadron spectroscopy data (see Chap. 5), are considerably larger than those of the QCD quarks. The values of these masses allow one to calculate the magnetic moments of the baryons and the radiation widths of the vector mesons (Sec. 5.2) in the framework of the quasinuclear quark model. The results of such calculations are in reasonable agreement with the experimental data, though there are also some discrepancies between the predicted values with the observed ones.

As one may see from Table 1.2, the values of masses of the bare (QCD) and dressed quarks are essentially different. For the u-quark the ratio of the dressed to current quark masses approaches two orders of magnitude. The question arises whether such a large difference is reasonable. One must take into account that the absence of free quarks makes it impossible to give an exact definition of the quark mass; it is possible only to consider an effective value of the quark mass. According to Ref. 44, it seems to be natural to define the quark mass through the inverse propagator $\hat{S}_q^{-1}(k) = \hat{k} - m_q(k^2)$, where k is the quark momentum. The quark mass must depend significantly on its virtuality. The variation of the $m(k^2)$-value when k^2 decreases from the large values, typical for the hard processes, to the small virtualities considered in the quark model, may be estimated starting from the perturbation theory. It was found in Ref. 45 that the increase of $m(k^2)$ by one to two orders of magnitude while k^2 tends to 0.1-0.5 GeV^2, typical for the quark model, looks quite reasonable.

Table 1.2 Quark masses

	light quarks			heavy quarks	
q	QCD (current) quark masses	Constituent (dressed) quark masses m_q	q	heavy quark masses	
u	4 MeV	$m_u \simeq m_d \simeq 300$	c	$\sim$ 1.5	GeV
d	7 MeV	- 400 MeV	b	$\sim$ 4.5	GeV
s	150 MeV	$m_s \simeq 3/2\ m_u$	t	30-50	GeV

The existence of the dressed quarks — quark-gluon clusters inside the hadron — must lead to a specific picture of high energy hadron interactions. Due to the quasinuclear hadron structure this interaction must obey quark additivity. The additive quark model (AQM) of hadron-hadron collisions predicts the ratio of the total nucleon-nucleon and pion-nucleon cross sections and is in good agreement with experiment[46,47])

$$\sigma_{tot}(NN)/\sigma_{tot}(\pi N) = \frac{3}{2} \quad . \tag{1.5}$$

Measurements of the cross sections of the strange particle (kaons and hyperons) interactions also agree with the AQM predictions (see Sec. 6.2).

Impressive arguments in favour of the quasinuclear hadron structure are found in hadron-nucleus high energy collisions. The probability for two or three quarks of the projectile hadron to interact in nuclear matter is rather large. For a hypothetical super-heavy nucleus ($A \to \infty$) all dressed quarks of the projectile interact practically with unit probability; in this case the ratio of the secondary multiplicities in the central region of high energy NA and πA collisions must be equal to the ratio of the number of dressed quarks in the projectiles[48]:

$$\langle n_{ch} \rangle_{NA} / \langle n_{ch} \rangle_{\pi A} = \frac{3}{2} \qquad \text{as} \qquad A \to \infty . \tag{1.6}$$

For real nuclei this ratio is less than 3/2 and depends on the probability of the dressed quark inelastic interaction with the nucleus. This probability may be calculated using the value of quark-nucleon inelastic cross section ($\sigma_{inel}(qN) \simeq 1/2\ \sigma_{inel}(\pi N) \simeq 1/3\ \sigma_{inel}(NN)$) and the nucleon-density distribution inside the nucleus. The same probability determines the inclusive cross section of secondary hadron production in the beam-fragmentation region, since the fragmentational particles are formed by the quark-spectators, which did not interact with the target. Numerous relations for the inclusive production in the central and fragmentation regions, obtained in Chap. 8 for hadron-nucleus collisions, are in a reasonable agreement with the experimental data.

A crucial point regarding hadron structure is the ratio of the size of the dressed quark (r_q) and that of the hadron (R_h). The values of r_q estimated from the data on hadron-hadron collisions belong to the interval

$$\frac{1}{30} \leq \frac{r_q^2}{R_N^2} \lesssim \frac{1}{5} \tag{1.7}$$