CLASSICAL THEORETICAL PHYSICS

Walter Greiner
Stefan Schramm
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Quantum Chromodynamics

Third Edition

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Foreword to Earlier Series Editions

More than a generation of German-speaking students around the world have worked their way to an understanding and appreciation of the power and beauty of modern theoretical physics – with mathematics, the most fundamental of sciences – using Walter Greiner's textbooks as their guide.

The idea of developing a coherent, complete presentation of an entire field of science in a series of closely related textbooks is not a new one. Many older physicists remember with real pleasure their sense of adventure and discovery as they worked their ways through the classic series by Sommerfeld, by Planck and by Landau and Lifshitz. From the students' viewpoint, there are a great many obvious advantages to be gained through use of consistent notation, logical ordering of topics and coherence of presentation; beyond this, the complete coverage of the science provides a unique opportunity for the author to convey his personal enthusiasm and love for his subject.

The present five volume set, *Theoretical Physics*, is in fact only that part of the complete set of textbooks developed by Greiner and his students that presents the quantum theory. I have long urged him to make the remaining volumes on classical mechanics and dynamics, on electromagnetism, on nuclear and particle physics, and on special topics available to an English-speaking audience as well, and we can hope for these companion volumes covering all of theoretical physics some time in the future.

What makes Greiner's volumes of particular value to the student and professor alike is their completeness. Greiner avoids the all too common "it follows that ... " which conceals several pages of mathematical manipulation and confounds the student. He does not hesitate to include experimental data to illuminate or illustrate a theoretical point and these data, like the theoretical content, have been kept up to date and topical through frequent revision and expansion of the lecture notes upon which these volumes are based.

Moreover, Greiner greatly increases the value of his presentation by including something like one hundred completely worked examples in each volume. Nothing is of greater importance to the student than seeing, in detail, how the theoretical concepts and tools under study are applied to actual problems of interest to a working physicist. And, finally, Greiner adds brief biographical sketches to each chapter covering the people responsible for the development of the theoretical ideas and/or the experimental data presented. It was Auguste Comte (1798–1857) in his *Positive Philosophy* who noted, "To understand a science it is necessary to know its history". This is all too often forgotten in modern physics teaching and the bridges that Greiner builds to the pioneering figures of our science upon whose work we build are welcome ones.

Greiner's lectures, which underlie these volumes, are internationally noted for their clarity, their completeness and for the effort that he has devoted to making physics an integral whole; his enthusiasm for his science is contagious and shines through almost every page.

These volumes represent only a part of a unique and Herculean effort to make all of theoretical physics accessible to the interested student. Beyond that, they are of enormous value to the professional physicist and to all others working with quantum phenomena. Again and again the reader will find that, after dipping into a particular volume to review a specific topic, he will end up browsing, caught up by often fascinating new insights and developments with which he had not previously been familiar.

Having used a number of Greiner's volumes in their original German in my teaching and research at Yale, I welcome these new and revised English translations and would recommend them enthusiastically to anyone searching for a coherent overview of physics.

Yale University
New Haven, CT, USA
1989

D. Allan Bromley
Henry Ford II Professor of Physics

Preface to the Third Edition

The theory of strong interactions, quantum chromodynamics (QCD), was formulated more than 30 years ago and has been ever since a very active field of research. Its continuing importance may be estimated by the Nobel prize in physics for the year 2004, which was awarded to Gross, Wilczek, and Politzer for their discovery of asymptotic freedom, one of the key features of QCD. The underlying equations of motion for the gauge degrees of freedom provided by QCD are nonlinear and minimally coupled to fermions with global and local SU(3) charges. This leads to spectacular problems compared with those of QED since the gauge bosons themselves interact with each other. On the other hand, it is exactly the self-interaction of the gluons which leads to asymptotic freedom and the possibility to calcuate quark–gluon interaction at small distances in the framework of perturbation theory. We discover one of the most complicated but most beautiful gauge theories which poses extremely challenging problems on modern theoretical and experimental physics today.

Quantum chromodynamics is the quantum field theory that allows us to calculate the propagation and interaction of colored quarks and gluons at small distances. Today's experiments do not allow these colored objects to be detected directly; instead one deals with colorless hadrons: mesons and baryons seen far away from the actual interaction point. The hadronization itself is a complicated process and not yet understood from first principles. Therefore one may wonder how the signature of quark and gluon interactions can be traced through the process of hadronization.

Very advanced analytical and numerical techniques have been developed in order to analyze the world of hadrons on the grounds of fundamental QCD. Together with a much improved experimental situation we seem to be ready to answer the question wether QCD is the correct theory of strong interactions at all scales or just an effective high-energy line of a yet undiscovered theory.

With the upcoming Large Hadron Collider (LHC) at CERN near Geneva, a proton-proton collider reaching a center-of-mass energy of 14 TeV per colliding nucleon pair, perturbative QCD will be tested with highest precision in a regime where it is expected to work extremely well. This will allow precision tests of QCD as the underlying theory of quarks and hadrons. Moreover, calculations performed using perturbative QCD are essential to define the background against which all potential signals of new physics – of the Higgs particle, supersymmetric particles, or exotic things we may not yet think of – will be gauged.

In this book, we try to give a self-consistent treatment of QCD, stressing the practitioners point of view. For pedagogical reasons we review quantum electrodynamics (QED) (Chap. 2) after an elementary introduction. In Chap. 3 we study scattering reactions with emphasis on lepton–nucleon scattering and introduce the language for describing the internal structure of hadrons. Also the MIT bag model is introduced, which serves as an illustrative and successful example for QCD-inspired models.

In Chap. 4 the general framework of gauge theories is described on the basis of the famous Standard Model of particle physics. We then concentrate on the gauge theory of quark–gluon interaction and derive the Feynman rules of QCD, which are very useful for pertubative calculations. In particular, we show explicitily how QCD is renormalized and how the often-quoted running coupling is obtained.

Chapter 5 is devoted to the application of QCD to lepton–hadron scattering and therefore to the state-of-the-art description of the internal structure of hadrons. We start by presenting two derivations of the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi equations. The main focus of this chapter is on the indispensable operator product expansion and its application to deep inelastic lepton–hadron scattering. We show in great detail how to perform this expansion and calculate the Wilson coefficients. Furthermore, we discuss perturbative corrections to structure functions and perturbation theory at large orders, i.e. renormalons.

After analyzing lepton–hadron scattering we switch in Chap. 6 to the case of hadron–hadron scattering as described by the Drell–Yan processes. We then turn to the kinematical sector where the so-called leading-log approximation is no longer sufficient. The physics on these scales is called small-x physics.

Chapter 7 is devoted to two promising nonperturbative approaches, namely QCD on the lattice and the very powerful analytical tool called the QCD sum rule technique. We show explicitely how to formulate QCD on a lattice and discuss the relevant algorithms needed for practical numerical calculations, including the lattice at finite temperature. This is very important for the physics of hot and dense elementary matter as it appears, for example, in high-energy heavy ion physics. The QCD sum rule technique is explained and applied to the calculation of hadron masses.

Our presentation ends with some remarks on the nontrivial QCD vacuum and its modification at high temperature and/or baryon density, including a sketch of current developments concerning the so-called quark–gluon plasma in Chap. 8. Modern high-energy heavy ion physics is concerned with these issues.

We have tried to give a pedagogical introduction to the concepts and techniques of QCD. In particular, we have supplied over 70 examples and exercises worked out in great detail. Working through these may help the practitioner in perfoming complicated calculations in this challenging field of theoretical physics.

In writing this book we profited substantially from a number of existing textbooks, most notably J.J.R. Aitchison and A.J.G. Hey: 'Gauge Theories in Particle Physics', O. Nachtmann: 'Elementarteilchenphysik', B. Müller: 'The Physics of the Quark–Gluon Plasma', P. Becher, M. Boehm and H. Joos: 'Eichtheorien', J. Collins: 'Renormalization', R.D. Field: 'Application of Perturbative QCD', and M. Creutz: 'Quarks, Gluons and Lattices', and several review articles, especially: L.V. Gribov, E.M. Levin and M.G. Ryskin: 'Semi-hard processes in QCD', Phys. Rep. 100 (1983) 1, Badelek, Charchula, Krawczyk, Kwiecinski, 'Small x physics in deep inelastic lepton hadron scattering', Rev. Mod. Phys. 927 (1992), L.S. Reinders, H. Rubinstein, S. Yazaki: 'Hadron properties from QCD sumrules', Phys. Rep. 127 (1985) 1.

We thank many members of the Institute of Theoretical Physics in Frankfurt who added in one way or another to this book, namely Dr. J. Augustin, M. Bender, C. Best, S. Bernard, A. Bischoff, M. Bleicher, A. Diener, A. Dumitru, B. Ehrnsperger, U. Eichmann, S. Graf, N. Hammon, C. Hofmann, A. Jahns, J. Klenner, O. Martin, M. Massoth, G. Plunien, D. Rischke, and A. Scherdin. Special thanks go to A. Steidel who drew the figures, to Dr. H. Weber for technical help, and to Dr. S. Hofmann who supervised the editing process of the second edition and gave hints for many improvements.

In this new edition, typographical errors have been removed, and data and references to the literature have been updated. We thank Dr. S. Scherer for his reliable and efficient assistance throughout the editing process.

Frankfurt am Main,
November 2006

Walter Greiner
Stefan Schramm
Eckart Stein

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Contents of Examples and Exercises

1. The Introduction of Quarks

About 70 years ago, only a small number of "elementary particles",[1] thought to be the basic building blocks of matter, were known: the proton, the electron, and the photon as the quantum of radiation. All these particles are stable (the neutron is stable only in nuclear matter, the free neutron decays by beta decay: $n \to p + e^- + \bar{\nu}$). Owing to the availability of large accelerators, this picture of a few elementary particles has profoundly changed: today, the standard reference *Review of Particle Properties*[2] lists more than 100 particles. The number is still growing as the energies and luminosities of accelerators are increased.

1.1 The Hadron Spectrum

The symmetries known from classical and quantum mechanics can be utilized to classify the "elementary-particle zoo". The simplest baryons are p and n; the simplest leptons e^- and μ^-. Obviously there are many other particles that must be classified as baryons or leptons.

The symmetries are linked to conserved quantum numbers such as the baryon number B, isospin T with z component T_3, strangeness S, hypercharge $Y = B + S$, charge $Q = T_3 + Y/2$, spin I with z component I_z, parity π, and charge conjugation parity π_c. Conservation laws for such quantum numbers manifest themselves by the absence of certain processes. For example, the hydrogen atom does not decay into two photons: $e^- + p \to \gamma + \gamma$, although this process is not forbidden either by energy–momentum conservation or by charge conservation. Since our world is built mainly out of hydrogen, we know from our existence that there must be at least one other conservation law that is as fundamental as charge conservation. The nonexistence of the decays $n \to p + e^-$ and $n \to \gamma + \gamma$ also indicates the presence of a new quantum number. The proton and neutron are given a baryonic charge $B = 1$, the electron $B = 0$. Similarly the electron is assigned leptonic charge $L = 1$, the nucleons $L = 0$. From the principle of simplicity it appears very unsatisfactory to regard all observed particles

[1] For a detailed discussion of the content of this chapter see W. Greiner and B. Müller: *Symmetries* (Springer, Berlin, Heidelberg 1994).

[2] See the *Review of Particle Physics* by W.-M. Yao et al., Journal of Physics G **33** (2006) 1, and information available online at http://pdg.lbl.gov/

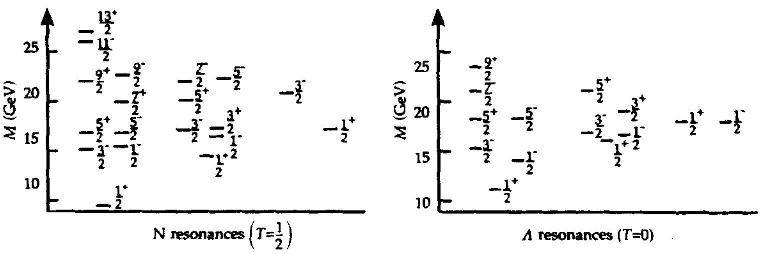

Fig. 1.1. The mass spectra of baryons. Plotted are the average masses of the multiplets. For example, the state $N_{5/2^+}$ at 1.68 MeV stands for two particles, one protonlike and one neutronlike, both with spin 5/2 and positive internal parity. The figure contains 140 particle states in total

as elementary. To give an impression of the huge number of hadrons known today, we have collected together the baryon resonances in Fig. 1.1. The data are taken from the "Review of Particle Properties". Particles for which there is only weak evidence or for which the spin I and internal parity P have not been determined have been left out. Note that each state represents a full multiplet. The number of members in a multiplet is $N = 2T + 1$ with isospin T. Thus the 13 Δ resonances shown correspond to a total of 52 different baryons.

When looking at these particle spectra, one immediately recognizes the similarity to atomic or nuclear spectra. One would like, for example, to classify the nucleon resonances (N resonances) in analogy to the levels of a hydrogen atom. The $\frac{1}{2}^+$ ground state (i.e., the ordinary proton and neutron) would then correspond to the $1s_{\frac{1}{2}}$ state, the states $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{1}{2}^+$ at approximately 1.5 GeV to the hydrogen levels $2p_{\frac{3}{2}}$, $2p_{\frac{1}{2}}$, and $2s_{\frac{1}{2}}$, the states $\frac{5}{2}^+$, $\frac{3}{2}^+$, $\frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{1}{2}^+$ to the sublevels of the third main shell $3d_{\frac{5}{2}}$, $3d_{\frac{3}{2}}$, $3p_{\frac{3}{2}}$, $3p_{\frac{1}{2}}$, $3s_{\frac{1}{2}}$, and so on.

Although one should not take this analogy too seriously, it clearly shows that a model in which the baryons are built from spin-$\frac{1}{2}$ particles almost automatically leads to the states depicted in Fig. 1.1. The quality of any such model is measured by its ability to predict the correct energies. We shall discuss specific models in Sect. 3.1.

We therefore interpret the particle spectra in Fig. 1.1 as strong evidence that the baryons are composed of several more fundamental particles and that most of the observable baryon resonances are excitations of a few ground states. In this way the excited states $\frac{3}{2}^-$ and $\frac{1}{2}^-$ are reached from the nucleon ground state N(938 MeV) $\frac{1}{2}^+$ by increasing the angular momentum of one postulated component particle by one: $\frac{1}{2}^+$ can be coupled with 1^- to give $\frac{1}{2}^-$ or $\frac{3}{2}^-$. As the energy of the baryon resonances increases with higher spin (i.e., total angular momentum of all component particles), one can deduce that all relative orbital angular momenta vanish in the ground states.

To investigate this idea further, one must solve a purely combinatorial problem: How many component particles (called *quarks* in the following) are needed, and what properties are required for them to correctly describe the ground states of the hadron spectrum? It turns out that the existence of several quarks must be postulated. The quantum numbers given in Table 1.1 must be given to them.

Table 1.1. Quark charge (Q), isospin (T, T_3), and strangeness (S)

	Q	T	T_3	S
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	0
d	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	0
s	$-\frac{1}{3}$	0	0	-1
c	$\frac{2}{3}$	0	0	0
t	$\frac{2}{3}$	0	0	0
b	$-\frac{1}{3}$	0	0	0

The three light quarks u, d, s can be identified with the three states in the fundamental representation of SU(3). This is initially a purely formal act. It gains importance only as one shows that the *branching ratios* of particle reactions and the *mass differences* between stable baryons show – at least approximately – the same symmetries. This means that the so-called *flavor* SU(3) can be interpreted as the symmetry group of a more fundamental interaction.

Hadrons are therefore constructed as flavor SU(3) states. As the spin of the quarks must also be taken into account, the total symmetry group becomes SU(3) × SU(2). As an example we give the decomposition of the neutron into quark states[3]:

$$\begin{aligned}|\mathrm{n}\uparrow\rangle = \frac{1}{\sqrt{18}}\Big(&2\,|\mathrm{d}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle\,|\mathrm{u}\downarrow\rangle - |\mathrm{d}\uparrow\rangle\,|\mathrm{d}\downarrow\rangle\,|\mathrm{u}\uparrow\rangle - |\mathrm{d}\downarrow\rangle\,|\mathrm{d}\uparrow\rangle\,|\mathrm{u}\uparrow\rangle \\ &- |\mathrm{d}\uparrow\rangle\,|\mathrm{u}\uparrow\rangle\,|\mathrm{d}\downarrow\rangle + 2\,|\mathrm{d}\uparrow\rangle\,|\mathrm{u}\downarrow\rangle\,|\mathrm{d}\uparrow\rangle - |\mathrm{d}\downarrow\rangle\,|\mathrm{u}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle \\ &- |\mathrm{u}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle\,|\mathrm{d}\downarrow\rangle - |\mathrm{u}\uparrow\rangle\,|\mathrm{d}\downarrow\rangle\,|\mathrm{d}\uparrow\rangle + 2\,|\mathrm{u}\downarrow\rangle\,|\mathrm{d}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle\Big) \ .\end{aligned} \tag{1.1}$$

Particularly interesting for the topic of this volume are the corresponding decompositions of the states Ω^-, Δ^{++}, and Δ^- (see [3]):

$$\begin{aligned}|\Omega^-\rangle &= |\mathrm{s}\uparrow\rangle\,|\mathrm{s}\uparrow\rangle\,|\mathrm{s}\uparrow\rangle \ , \\ |\Delta^{++}\rangle &= |\mathrm{u}\uparrow\rangle\,|\mathrm{u}\uparrow\rangle\,|\mathrm{u}\uparrow\rangle \ , \\ |\Delta^-\rangle &= |\mathrm{d}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle\,|\mathrm{d}\uparrow\rangle \ .\end{aligned} \tag{1.2}$$

To obtain the spin quantum numbers of hadrons, one must assume that the quarks have spin $\frac{1}{2}$. This poses a problem: spin-$\frac{1}{2}$ particles should obey Fermi statistics, i.e., no two quarks can occupy the same state. So the three quarks in Ω^-, Δ^{++}, and Δ^- must differ in at least one quantum number, as we shall discuss in Chapt. 4. Before proceeding to the composition of baryons from quarks, we shall first repeat the most important properties of the symmetry groups SU(2) and SU(3).

SU(2) and SU(3) are special cases of the group SU(N) the special unitary group in N dimensions. Any unitary square matrix $\hat{U}$ with N rows and N columns can be written as (for more details see [3])

$$\hat{U} = \mathrm{e}^{\mathrm{i}\hat{H}} \ , \tag{1.3}$$

where $\hat{H}$ is a Hermitian matrix. The matrices $\hat{U}$ form the group SU(N) of unitary matrices in N dimensions. $\hat{H}$ is Hermitian, i.e.,

$$\hat{H}^*_{ij} = \hat{H}_{ji} \ . \tag{1.4}$$

Of the N^2 complex parameters (elements of the matrices), N^2 real parameters for $\hat{H}$ and hence for $\hat{U}$ remain, owing to the auxiliary conditions (1.4). Since $\hat{U}$

[3] W. Greiner and B. Müller: *Quantum Mechanics: Symmetries* (Springer, Berlin, Heidelberg, 1994).

is unitary, i.e. $\hat{U}^\dagger \hat{U} = 1$, $\det \hat{U}^\dagger \det \hat{U} = (\det \hat{U})^* \det \hat{U} = 1$ and thus

$$\left|\det \hat{U}\right| = 1 \ . \tag{1.5}$$

Owing to (1.4), $\mathrm{tr}\left\{\hat{H}\right\} = \alpha$ (α real) and

$$\det \hat{U} = \det\left(\mathrm{e}^{\mathrm{i}\hat{H}}\right) = \mathrm{e}^{\mathrm{i}\,\mathrm{tr}\hat{H}} = \mathrm{e}^{\mathrm{i}\alpha} \ . \tag{1.6}$$

If we additionally demand the condition

$$\det \hat{U} = +1 \ , \tag{1.7}$$

i.e., $\alpha = 0 \mod 2\pi$, only $N^2 - 1$ parameters remain. This group is called the *special unitary group* in N dimensions (SU(N)).

Let us now consider a group element $\hat{U}$ of U(N) as a function of N^2 parameters ϕ_μ ($\mu = 1, \dots, n$). To this end, we write (1.3) as

$$\hat{U}(\phi_1, \dots, \phi_n) = \exp\left(-\mathrm{i}\sum_\mu \phi_\mu \hat{L}_\mu\right) \ , \tag{1.8}$$

where $\hat{L}_\mu$ are for the time being unknown operators:

$$-\mathrm{i}\hat{L}_\mu = \left.\frac{\partial \hat{U}(\boldsymbol{\phi})}{\partial \phi_\mu}\right|_{\boldsymbol{\phi}=0} \tag{1.9}$$

($\boldsymbol{\phi} = (\phi_1, \dots, \phi_n)$). For small $\phi_\mu(\delta\phi_\mu)$ we can expand $\hat{U}$ in a series ($\mathbf{1}$ is the $N \times N$ unit matrix):

$$\hat{U}(\boldsymbol{\phi}) \approx \mathbf{1} - \mathrm{i}\sum_{\mu=1}^{n} \delta\phi_\mu \hat{L}_\mu - \frac{1}{2}\sum_{\mu,\nu} \delta\phi_\mu \delta\phi_\nu \hat{L}_\mu \hat{L}_\mu + \dots \ . \tag{1.10}$$

Boundary conditions (1.4) and (1.5) imply after some calculation that the operators $\hat{L}_i$ must satisfy the commutation relations

$$\left[\hat{L}_i, \hat{L}_j\right] = c_{ijk}\hat{L}_k \ . \tag{1.11}$$

Equation (1.11) defines an algebra, the *Lie algebra* of the group U(N).

The operators $\hat{L}_i$ generate the group by means of (1.10) and are thus called *generators*. Obviously there are as many generators as the group has parameters, i.e., the group U(N) has N^2 generators and the group SU(N) has $N^2 - 1$. The quantities c_{ijk} are called *structure constants* of the group. They contain all the information about the group. In the Lie algebra of the group (i.e., the $\hat{L}_k$), there is a maximal number R of commutating elements $\hat{L}_i$ ($i = 1, \dots, R$)

$$\left[\hat{L}_i, \hat{L}_j\right] = 0 \quad (i = 1, \dots, R) \ . \tag{1.12}$$

R is called the *rank* of the group. The eigenvalues of the $\hat{L}_i$ are, as we shall see, used to classify elementary-particle spectra. We shall now discuss the concepts