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Quantum Chromodynamics

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Edited by J. L. Alonso & R. Tarrach

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QUANTUM CHROMODYNAMICS

X INTERNATIONAL SEMINAR ON THEORETICAL PHYSICS

Jaca, June 4 - 9, 1979

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FOREWORD

This volume contains the Lectures delivered at the X G.I.F.T.* International Seminar on Theoretical Physics on the subject "Quantum Chromodynamics" which was held at Jaca, Huesca, (Spain) in June 1979. The lecturers were J. Bartels, H. Fritzsch, H. Leutwyler, H. Lynch, E. de Rafael, and C. Sachrajda, who covered both theoretical and phenomenological aspects of Q.C.D. Around 80 physicists attended the Lectures at the Residence of the University of Zaragoza in Jaca. The members of the Organizing Committee of the Seminar were J.L. Alonso (Zaragoza University), J. Bernabéu (Valencia University), C. Pajares (Barcelona Autonomous University), R. Tarrach (Barcelona University) and F.J. Yndurain (Madrid Autonomous University).

The Seminar was supported financially by the Instituto de Estudios Nucleares, Madrid and I.C.E., Zaragoza. We wish to express our thanks to the J.E.N. (Junta de Energia Nuclear) and the University of Zaragoza for their support. The efficient help of Ms. Maribel Ramoneda, Secretary of the course, is gratefully acknowledged.

J.L. Alonso

R. Tarrach

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* The Spanish Interuniversity Group of Theoretical Physics (G.I.F.T.) associates Physicists working in Theoretical Physics all over Spain. Its aim is stimulating and coordinating research as well as the training of physicists devoted to research and teaching.

QUANTUM CHROMODYNAMICS

AS A THEORETICAL FRAMEWORK OF THF HADRONIC INTERACTIONS

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PREFACE

These notes are the written version of the lectures I gave at the Gif Summer School in September 1978 and at the GIFT Seminar in June 1979. The lectures were supposed to provide an elementary theoretical background to the topics covered by the other lectures at the Gif and Gift Seminars . Some of the topics I talked about have been considerably developped in this written version; in particular the relation between different renormalization schemes, and questions related to quark masses. On the other hand I have not included here other topics which were discussed in the lectures, like the infrared behaviour of perturbative QCD; and large p_T -behaviour of perturbative gauge theories. A short review of these two topics with earlier references can be found in the talk I gave at the France-Japan joint seminar (see ref.[R.31]). On the latter subject, large p_T -behaviour, there has been a lot of progress since then, specially in connection with applications to hard scattering hadronic processes. I recommend for a review Sachrajda's lecture at the XIIIth rencontre de Moriond (see ref.[R.32]).

Another topic not covered in these lectures is the application of QCD to deep inelastic scattering of leptons on nucleons. There is a recent review of the subject by Peterman (see ref.[R.33]).

There is another interesting development not included in these lectures, the subject of current algebra spectral function sum rules viewed from QCD. Two detailed references on this topic are [R.34] and (6.2).

References and footnotes are collected at the end of each chapter. References to textbooks, lecture notes and review articles [R] are collected at the end.

In writing these lectures I have benefited very much from the comments and questions of the stimulating audience at Gif and from my colleagues at the CPT in Marseille; in particular, Robert Coquereaux.

1. INTRODUCTION

The most succesful quantum field theory we have at present is Quantum Electrodynamics (QED). It describes the interaction of photons with matter. The quantitative success of the theory lies on the empirical fact that there exist particles in Nature, the charged leptons (electrons, muons, ...), whose dominant interaction is electromagnetic. Precise measurements of various electromagnetic observables have been confronted with perturbative approximations to the equations of motion of QED to the remarkable accuracy of a few parts per million[1]. The Lagrangean of QED reads

$$\mathcal{L}_{QED}(x) = -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) + i\,\bar{\Psi}(x)\gamma^\mu \partial_\mu \Psi(x) - m\,\bar{\Psi}(x)\Psi(x) - e\,\bar{\Psi}(x)\gamma^\mu \Psi(x) A_\mu(x) \tag{1.1}$$

where

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x) \tag{1.2}$$

is the electromagnetic field tensor and $A_\mu(x)$ the vector potential describing the photon field. The first term in eq. (1.1) describes free radiation. The second and third terms are associated to free matter, spin 1/2 particles with mass m. The interaction matter-radiation is governed by the last terms where e denotes the electric charge of the matter field ($e^2/4\pi = \alpha$ the fine structure constant, $\hbar = c = 1$). When the fields $A_\mu(x)$ and $\Psi(x)$ are quantized and the interaction term is treated as a perturbation of the free Lagrangean, a well defined picture emerges with which to calculate observables to the required degree of accuracy. The theory is then a relativistic quantum field theory treated perturbatively and in that respect it is a triumph of the quantization concept when extended to relativistic systems with an infinite number of degrees of freedom.

Since the advent of QED in the late 40's the challenge of theoretical physicists has been to find dynamical theories which could describe the other interactions observed in Nature in the way that QED describes the electromagnetic interactions. During the last decade there has been a tremendous progress in developing quantum field theories potentially useful to incorporate both the electromagnetic and weak interactions of the fundamental constituents of matter: the leptons and the quarks. These are non-abelian gauge quantum field theories with spontaneous symmetry breakdown[2]. On the other hand, there are good indications that the observed strong interactions are governed by a gauge theory as well: a non abelian gauge field theory with unbroken symmetry which describes the interaction of the colour degree of freedom of the constituents of hadronic matter, the quarks, with massless gauge fields, the gluons. This theory is called Quantum Chromo dynamics (QCD)[3].

The quark fields $\psi_j^{\alpha}(x)$ carry two types of indices: α colour index

$$\alpha = \text{blue, red and yellow} \tag{1.3}$$

and a flavour index

$$j = \text{up, down, strange, charm, bottom, } \ldots \tag{1.4}$$

The three colours are associated to the fundamental representation $\underline{3}$ of the gauge group

$$SU(3)_{colour} \tag{1.5}$$

The flavour index is introduced so as to incorporate in a minimal group theoretical structure all the known quantum numbers which govern the strong interaction reactions. Flavours are distributed in two axes of electric charge $Q = \frac{2}{3}$ and $Q = \frac{1}{3}$ as shown in Fig. (1.1). The doublet (u, d) defines the fundamental representation of the isospin group $SU(2)$. The triplet (u, d, s) defines the fundamental representation of the internal symmetry group $SU(3)$ which incorporates isospin and strangeness. The quadruplet (u, d, s, c) the fundamental representation of a symmetry group $SU(4)$ which incorporates isospin, strangeness and charm, etc. The observed hadrons are members of irreducible representations of flavour $-SU(n)$ obtained from tensor products of the constituent quarks:

$$q\bar{q} \quad \text{for mesons ;} \quad qqq \quad \text{for baryons} \tag{1.6}$$

The original motivation for the quark "colour" degree of freedom is quark statistics [see refs. (1.6) and (1.7)]. Consider e.g., the Δ^{++} resonance in the $J_3 = \frac{3}{2}$ state. In terms of quarks it is described by the state

$$| \Delta^{++}, J_3 = \tfrac{3}{2} \rangle = | u^{\uparrow} u^{\uparrow} u^{\uparrow} \rangle \tag{1.7a}$$

where the arrow denotes the quark spin $(+ \frac{1}{2})$. If quarks are fermions then Fermi-Dirac statistics requires the wave function of the Δ^{++} to be antisymmetric under exchange of the space coordinates of each quark pair. On the other hand the Δ^{++} being described by the ground state of the uuu system one expects it to be in an s-wave state and hence symmetric under space coordinate exchanges. One way out of this paradox is to assume that each of the u quarks comes in three colours and that the baryon wave function is indeed symmetric in space and spin but antisymmetric in colour:

$$| u u u \rangle \rightarrow \frac{1}{\sqrt{6}} \epsilon^{\alpha\beta\gamma} | u_\alpha u_\beta u_\gamma \rangle \tag{1.7b}$$

α, β, γ = blue, red and yellow.

So far we have spoken of two different groups for the quarks:

$$\text{flavour} - SU(n) \equiv SU(n)_F \quad \text{and} \quad \text{colour} - SU(3) \equiv SU(3)_c \tag{1.8a,b}$$

The first one is a generalization of the old Eightfold way SU(3) (see ref. [R.8] for a review). The generators do not correspond to exact conservation laws. By contrast colour -SU(3) is assumed to be an exact symmetry: quarks of the same flavour and different colours are otherwise indistinguishable. Furthermore, all observables in Nature are assumed to be color singlets. This is the so-called confinement hypothesis, which is expected to be implemented by the dynamical content of QCD itself.

With quarks assigned to the 3 representation of $SU(3)_c$, the simplest colour singlet configurations we can make out of colour-triplets are

$$3 \times \bar{3} = 1 \text{ (MESONS)} + 8 \quad ; \tag{1.9}$$

and

$$3 \times 3 \times 3 = 1 \text{ (BARYONS)} + 8 + 8 + 10 \tag{1.10}$$

Notice that we cannot make colour singlets out of two-quarks since

$$3 \times 3 = \bar{3} + 6 \neq 1 \tag{1.11}$$

neither out of 4-quarks . There are of course other configurations than (1.9) and (1.10) which can exist as colour singlets, but they are more complicated e.g.,

$$\bar{3} \times 3 \times \bar{3} \times 3 \rightarrow \text{DIMESONS} \qquad (1.12)$$

$$3 \times 3 \times 3 \times \bar{3} \times 3 \rightarrow \text{MESOBARYONS} \qquad (1.13)$$

In fact, candidates for bayonium states of the type $\bar{q}q\bar{q}q$ have already been observed[4].

The colour forces between quarks are mediated by massless vector bosons -the so called gluons much the same as photons mediate the electromagnetic forces between charged leptons. The gluons are the gauge fields belonging to the adjoint representation of $SU(3)_c$. There are altogether eight gluons, one associated to each generator of the group $SU(3)_c$. In the case of QED, the photon field is the gauge field associated to the generator of the abelian group U(1) : the group of gauge transformations. The crucial difference between QED and QCD is that, because of the non-abelian structure of SU(3) the gluons have self-interactions described by a Yang-Mills type Lagrangean [see ref. (1.8)] . The full Lagrangean of QED is given in eq. (2.1). Before we enter into a technical description of this Lagrangean, which is the subject of section 2, I shall spend the rest of this introduction giving a brief review of the evolution of ideas which has lead to our present understanding of particle physics. This is by no means necessary to follow the next lectures. I think, however, that it may help to have a certain perspective of how many of the ideas developed in the 50's and the 60's are incorporated in the present scheme. Also you will see that in spite of the progress made there remain many old problems unsolved.

Wisdom of the 50's:

1. Largely motivated by the challenge of giving a field theoretical framework to the concept of isospin invariance, Yang and Mills (1.8) extend the concept of local gauge invariance from abelian to non-abelian groups. They show this explicitly in the case of SU(2), and construct a gauge invariant Lagrangean out of the three gauge fields $\vec{W}_\mu(x)$ associated to the three generators of isospin $\vec{T}$

$$\mathcal{L}^{(x)}_{Yang-Mills} = -\frac{1}{4}\vec{F}_{\mu\nu}(x)\,\vec{F}^{\mu\nu}(x) \tag{1.14a}$$

where $\vec{F}_{\mu\nu}$ denotes the three field-strength tensors

$$\vec{F}_{\mu\nu}(x) = \partial_\mu \vec{W}_\nu(x) - \partial_\nu \vec{W}_\mu(x) + g\,\vec{W}_\mu(x) \times \vec{W}_\nu(x) \tag{1.14b}$$

with g a coupling constant describing the self interaction of the gauge fields.

2. In an attempt to understand the short-distance behaviour of QED Gell-Mann and Low (1.9) and independently Stueckelberg and Peterman (1.10) develop the concept of <u>Renormalization group</u> Invariance. The importance of the renormalization group as a potential tool to understand the hadronic interactions at short distances will be repeatedly stressed later on by K.G. Wilson (see e.g. ref. (1.11)).

3. The formulation of an effective <u>Lagrangean</u> of the <u>current x current</u> form[5)] for the description of <u>Weak interaction phenomenology</u>

$$\mathcal{L}(x) = \frac{G}{\sqrt{2}}\, J_\mu(x)\, J^\mu(x)^+ \tag{1.15}$$

with

$$J_\mu(x) = \bar{e}(x)\,\gamma_\mu(1-\gamma_5)\,\nu_e(x) + e \leftrightarrow \mu + \text{hadronic currents} \tag{1.16}$$

and G a universal coupling constant, the Fermi constant, fixed from μ decay,

$$G = 1.03\ 10^{-5}\ M^{-2}_{proton} \tag{1.17}$$

An important concept introduced in the late 50's by Feynman and Gell-Mann (1.12) is that of the <u>conserved vector current</u> CVC. For the first time the abstraction of currents from their probe interactions is made: the weak hadronic current and the electromagnetic current are considered as components of the same entity. This will be the basis of the Current Algebra development in the 60's.

Wisdom of the 60's :

1. The Eightfold Way [R.8] . A successful description of the spectroscopy of particles is obtained when the SU(2) group of isospin is enlarged to SU(3) . Hadrons are classified in families of irreducible representations of SU(3) : octets and decuplets.

2. Current Algebra (See refs. [R.8] and [R.11] for a review). The CVC concept is extended to an octet of vector currents and an octet of axial vector currents.

3. The Quark Model (refs. (1.13), (1.14)). Hadrons are considered as being built up out of quarks: fundamental entities associated to the representations 3 and $\bar{3}$ (antiquarks) of the eightfold way SU(3)). The quantum numbers of the quarks are:

	UP	DOWN	STRANGE
Baryon Number	1/3	1/3	1/3
Electric Charge	2/3	-1/3	-1/3
Isospin (1, I_3)	1/2, 1/2	1/2, -1/2	0
Strangeness	0	0	1

In the SU(3) quark model, the weak hadronic current takes the specific form, as proposed by Cabibbo

$$J_\mu^+(x) = \bar{u}(x)\gamma_\mu(1-\gamma_5)\left[d(x)\cos\theta + s(x)\sin\theta\right] \quad (1.18)$$

with θ the Cabibbo angle, a phenomenological parameter fixed from hadronic weak decays ($\theta = 0.23$ radians) .
The electromagnetic hadronic current is then (in units of the electric charge e)

$$J_\mu^{EM}(x) = \frac{2}{3}\bar{u}(x)\gamma_\mu u(x) - \frac{1}{3}\bar{d}(x)\gamma_\mu d(x) - \frac{1}{3}\bar{s}(x)\gamma_\mu s(x) \quad (1.19)$$

These currents (1.18) and (1.19) are two particular combinations of an octet of vector currents and an octet of axial-vector currents one can construct with the quark fields i.e., the quark model gives a precise construction of the algebra of hadronic currents. The basic hypothesis of the algebra of currents is that the equal-time commutators of the time components of the hadronic currents are precisely those of the quark model.

The Lagrangean in eq. (1.15) with currents defined by eqs. (1.16) and (1.18) is a non-renormalizable Lagrangean. This is more than a technical difficulty in the sense that attempts to formulate a phenomenological theory by introducing an arbitrary regulator, a mass scale Λ, to give a meaning to a perturbation theory in powers of the Fermi coupling constant fail. Inconsistent limits for Λ are obtained from different processes.

The idea that $\mathcal{L}(x)$ in eq. (1.15) must be some effective limit of a Yang-Mills type theory has been suspected for a long time. Two stumbling blocks, however, had to be overcomed to pursue that line of thought:

1. the empirical fact that neutral currents were not observed in the easiest processes where they could be detected: strangeness changing decays like $K \to \mu^+\mu^-$ and $K \to \pi e^+e^-$. In a gauge theory, neutral currents appear in a natural way because the commutator of two charged currents gives a neutral current

$$[J^+, J^-] = J^0$$

2. the theoretical difficulty to formulate a renormalizable non-abelian gauge field theory with <u>massive</u> gauge fields (the intermediate vector bosons). The fact that intermediate vector bosons have to be massive is an inevitable constraint dictated by the short range character of the weak forces.

The way out of the first difficulty was found by <u>Glashow-Iliopoulos and Maiani</u> (1.16): there are four flavoured quarks instead of three which, as regards the weak interactions, combine in two fundamental doublets

$$\begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} c \\ -d\sin\theta + s\cos\theta \end{pmatrix} \qquad (1.20)$$

much the same as their leptonic partners

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \tag{1.21}$$

The new charm quark c chooses as a partner precisely the orthogonal combination of the d and s quarks introduced by Cabibbo. Neutral currents in the strangeness changing sector are then avoided. This mechanism, when incorporated into the minimal $SU(2)_L \times U(1)$ model previously suggested[6] by Weinberg (1.17) and Salam (1.18), leads to three specific predictions:

i) there should be sizeable neutral leptonic currents e.g. of the type

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \tag{1.22}$$

ii) there should be sizeable neutral hadronic strangeness conserving currents of the type

$$\nu_\mu + N \longrightarrow \nu_\mu + \text{HADRONS} \tag{1.23}$$

iii) hadrons spectroscopy must require a new quantum number associated to the postulated charm quark.
As you know, the three predictions have been confirmed and the experimental evidence of the three of them is now well established.

The second difficulty has been solved thanks to the work of 't Hooft (1.20) which proved the renormalizability of non-abelian Lagrangean field theories[7].

The introduction of arbitrary mass terms in the symmetric $SU(2)_L \times U(1)$ model violates the local gauge invariance of the Lagrangean and leads in general to a non-renormalizable theory. Up to now, only one mechanism of generating masses has been proved to be tolerable: the spontaneous symmetry breakdown mechanism [see ref. [R.2] for a review and references].

An intersting interplay between the weak and electromagnetic interactions as described by the $SU(2)_L \times U(1)$ model on the one hand, and the colour degree of freedom appears when the perturbation theory of the Weinberg-Salam Lagrangean is examined at higher orders. Because