объединенный
институт
ядерных
исследований
дубна

E2-91-253

D.Ebert*

HADRONIZATION OF QCD

Invited talk presented at the Recontres de Moriond meeting "High Energy Hadronic Interactions", March 17-23, 1991

---

*On leave of absence from Fachbereich Physik, Humboldt-Universität, Berlin

1991

Эберт Д. E2-91-253

Адронизация КХД

Данный доклад является введением в идеи адронизации КХД без каких-либо формализмов. Как выясняется, связанные состояния КХД, массы конституентных кварков и спонтанное нарушение киральной симметрии можно понимать с единой точки зрения.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1991

Ebert D. E2-91-253

Hadronization of QCD

This talk is meant to give an introduction into the main ideas of hadronization of QCD without almost any formalism. As it turns out, QCD bound states, constituent quark masses, and spontaneous chiral symmetry breaking may now be understood within a coherent framework.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1991

Introduction

Quantum chromodynamics (QCD), the nonabelian gauge theory of coloured quarks and gluons with gauge group $SU(3_c)$, is well known to be a successful theory in the description of high-energy interactions of hadrons. The QCD Lagrangian with three light quarks $q^i \equiv \begin{pmatrix} u^i \\ d^i \\ s^i \end{pmatrix}$ (i=1,2,3 - colour index) is defined by

$$\mathcal{L}_{QCD}(q, G_\mu) = -\frac{1}{4}\sum_{a=1}^{8} G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}(i\gamma^\mu\partial_\mu - \hat{m}_0)q - g_s\sum_{a=1}^{8}\bar{q}\gamma^\mu\frac{\lambda^a}{2}qG^a_\mu. \quad (1)$$

Here G^a_μ is the gluon field, $G^a_{\mu\nu}$ is the gluon field strength tensor

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f_{abc}G^b_\mu G^c_\nu, \quad (2)$$

with g_s the colour coupling constant ($\alpha_s = g_s^2/4\pi$), and $\hat{m}_0$ is the matrix of current quark masses. Notice the remarkable fact that QCD is asymptotically free, i.e. in the short distance ($r \ll 1\ fm$), large momentum transfer region ($Q \gg 1\ GeV$) the running coupling between quarks, $g_s(Q) = 4\pi(b\ln Q^2/\Lambda^2)^{-1/2}$, becomes weak. As a consequence, perturbation theory can be employed in close conceptual analogy to quantum electrodynamics (QED), the abelian gauge theory of electrons and photons with gauge group $U(1)$ (compare Table 1). On the other hand, at low energies the running coupling between quarks becomes strong and thus perturbation theory does not work. It is conjectured that this property of QCD would explain why quarks and gluons are not observed but bound inside colour-singlet $\bar{q}q$ meson or qqq nucleon states. Thus, the calculation of low energy hadron observables from QCD always involves the dynamics of bound states which are intrinsically nonperturbative and thus very complicated.

Among the most important aspects of low-energy hadron physics is the concept of chiral symmetry $SU(3)_L \times SU(3)_R$ and its spontaneous breakdown signalled by nonvanishing quark and gluon condensates $< \bar{q}q >$, $< G^a_{\mu\nu}G^a_{\mu\nu} >$. This mechanism is believed to be responsible for the transition of current quarks into constituent quarks as well as for the emergence of the $SU(3)$-

Table 1: Conceptual similarities between QED and QCD.

QED	QCD
electron field: $e(x)$	quark field: $q^{\alpha i}(x)$
	($i-$ colour, $\alpha-$ flavour)
local charge conservation: $U(1)$	local colour conservation: $SU(3_c)$
Lagrangian: $\mathcal{L}_{QED}(e, A_\mu)$	Lagrangian: $\mathcal{L}_{QCD}(q, G^a_\mu)$
photon A_μ	gluons $G^a_\mu (a = 1, \ldots 8)$
$\Downarrow$	$\Downarrow$
atoms	hadrons
molecules	nucleus

nonet of pseudoscalar mesons as Goldstone bosons. Thus, if QCD is the correct theory for the low-energy dynamics of the light hadrons, it must follow the scenario that the $SU(3)_L \times SU(3)_R$ chiral symmetry is broken down to the $SU(3)_V$ symmetry spontaneously. It has been a challenge for the theorists to construct an effective low-energy theory of hadrons that realizes these symmetry properties and reflects the underlying composite structure of the $q\bar{q}$-states (Table 2).

Hadronization and Effective Chiral Lagrangians (ECL)

To describe low-energy strong interaction processes and properties of hadrons it is necessary to use nonperturbative calculational schemes. The most popular ones among them are:

- the method of QCD sum rules [1],
- QCD lattice calculations [2],
- the functional integral approach to effective chiral Lagrangians [3], [4].

This talk is devoted to the ECL-method. There has recently been significant progress in the development of this approach in which one derives the low-energy effective Lagrangian for hadrons either directly from QCD [5] or from some simpler QCD-motivated Nambu-Jona-Lasinio quark models [6]

Table 2: Characteristics of perturbative and nonperturbative QCD.

Perturbative QCD ($\alpha_s \ll 1, Q \gg 1GeV$)	Nonperturbative QCD ($\alpha_s \sim 1$, $Q \lesssim 1GeV$)
Hard (deep inelastic) processes	Soft processes
"Simple" ground state (vacuum $\|0>$)	Complicated ground state (vacuum $\|\tilde{0}>$)
Asymptotic freedom & conceptual similarity with QED	Spontaneous breakdown of chiral symmetry ($<\bar{q}q> \neq 0$, $<G^a_{\mu\nu}G^a_{\mu\nu}> \neq 0$)
	Confinement ?
Microscopic fields: quarks & gluons	Composite fields: hadrons (pion as Goldstone boson)

by using functional integration techniques. That is, in the generating functional of quark Green's functions of QCD one performs a change of variables from quark and gluon fields to the observable hadron fields. In this way, QCD bound states, constituent quark masses and spontaneous chiral symmetry breaking may be understood within a coherent framework. Let us discuss this in some more detail by starting with the generating QCD functional. The idea of hadronization is then summarized by the following relation

$$\int Dq D\bar{q} DG_\mu \exp i \int d^4x [\mathcal{L}_{QCD}(q, G_\mu) + sources]$$
$$\approx \int D\sigma D\pi D\rho Da_1 DN D\bar{N} \exp i \int d^4x [\mathcal{L}_{eff}(\sigma, \pi, \rho, a_1, N) + sources] \quad (3)$$

or

$$\mathcal{L}_{QCD}(q, G_\mu) \Longrightarrow \mathcal{L}_{eff}(\sigma, \pi, \rho, a_1, N). \quad (4)$$

Here σ, π, ρ, a_1 denote the four $SU(3)$-nonets of mesons with $J^P = 0^+, 0^-, 1^-$ and 1^+, and N is the nucleon field. The proof of the above equivalence is a highly nontrivial task. For practical reasons, it requires to consider the limit of large numbers of colours N_c and to use an expansion in field derivatives

which is valid for low energies. Note that the masses and coupling constants of the composite mesons in $\mathcal{L}_{eff}$ are then expressed in terms of QCD parameters only: quark (gluon) condensates, current quark masses and numbers of colours.

For illustrations, let us quote the nonlinear meson Lagrangian including higher-order derivative terms. In the following we restrict ourselves to the sector of pseudoscalar mesons and consider the case of exact $SU(3)$ flavour symmetry ($\hat{m}_0 = m_0$ 1). The effective chiral meson Lagrangian $L_{eff}(\bar{\pi})$ is conveniently represented in terms of the chiral field U and $\mathcal{L}_\mu = (\partial_\mu U)U^+$,

$$U = \exp i\frac{2\bar{\pi}}{F}, \quad \bar{\pi} = \frac{1}{2}\sum_{a=0}^{8} \pi_a \frac{\lambda_F^a}{2}, \quad (5)$$

where π_a is the $SU(3)$-nonet of 0^--fields and $F = 93.3\,MeV$ is the pion decay constant. We have [6]

$$L_{eff}(\bar{\pi}) = L^{(2)}(\bar{\pi}) + L^{(4)}(\bar{\pi}) + L_{WZ}(\bar{\pi}) + L_{SB}(\bar{\pi}). \quad (6)$$

Here

$$L^{(2)}(\bar{\pi}) = \frac{F^2}{4} tr \partial_\mu U \partial^\mu U^+ \equiv -\frac{F^2}{4} tr L_\mu L^\mu \quad (7a)$$

is the standard kinetic part of the chiral meson Lagrangian containing only second-order derivatives. The Lagrangian

$$L^{(4)}(\bar{\pi}) = \frac{N_c}{32\pi^2} tr \left\{ \frac{1}{12}[L_\mu, L_\nu][L^\mu, L^\nu] - \frac{1}{3}(\partial_\mu L^\mu)^2 + \frac{1}{6}(L_\mu L^\mu)^2 \right\} \quad (7b)$$

contains new interactions of fourth order in derivatives. In particular, the first term in the curly bracket is recognized as the well-known Skyrme Lagrangian, but now with a fixed coupling constant $e^2 = 12\pi^2/N_c$. Moreover,

$$\int d^4x L_{WZ}(\bar{\pi}) = \frac{iN_c}{240\pi^2} \int_B d^5x \epsilon^{\mu\nu k\lambda\rho} tr(L_\mu L_\nu L_k L_\lambda L_\rho)$$
$$= \frac{-2N_c}{15\pi^2 F^5} \int d^4x \epsilon^{\mu\nu k\lambda} tr(\bar{\pi}\partial_\mu\bar{\pi}\partial_\nu\bar{\pi}\partial_k\bar{\pi}\partial_\lambda\bar{\pi}) + O(\bar{\pi}^7) \quad (7c)$$

is the famous anomalous Wess-Zumino term. Finally, $L_{SB}(\bar{\pi})$ is a term describing explicit breaking of chiral symmetry,

$$L_{SB}(\bar{\pi}) = \frac{F^2}{4} m_\pi^2 tr(U + U^+ - 2) \approx -\frac{m_\pi^2}{2}\pi_a^2 + O(\bar{\pi}^4). \quad (7d)$$

Note that in the limit $m_0 \rightarrow 0$

$$m_\pi^2 = -\frac{2m_0 < \bar{q}q >}{F^2} \longrightarrow 0, \tag{8}$$

i.e. the pion becomes a massless Goldstone boson. For the complete Lagrangian with $0^+, 0^-, 1^-$ and 1^+ mesons the reader is referred to [3]where a variety of other results as well as of phenomenological applications can be found. Let us quote among them the following ones: i) Weinberg relation $m_{a_1} = \sqrt{2}m_\rho$, ii) KSFR relation $m_\rho^2 = 2g_{\rho\pi\pi}F^2$, iii) vector-axialvector dominance of electro-weak currents, iv) Goldberger-Treiman relation and v) predictions for CP-violation asymmetries in $K \rightarrow 3\pi$ decays. In conclusion, we mention the recent interesting approaches towards the baryon as a diquark-quark bound state [7].

References

[1] M.A.Shifman, A.I.Vainshtein, V.I.Zakharov, Nucl. Phys. B147(1979)385.

[2] See e.g. G.Martinelli, Nucl. Phys. B(Proc. Suppl.) 10A(1989)146.

[3] D.Ebert, H.Reinhardt, V.N.Pervushin, Sov. J. Part. Nucl. 10(1979)444; D.Ebert, A.N.Ivanov, M.K.Volkov, Fortschr. Phys. 37(1989)487; A.A.Bel'kov, D.Ebert, V.N.Pervushin, Sov. J. Part. Nucl. 22(1991)5 and references therein.

[4] H.Kleinert, in: Understanding the Fundamental Constituents of Matter (Erice Lectures 1978), ed. A.Zichichi (Plenum, New York, 1978).

[5] J.Praschifka, R.T.Cahill, C.D.Roberts, International Journal of Modern Physics A, vol. 4, No.18 (1989)4929.

[6] D.Ebert, H.Reinhardt, Nucl. Phys. B271(1986)188; Phys. Lett. B173(1986)453.

[7] R.T.Cahill, C.D.Roberts, J.Praschifka, Aust. J. Phys. 42(1989)129.

RECEIVED BY PUBLISHING DEPARTMENT
ON MAY 28, 1991.