CHIRAL NUCLEAR DYNAMICS

This page is intentionally left blank

CHIRAL NUCLEAR DYNAMICS

Maciej A. Nowak

Institute of Physics, Jagellonian University, Cracow, Poland

Mannque Rho

Service de Physique Théorique, Saclay, France

Ismail Zahed

Department of Physics, SUNY, Stony Brook, USA

World Scientific

Singapore • New Jersey • London • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.

P O Box 128, Farrer Road, Singapore 912805

USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication Data

Nowak, M. A. (Maciej A.)

Chiral nuclear dynamics / by M. A. Nowak, Mannque Rho, I. Zahed.

552 p., 21.5 cm.

Includes bibliographical references and index.

ISBN 9810210000

1. Particles (Nuclear physics) -- Chirality. 2. Quantum
chromodynamics. I. Rho, Mannque. II. Zahed, Ismail. III. Title.

QA793.3.C54.N69 1996

539.7'548--dc20

96-16455

CIP

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Cover design by Alina Mokrzycka-Juruś and Oliver Rho.

Copyright © 1996 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

This book is printed on acid-free paper.

Printed in Singapore by Uto-Print

*To Our Wives
Ewa, Helga, and Adella*

This page is intentionally left blank

PREFACE

The physics of strongly interacting many-body systems known as nuclear physics is a mature discipline which has achieved a remarkably quantitative success. It has explained with an impressive accuracy the properties of nuclei from the deuteron to heavy nuclei containing several hundreds of nucleons. This is the more remarkable when one realizes that in no way did the success depend on the existence of, or knowledge derived from, the fundamental theory of strong interactions now believed to be quantum chromodynamics (QCD). Guided mostly by a wealth of experimental observations and with the help of symmetry patterns, nuclear physicists were able to build models valid in different regimes, such as the shell model, Fermi liquid model, collective model, interacting boson model, etc. and deduce relations between each other. The only “microscopic” information if ever needed was at the level of mesons and baryons and forces mediating between them. Interactions probed in nuclear processes range from long-distance regime, say of a pion Compton wavelength, to a tenth of fermi corresponding to a hard core: Nuclear forces involve the ranges from zero to several fermis while a nucleon has a size of roughly 1 fermi.

QCD dictates that quarks must be confined within a region of about 1 fermi in radius to give a hadron, so one would expect that as two or more nucleons approach each other within a nucleus, quarks and gluons should take over the dynamics and show up in observables. So the puzzle is: How is a nucleus understood without ever invoking explicitly quarks and gluons and furthermore why do quark-gluon signatures not show up in processes involving short-distance encounters?

This monograph is a first attempt to explain how this puzzle can be

understood. We should stress, to start with, that this volume is mostly a collection of works and thoughts of the three authors and as such may not represent a broad review of what has been done in the field although we devote a large portion of the volume to the basic notions developed by other workers. It is certainly not a textbook. It is also largely incomplete. First of all, we have no understanding of how quarks are confined. This explains why the volume hardly touches on this topic although when we treat hadrons, confinement is implicitly assumed. Second, we have no clear idea as to how a nucleus is formed of nearly independent “bags” of quarks and gluons, although this issue may be related to the first. Despite these considerable limitations, we find we can make a significant progress towards understanding nuclei from QCD. The key to this understanding is found in chiral symmetry and its spontaneous breaking in the hadronic world. Throughout most of the book, nonperturbative calculation schemes will be used in the form of semi-classical arguments or chiral counting arguments, providing the seeds for a systematic analysis.

In Chapter 1, the central concept of asymptotic freedom in QCD is discussed from the point of view of the external field problem. Despite that QCD is intractable in the infrared by conventional perturbative methods, a number of nonperturbative results are known. They are related to the structure of the QCD anomalies and to the fact that the QCD vacuum is constrained by a number of symmetries. In this chapter, we discuss the Goldstone theorem, the Vafa-Witten theorem for vector symmetries and 't Hooft's anomaly matching conditions. A generic behavior of the QCD Dirac spectrum is also discussed in the context of random matrix theory.

In Chapter 2, we develop the idea that the QCD vacuum consists of a dilute and random system of instantons and anti-instantons. Although this system screens color and hence does not confine it, we show that most of the theorems listed above are actually realized. After introducing the basics of instanton calculus, we go on to characterize the QCD vacuum as a grand canonical ensemble of instantons and anti-instantons. In the long-wavelength approximation the bulk properties as well as the low-lying excitations of the system can be derived from an effective action for a large number of colors $N_c \gg 1$, in agreement with instanton simulations and cooled lattice calculations.

In Chapter 3, the spectrum of two-dimensional QCD in the limit of large number of colors is analyzed. Some key issues related to the 't Hooft

equation as well as the bosonization program are discussed. Following the original ideas of 't Hooft and Witten, we outline what is presently understood of four-dimensional QCD in the large N_c limit. In particular, we show the emergence of an effective theory of weakly interacting mesons that embodies chiral symmetry, and from which baryons arise as solitons.

In Chapter 4, we review the historical role of chiral symmetry in the strong-interaction physics in the context of current algebra. After defining the basic physical currents in hadronic physics, we go over to Gell-Mann current algebra and its embodiment in the linear and nonlinear sigma models. A number of low-energy theorems are discussed from the point of view of conventional PCAC.

In Chapter 5, the current algebra and the PCAC hypothesis are systematized into an effective Lagrangian field theory, namely, chiral perturbation theory. In this part, we follow the historical route through the works of Li, Pagels, Weinberg, Dashen and Weinstein. In particular, we analyze in simple terms the effects of chiral loops on processes involving pions and nucleons. Weinberg's seminal proposal for analyzing the S-matrix in the soft-pion region, together with the chiral power counting, is discussed, laying the ground for modern chiral perturbation theory.

In Chapter 6, Weinberg's program for the S-matrix is extended to all Green's functions, following the work of Gasser and Leutwyler. A number of results in chiral perturbation theory in the meson sector are briefly reviewed, with a thorough presentation of chiral anomalies. Chiral perturbation theory exploits the chiral Ward identities around the chiral point, using power counting in the pion mass. As such, it is limited. We briefly explore in this chapter the possibility of exploiting the chiral Ward identities *on-shell*, without recourse to any power counting.

In Chapter 7, we extend the chiral structure of QCD to the basic structure of the baryons, reviving in the modern context Skyrme's brilliant conception of unified structure of the hadrons. Using the large N_c reasoning of Chapter 3, we discuss how baryons emerge as chiral solitons of the Skyrme type from a weakly-coupled meson Lagrangian. Their structure and properties are presented both for two and three flavors. The picture of strange hyperons developed by Callan and Klebanov is discussed here and taken up later in Chapter 9.

In Chapter 8, we introduce the notion of Cheshire Cat Principle in hadrons and use the Cheshire Cat Mechanism to show the equivalence be-

tween the chiral soliton description of baryons and the chiral bag model. This may be viewed as a hadronic realization of an approximate duality. A number of interesting quantum phenomena taking place in the chiral bag is reviewed. We stress that the emergence of anomalies and nonabelian Berry phases is the key to understanding the duality between the bag formulation and the soliton formulation in four dimensions.

In Chapter 9, the role of strangeness in the structure of non-strange baryons is discussed. Also discussed is the possibility that the strange quark may be considered in certain circumstances as "heavy." Heavy-flavor QCD is formulated, and an effective action for the soft interactions between heavy and light flavors is discussed in the context of the instanton model of Chapter 2. The model is approximately bosonized and shown to yield the standard heavy-quark effective actions. In the large N_c limit, the effective action describes baryons as heavy solitons. We show that the heavy solitons acquire their quantum numbers through Berry phases, along the line of reasoning given in Chapters 7 and 8.

In Chapter 10, we show how some of the basic concepts developed in the preceding chapters can be exploited in analyzing hadronic matter, both at normal density and at higher density. The strong coupling problem is analyzed using both semi-classical techniques (solitons) and chiral power counting (chiral perturbation theory). We start by showing how the basic structure of the nucleon-nucleon interaction can be recovered from the two-skyrmion system, and how many-nucleon systems may eventually emerge from a multi-skyrmion solution. We go on to show that the basics of chiral perturbation theory can be incorporated into an effective description of the nuclear medium. A number of applications involving few-body and many-body systems (*i.e.*, light and heavy nuclei) is presented. This chapter represents an early and crude attempt in this unexplored domain of physics.

In Chapter 11, chiral symmetry, current algebra and PCAC are used to analyze the bulk structure of QCD at low temperature. A number of low-temperature results in the chiral limit are derived. We discuss the use of finite-temperature sum rules, instanton models, Nambu-Jona-Lasinio models and random matrix formulations for studying the physics taking place in the chiral phase transition region. The phase transition is analyzed using universality arguments and lattice QCD results. A brief account of the nonperturbative aspects of QCD at high temperature is also given, with special emphasis on the space-like correlations. This chapter is meant

to make the bridge to the regime where the effective degrees of freedom figuring in this volume cede to the fundamental QCD degrees of freedom.

In the course of writing this volume, we have benefited immeasurably from generous support and encouragement from many institutes and many people. Stony Brook Nuclear Theory Group through the DOE-grant DE-FG-88ER40388, Saclay's Service de Physique Théorique and Theory Division at Jagellonian University through its Zakopane School 1993 provided financial support so that all three authors could get together at their places at various stages of writing. The National Institute for Nuclear Theory (INT) of the University of Washington, through its 1995 Spring session on chiral dynamics in hadrons and nuclei, and the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt and the Humboldt Foundation of Germany, through their generous support, provided the crucial opportunity to get together to finalize the volume. We have benefited from lively discussions on all aspects of the book with the participants of the INT session as well as with the members of the host institutes (at Stony Brook, Saclay, Cracow, Seattle and Darmstadt). The structure of the volume – particularly its philosophy if one is permitted to use such an expression – is greatly influenced by our collaborators, with whom much of the original work was done and with whom we have had extensive discussions. We owe our deep gratitude in particular to Gerry Brown, Fred Goldhaber, Hans Hansson, Andy Jackson, Marek Jeżabek, Kuniharu Kubodera, Chang-Hwan Lee, Hyun Kyu Lee, Paweł Mazur, Dong-Pil Min, Hélène Nadeau, Holger Bech Nielsen, Byung-Yoon Park, Tae-Sun Park, Madappa Prakash, Michał Przaszłowicz, Georges Ripka, Dan Olof Riska, Norberto Scoccola, Edward Shuryak, Vicente Vento, Jac Verbaarschot, Andreas Wirzba, and Hidenaga Yamagishi.

Special thanks go to Oliver Rho who spent numerous hours patiently editing the volume with imaginative suggestions for style, correcting as best as he could our poor English and eliminating, most of all, physics jargons employed much too carelessly.

Maciej A. Nowak, Mannque Rho, Ismail Zahed

Cracow – Paris – Stony Brook
December 1995

This page is intentionally left blank

CONTENTS

Preface	vii
 CHAPTER 1. INTRODUCTION TO CHIRAL DYNAMICS	
1.1. Basics of Quantum Chromodynamics	1
1.2. Symmetries and Anomalies of QCD	6
1.2.1. Symmetries	6
1.2.2. Anomalies	10
1.2.3. Axial anomaly	11
1.2.4. Trace anomaly	15
1.3. Symmetries of the QCD Vacuum	17
1.3.1. Goldstone theorem	18
1.3.2. Vafa-Witten theorem	19
1.3.3. Anomaly matching conditions	20
1.4. Banks-Casher Relation	23
1.4.1. Dirac spectral density	23
1.4.2. Vafa-Witten theorem revisited	26
1.4.3. Universal properties of the QCD Dirac spectrum	27
Appendix	34
References	36

CHAPTER 2. INSTANTON VACUUM

2.1. Basics of Instantons 37

2.1.1. $SU(2)$ instantons 39

2.1.2. Quark zero modes 41

2.2. Vacuum State 42

2.2.1. Instanton-anti-instanton molecule 44

2.2.2. Instanton-anti-instanton ensemble 45

2.3. Random Instanton Vacuum 48

2.3.1. Quark propagator 48

2.3.2. Effective action 50

2.3.3. Anomalies 59

2.3.4. Glueballs 60

2.3.5. Mesons 61

Appendix 67

References 70

CHAPTER 3. LARGE N_c

3.1. Generalities 73

3.2. Two-Dimensional QCD in Large N_c 74

3.2.1. Mesons 74

3.2.2. Baryons 80

3.3. Four-Dimensional QCD in Large N_c 87

3.3.1. Confinement and chiral symmetry 87

3.3.2. Diagrammatics 88

3.3.3. Mesons 90

3.3.4. Baryons 93

Appendix 100

References 103

CHAPTER 4. CURRENT ALGEBRA

4.1. Introduction	105
4.2. Physical Currents	105
4.2.1. Electromagnetic current	106
4.2.2. Weak currents	107
4.3. CVC Hypothesis	110
4.4. Gell-Mann Current Algebra	111
4.4.1. Basics	111
4.4.2. Connection to sum rules	112
4.4.3. Hypothesis	113
4.5. Symmetries and Algebra	113
4.6. Current Algebra from Models	115
4.6.1. The σ model	116
4.6.2. The quark model	117
4.7. Low-Energy Theorems	118
4.7.1. Two soft photons	118
4.7.2. One soft pion	121
4.7.3. Two soft pions (Tomozawa-Weinberg relation)	127
4.7.4. One photon and one pion (photoproduction)	129
4.7.5. Low-energy theorems for $\rho \rightarrow \pi\pi$	131
4.7.6. Anomalies and current algebra: $\pi^0 \rightarrow \gamma\gamma$	133
4.8. Hadronic Sum Rules	135
4.8.1. Generic sum rule in current algebra	135
4.8.2. Examples of current algebra sum rules	137
4.9. Further Developments	141
Appendix	142
References	147

CHAPTER 5. EFFECTIVE CHIRAL LAGRANGIANS

5.1. Introduction	149
5.2. Chiral Lagrangians	150

5.2.1. Linear σ model 151

5.2.2. Nonlinear σ model 153

5.3. Applications 156

5.3.1. Goldberger-Treiman relation 157

5.3.2. Weinberg-Tomozawa relation 157

5.4. Chiral Perturbation Theory 160

5.4.1. Chiral logarithms 161

5.4.2. Chiral loops and the pion 162

5.4.3. Chiral loops and the nucleon 164

5.4.4. The sigma term 167

5.5. Weinberg “Theorem” 169

5.5.1. Chiral counting 170

5.5.2. $\pi\pi$ scattering 172

5.5.3. Renormalization in nonrenormalizable theories 174

5.5.4. Chiral symmetry breaking 176

References 177

CHAPTER 6. QCD EFFECTIVE ACTION

6.1. Introduction 179

6.2. Elements of Effective Action 180

6.3. Role of the Effective Action 182

6.3.1. External gauge symmetries 183

6.3.2. Nonabelian chiral anomaly 184

6.3.3. Coordinates of the nonlinear σ model 189

6.4. Construction of Effective Action:

Chiral Perturbation Theory 192

6.4.1. W_2 193

6.4.2. W_4 195

6.5. Some Applications 200

6.5.1. Pion parameters 200

6.5.2. Fermion condensate 201

6.5.3. The $\pi\pi$ scattering 202

6.5.4. Other applications	204
6.6. Limitations of Effective Action	205
6.7. “Master Equation” Approach	206
Appendix	214
References	231

CHAPTER 7. CHIRAL SOLITONS

7.1. Introduction	233
7.2. Soliton	234
7.2.1. Stability of the soliton	234
7.2.2. Structure of the soliton	237
7.2.3. Quantization of the soliton	242
7.3. Baryons as Skyrmions	244
7.3.1. $SU(2)$ skyrmions	244
7.3.2. Static properties	246
7.3.3. The Casimir energy	247
7.3.4. $SU(3)$ skyrmions	249
References	271

CHAPTER 8. CHIRAL BAGS

8.1. Introduction	273
8.2. The Cheshire Cat Mechanism	274
8.2.1. (1+1) dimensions	274
8.2.2. (3+1) dimensions	288
8.2.3. Cheshire Cat as a gauge symmetry	295
8.3. Induced (Berry) Gauge Fields in Hadrons	299
8.3.1. “Magnetic monopoles” in flavor space	299
8.3.2. Induced nonabelian gauge field	309
8.3.3. Berry phases in the chiral bag model	317
8.3.4. Baryon excitations	323

Appendix	325
References	327

CHAPTER 9. STRANGE AND HEAVY BARYONS

9.1. Introduction	331
9.1.1. Quark masses	332
9.1.2. Strangeness content of the proton	334
9.1.3. KN sigma term	338
9.2. Heavy Quark Hadrons	338
9.2.1. Generalities	339
9.2.2. Bag model estimate	339
9.2.3. Heavy quark expansion	340
9.2.4. Heavy quark propagator	341
9.2.5. Effective interactions	343
9.2.6. Heavy hadron spectra	345
9.2.7. Heavy meson effective action	351
9.3. Heavy Solitonic Baryons	355
9.3.1. Heavy solitons	355
9.3.2. Hyperon spectrum	361
9.3.3. Connection to Berry structure	362
9.3.4. Connection to large N_c QCD	364
References	365

CHAPTER 10. BARYONIC MATTER

10.1. Introduction	369
10.2. Nuclei as Skyrmions	372
10.2.1. Deuteron	373
10.2.2. Nuclear forces	376
10.3. Nuclear Effective Chiral Lagrangians	381
10.3.1. Chiral symmetry in complex nuclei	381

10.3.2. Chiral Lagrangians for baryons and Goldstone bosons	381
10.3.3. Chiral power counting	386
10.3.4. Effective theories in nuclear medium	390
10.3.5. Applications	396
10.3.6. Nuclei in the “swelled world”	412
10.4. Hadronic Phase Transitions	414
10.4.1. Nuclear matter	414
10.4.2. Goldstone boson condensation	416
10.4.3. Vector symmetry	434
References	440

CHAPTER 11. HADRONS AT FINITE TEMPERATURE

11.1. Introduction	443
11.2. Properties of Matter at Finite T	444
11.2.1. Pion gas	444
11.2.2. Pion mean-free path	446
11.2.3. Bulk parameters	448
11.2.4. Hadron parameters	452
11.3. Correlators	457
11.3.1. Hadron correlators	457
11.3.2. Finite T sum rules	460
11.3.3. OPE at finite T	460
11.3.4. Hadrons in medium	462
11.4. Chiral Models at Finite Temperature	464
11.4.1. Instantons at finite temperature	464
11.4.2. NJL models	475
11.4.3. Random matrix models	478
11.5. Finite Temperature and Confinement	484
11.6. Hagedorn Temperature	487
11.7. Chiral Critical Point	489
11.7.1. Universality class of chiral transition	489
11.7.2. Disoriented chiral condensate	491

11.7.3. Mean-field scaling of chiral transition	492
11.8. QCD Phase Diagram	493
11.9. Dirac Spectrum	495
11.9.1. Instantons	495
11.9.2. Random matrix	497
11.10. Lattice Results	497
11.11. Field Theories at High Temperature	503
11.11.1. Hot $O(N)$	503
11.11.2. Hot three-dimensional QCD (QCD_3)	507
11.11.3. Hot QCD_4	514
References	519
Index	523