

# Preface

This monograph is a sequel to the previous volume entitled *Chiral Nuclear Dynamics* (CND-I for short) that I co-authored with Maciek Nowak and Ismail Zahed and it develops further on the main theme of, and presents new perspectives on, the topics treated in that volume. The present volume is not intended to replace or improve on what was treated there. Apart from a mini-summary, I will skip essentially all the chapters dealing with basic concepts contained in CND-I up to Chapter 6 and pick up some of the issues that have either not been completely dealt with or touched on only briefly in the second half of CND-I, and expand them in the light of new developments that have generated renewed interest in the past decade.

What motivated me to write this volume was the need for a *single* unified framework that puts under a systematic control a large variety of phenomena taking place in hadronic matter under normal as well as extreme conditions of high temperature and high density. There is admittedly no such framework available at present that is truly realistic, but a first attempt is made in this monograph to see to what extent such a framework can be formulated. As such, though ambitious, the scope is rather limited. The subject matter treated in this volume belongs properly to the domain of nuclear physics, nowadays categorized more as hadronic physics than as nuclear physics. The core of the matter, which will be further elaborated upon in the Introduction, is intricately connected with the origin of hadron masses and is tied intimately with the fundamental structure of the complex vacuum associated with the strong interactions. But it also has striking ramifications on “standard” (or mundane) nuclear interactions. The recent intensive endeavor to unravel the phase structure of hadronic matter at very high temperature as in the environment of the Early Universe and at super-high density as in the core of compact stars highlights this matter in the guise of how chiral symmetry and confinement/deconfinement of quarks and gluons of QCD manifest themselves in Nature. Much of what might be happening in matter under the “extreme” conditions cannot be accessed directly and reliably by QCD *proper*, so one is forced to rely on models to access such environments. Various different models, mimicking the true theory of the strong interactions, QCD, have been studied extensively. However lacking experimental guidance and model-independent theoretical tools, they can address, at best, only

certain limited sectors of the strong interactions more or less disconnected from other sectors. This makes it difficult to assess the validity of the various scenarios proposed and to make falsifiable predictions in the conditions that are non-ordinary as one expects at high temperature/density.

Hadronic matter at high density illustrates what is meant above. The situation is similar for high temperature. The ultimate goal in studying matter much denser than nuclear matter would be to determine what the equation of state (EOS) is in the dense matter present in the deep interior of compact stars, either stabilized in binary pulsars or on the verge of collapse into black holes. One of the currently popular ideas is that certain compact stars may support quark matter in a variety of different forms. Now if the star had a core of quark matter, that would carry information on QCD at high density with its intriguing landscape of phases. Physicists would like to produce and study such a matter by laboratory experiments, by typically colliding nuclei on nuclei. Nucleons in nuclei are in interactions involving virtual as well as real mesons, so their interactions are effectively described in terms of hadrons, with their masses and coupling constants suitably determined in the condition in which the measurement is made and for which the theory is defined. The pertinent question is: How does the matter change over from nuclear matter – that we understand – to quark matter – that we do not – as the system is strongly compressed? There are currently two theoretical approaches to this issue. One is “bottom-up” which starts with what is known in the (zero-density) free space and then brings, perturbatively, the system to the state of extreme conditions. The other is “top-down” which starts at an asymptotic density for which QCD is well under control and goes down to a sub-asymptotic density relevant to compact stars. The accepted lore is that the first is well-defined at zero density and the second at asymptotic density. The question is: what happens in between? Here the situation is not at all clear.

In going from a dilute (zero-temperature) hadron state to a highly dense matter supposedly populated with quarks/gluons, one must encounter a variety of different “phases.” At very low density, the matter is a Fermi gas. Next, one encounters Fermi liquid (nuclear matter), possibly condensed mesons, condensed Cooper pairs (color superconductivity) or quark matter and ultimately the color-flavor-locked state. At present each stage is handled separately. What happens in one has little connection to what happens in the other, for the simple reason that there is no systematic theoretical tool reliable enough to guide one to go from one to the other. Can one make a reasonable prediction of what might be happening in compact stars in this situation?

To address this question, let us see what is being done in the search for a “smoking gun” for chiral symmetry restoration at high temperature/density, which is one of the most puzzling and urgent issues in hadron physics. This has bearing on how hadronic masses are generated as I will elaborate in the Introduction, so it is a crucial issue for us. Current experimental and theoretical efforts work to

“restore” – partially or fully – chiral symmetry of the QCD vacuum by “melting” the quark condensate. This is done typically by studying spectral functions in the vector meson channels in heavy-ion collisions. Independent of whether or not such signals are visible in the spectral functions, one can ask whether the order parameter for chiral symmetry, namely, the quark condensate, can be isolated in a unique way from what takes place in the plethora of complex nuclear interactions involved in the experiments. Phrased differently, can one distinguish the would-be signal for full or partial restoration of chiral symmetry in dense medium from what might appear to be *mundane* phenomena in nuclei? I will argue that the answer to this is negative unless one is looking at processes in the close vicinity of the critical point where chiral symmetry is supposedly restored, an experimental condition that is difficult to access unencumbered by “trivial” complications. The matter must be much subtler than what we naively think. We are already familiar with one such situation in nuclear physics where the subtlety had challenged nuclear physicists for decades, namely, the meson exchange current. Yukawa’s meson theory for nuclear forces dictated that there be meson exchange currents but it required the advent of chiral perturbation theory and the astute identification of the processes to look at, to unambiguously “see” how the mesons, and in particular, pions, intervene in nuclear processes.

We expect that the manifestation of chiral symmetry, and consequently the vacuum change of the strong interactions that govern the mass will be a lot subtler than the case of meson exchange currents. The currently available piece-meal treatments cannot provide a clear picture of what happens to the vacuum in nuclear interactions, be it under normal conditions or extreme conditions. In this volume, I will adopt a different strategy by starting with a (perhaps overly) simplified theory which is however not proven to be wrong but has the virtue of being adaptable to the whole range of conditions concerned. It has the definite advantage of being falsifiable at various stages as will be explicitly specified. I will accept the main premise of CND-I that the properties of many-nucleon systems, *i.e.*, nuclei, nuclear matter and hadronic matter at high density and/or high temperature can be deduced or guessed from the fundamental theory of the strong interactions and that this can be done by means of effective field theories consistent with Weinberg’s “folk theorem,” explained and followed closely in this volume. The best one can hope to do along this line is, then, to meet as many as possible the conditions required for the theorem. For this, I exploit the notion of hidden local symmetry developed by Harada and Yamawaki.

In the framework developed in this volume, limited to the minimum possible number of assumptions, we will see emerging an intricate connection between what *does* happen in standard nuclear processes under normal conditions that have been well studied and understood for decades and what *could* happen under extreme conditions that are as yet unexplored. For instance, what could be a signal for chiral phase transition at some high temperature and/or density with a vanish-

ing quark condensate that also indicates the vanishing hadron mass, is found to be intricately connected to such diverse objects or phenomena as tensor forces in normal nuclear interactions, meson exchange currents, Landau Fermi-liquid interactions, a Kohn-Sham-type density functional for nuclear matter, the anomalous gyromagnetic ratio, kaon condensation and the collapse of compact stars into black holes *etc.*

This monograph draws largely from work done and discussion with a large number of collaborators. It was most strongly influenced by Gerry Brown with whom I have worked on practically all aspects of the subjects treated and whose views pervade throughout the volume. The original inception of this monograph was already there when the volume CND-I was completed in mid-1990's but the major part of the material comes from the work done in Korea beginning from 1998 when I started to regularly visit Korea and work with Korean theorists, especially at Seoul National University, Korea Institute for Advanced Study, Hanyang University, and Pusan National University. Both Maciek Nowak and Ismail Zahed visited Korea with me on several occasions and contributed invaluable to the development of the field coined then as "astro-hadron physics" that combines hadron physics and astrophysics. I have had the great fortune of working with, and learning from, many Korean colleagues. Among them, I should mention Dong-Pil Min and his former students at Seoul National University who are now established theorists: Chang-Hwan Lee, Byung-Yoon Park, Tae-Sun Park, and Chaejun Song. Most of their contributions figure prominently in this volume. I should also mention Hyun Kyu Lee and Sang-Jin Sin of Hanyang University who helped me to better understand a variety of subtle issues on geometric phases, topology and renormalization group in hadron physics reflected throughout the volume. Also participating in the research with young Koreans in the years 1999–2003 were Kuniharu Kubodera of South Carolina, USA, Vicente Vento of Valencia, Spain and Bengt Friman of Darmstadt, Germany. The results of their research carried out in Korea make up important parts of this volume.

One of the most crucial developments that turned out to provide the validation of "Brown-Rho scaling" and form the foundation of the principal thesis developed here, is the remarkable but hitherto little appreciated work done by Masayasu Harada and Koichi Yamawaki of Nagoya University on hidden local symmetry in hadron dynamics. I am most grateful for extensive discussions and collaborations with them as well as with Chihiro Sasaki, whose thesis work offers the only consistent framework that I know of for confronting Nature with the notion of hidden local symmetry in matter under extreme conditions.

I would also like to acknowledge the kind help of Chang-Hwan Lee of Pusan National University on the astrophysics part of Chapters 10 and 11, which covers some of his works with Gerry Brown and the late Hans Bethe. For the more recent development on holographic dual QCD which opens up a new perspective in the field and of which I give a brief discussion, I would like to thank Deog Ki Hong

of Pusan National University, and Ho-Ung Yee and Piljin Yi of Korea Institute for Advanced Study.

Finally and above all, without the patient support and continuous encouragement of Helga, this volume would not have seen its day.

*Mannque Rho*