QUARK–GLUON PLASMA

From Big Bang to Little Bang

This book introduces quark–gluon plasma (QGP) as a primordial matter composed of two types of elementary particles, quarks and gluons, created at the time of the Big Bang. During the evolution of the Universe, QGP undergoes a transition to hadronic matter governed by the law of strong interactions, quantum chromodynamics. After an introduction to gauge theories, various aspects of quantum chromodynamic phase transitions are illustrated in a self-contained manner. The field theoretical approach and renormalization group are discussed, as well as the cosmological and astrophysical implications of QGP, on the basis of Einstein's equations. Recent developments towards the formation of QGP in ultra-relativistic heavy ion collisions are also presented in detail.

This text is suitable as an introduction for graduate students, as well as providing a valuable reference for researchers already working in this and related fields. It includes eight appendices and over 100 exercises.

KOHSUKE YAGI is a professor at the Department of Liberal Arts, Urawa University. He has held positions at the Institute for Nuclear Study at the University of Tokyo, Osaka University and the University of Tsukuba. He has also held several chairs, including in the Japan Nuclear Physics Committee, the Japan–Brookhaven National Laboratory RHIC-PHENIX Project and the International Conference on Quark Matter. He has published 210 articles and written or edited seven books on subatomic physics and general physics, as well as teaching the subject at undergraduate and graduate levels.

TETSUO HATSUDA is a professor in the Department of Physics at the University of Tokyo. He has held positions at the University of Washington, the University of Tsukuba and Kyoto University. He has taught subatomic physics and quantum many-body problems at undergraduate and graduate levels. He has published over 120 scientific articles.

YASUO MIAKE is Professor of Physics at the Institute of Physics, University of Tsukuba. He has conducted research and taught at the University of Tokyo and Brookhaven National Laboratory and the University of Tsukuba. He has experience of teaching electromagnetism and special relativity to undergraduates and subatomic physics to graduates. He has published over 120 scientific articles.

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KOHSUKE YAGI
Urawa University

TETSUO HATSUDA
University of Tokyo

YASUO MIAKE
University of Tsukuba

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Preface

Modern physical science provides us with two key concepts: one is the standard model of elementary particles on the basis of the principle of local gauge invariance, and the other is the standard Big Bang cosmology on the basis of the principle of general relativity. These concepts provide us with a clue which may help us to answer the following two questions: (i) what are the building blocks of matter? and (ii) when was the matter created? The main topic of this book is quark–gluon plasma (QGP), which is deeply connected to these questions. In fact, QGP is a primordial form of matter, which existed for only a few microseconds after the birth of the Universe, and it is the root of various elements in the present Universe.

The fundamental theory governing the dynamics of strongly interacting elementary particles (quarks and gluons) is known to be quantum chromodynamics (QCD). QCD suggests that ordinary matter made of protons and neutrons undergoes phase transitions: to a hot plasma of quarks and gluons for temperatures larger than 10^{12} K, and to a cold plasma of quarks for densities larger than 10^{12} kg cm^{-3}. The early Universe, and/or the central core of superdense stars, are the natural places where we expect such phase transitions. It has now become possible to carry out laboratory experiments to produce hot/dense fireballs ("Little Bang") through high-energy nucleus–nucleus collisions using heavy ion accelerators. We expect individual nucleons in the colliding nuclei to dissolve into their constituents to form QGP.

The intention of this book is to introduce the reader who has a limited background in elementary particle physics, nuclear physics, condensed matter physics and astrophysics to the physics of QGP, a fundamental and primordial state of matter. In particular, the authors have in mind advanced undergraduates and beginning graduate students in physics, those not only studying the above-mentioned fields, but also those studying accelerator science and computer science. In addition, the authors hope that the book will serve as a reference text for researchers already working in the fields mentioned above.

Chapter 1 is an introductory chapter, which illustrates the essentials of the physics of QGP and provides a perspective on the discovery of QGP. Methodology quite common to studies of the early structure of the Universe (the Big Bang) and of the structure of QGP (the Little Bang) is emphasized. The text is then divided into three parts.

Part I provides a theoretical background in the physics of QGP and in the QCD phase transitions. Part I may be read independently from the other Parts in order to understand modern gauge field theories, with applications such as color confinement, asymptotic freedom and chiral symmetry breaking in QCD, the basics of thermal field theory and lattice gauge theory, and the physics of phase transitions and critical phenomena.

Part II is devoted to the implications of QGP on cosmology and stellar structures. The physics of an expanding hot Universe and of superdense stars (neutron and quark stars) are discussed with relation to Einstein's theory of general relativity. Appendix D is included for readers who have little knowledge about Riemann space, Einstein's equation, Schwarzschild's solution, etc.

In Part III, the reader will find an overview of the physics of relativistic and ultra-relativistic nucleus–nucleus collisions. This type of collision is the only way of creating and investigating QGP and QCD phase transitions by means of *laboratory experiments*. The relativistic hydrodynamics and the relativistic kinetic theory are introduced in some detail as guiding principles with which to investigate the dynamics of hot/dense matter produced in the collisions. After discussing the various experimental signatures of QGP, the fixed-target experiments are summarized. Then we present the outstanding results achieved with the world's first Relativistic Heavy Ion Collider (RHIC at Brookhaven National Laboratory), for which special emphasis is put on the evidence for a QGP phase. In addition, the special features of detectors used in high-energy heavy ion experiments are discussed.

We have tried to cover topics ranging from fundamentals to frontiers, from theories to experiments, and from the Big Bang and compact stars in the Universe to the Little Bang experiments on Earth. The authors assume that the reader has some familiarity with intermediate level quantum mechanics, the basic methods of quantum field theory, statistical thermodynamics and the special theory of relativity, including the Dirac equation. However, the authors have recapitulated necessary and sufficient introductory elements from these fields. As far as possible, the presentation is self-contained. To accomplish this, the authors have placed key proofs and derivations in eight Appendices and also in about 160 exercises, which may be found at the ends of each chapter.

It was not the authors' intention to provide a complete reference list for the subject of QGP; only references which are particularly useful to students are listed. The reader can find general and up-to-date surveys of the subject in the recent proceedings of the "Quark Matter" Conference series: Heidelberg (1996), Tsukuba (1997), Torino (1999), Brookhaven – Stony Brook (2001), Nantes (2002) and Berkeley (2004).[1]

Some parts of the original manuscript were used for a series of lectures given to graduate students at the University of Tsukuba and the University of Tokyo; the authors wish to thank the students who attended these lectures. The authors also thank Homer E. Conzett, who carefully read parts of the manuscript and made many grammatical and style suggestions. They also wish to express their gratitude to our editors at Cambridge University Press, Simon Capelin, Tamsin van Essen, Vince Higgs and Irene Pizzie, for a pleasant working relationship. Thanks are due to many friends and colleagues, especially to Masayuki Asakawa, Gordon Baym, Hirotsugu Fujii, Machiko Hatsuda, Tetsufumi Hirano, Kazunori Itakura, Teiji Kunihiro, Tetsuo Matsui, Berndt Müller, Shoji Nagamiya, Atsushi Nakamura, Yasushi Nara, Satoshi Ozaki, Shoichi Sasaki and Hideo Suganuma, who have either provided us with data or were involved in helpful discussions.

QGP forms one of the main areas of research in the physics of QCD which is developing rapidly. In spite of this, the authors hope this book will serve for a long time as a good introduction to the basic concepts of the subject, so that readers can enter the forefront of research without much difficulty.

Although this book is primarily written as a textbook for the physics of QGP, several other teaching options in undergraduate/graduate courses are also recommended.

(a) For a course on an introduction to gauge field theories, we suggest the following sequence: Chapter 2 → Chapter 4 → Chapter 5 → Chapter 6.
(b) For an advanced statistical mechanics and phase transition course, we suggest Chapter 3 → Chapter 4 → Chapter 5 → Chapter 6 → Chapter 7 → Chapter 12.
(c) For a course on an introduction to the applications of general relativity to cosmology and stellar structure, Appendix D → Chapter 8 → Chapter 9.
(d) For an advanced nuclear (hadron) physics course, Chapter 1 → Appendix E → Chapter 9 → Chapter 10 → Chapter 11 → Chapter 13 → Chapter 14 → Chapter 15 → Chapter 16 → Chapter 17.

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[1] See Braun-Munzinger *et al*. (1996), Hatsuda *et al*. (1998), Riccati *et al*. (1999), Hallman *et al*. (2002), Gutbrod *et al*. (2003) and Ritter and Wang (2004).

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Finally, although the authors have tried to eradicate conceptual and typographical errors, they are afraid that some of them may have slipped through. A list of typos and corrections will be posted on the World Wide Web at the following URL: http://utkhii.px.tsukuba.ac.jp/cupbook/. The authors would be grateful if the readers would report/send other errors/comments to this address.

The authors are proud to publish the book in 2005, World Year of Physics (WYP2005), the centennial anniversary of Einstein's three great works on the particle nature of light, the molecular theory of Brownian motion, and the special theory of relativity.