Preamble

Most physicists and astrophysicists believe that space, time, and all the matter and radiation in the Universe were formed during the big-bang some 15 billion years ago. A key challenge is to understand how the Universe we live in today evolved from the cosmic fireball created in the big-bang. As our understanding of the laws of physics improves, we are able to look further back in time, and unravel the structure of the early Universe and its subsequent evolution.

It is widely believed that almost equal amounts of matter and antimatter were created in the big-bang, and that most of the antimatter, if not all of it, annihilated on matter after the Universe had cooled and expanded. This annihilation, which started about 20 μs after the big-bang, occurred after most of the matter we see in the Universe today was already in the form of neutrons, protons, and other hadrons made of quarks. Before the Universe hadronized, it existed in a phase of quarks and gluons in which the matter–antimatter asymmetry which makes the Universe around us today had been a small and insignificant aberration. We are attempting to recreate this phase today, and to study it in the laboratory.

This primordial state of hadronic matter called quark–gluon plasma (QGP) for all purposes an inescapable consequence of our current knowledge about the fundamental hadronic interactions, which is qualitatively rooted in the $SU(3)$-gauge theory, quantum chromodynamics (QCD). We are seeking to verify this prediction and to understand this novel form of matter. To accomplish this, we 'squeeze' the normal nuclear matter in relativistic nuclear collisions at sufficiently high energy. The individual nucleons dissolve, and we hope and expect that their constituents will form the sought-after state, the (color-charged) plasma of freely moving deconfined quarks and gluons.

Pertinent experiments are being carried out today at the European Laboratory for Particle Physics, CERN, located on the French–Swiss border 20 km north of the lake and city of Geneva, and in the USA at the Brookhaven National Laboratory, BNL, on Long Island, some 100 km east of New York City. The most violent central encounters, in which large chunks of projectile–target matter participate, are of particular interest. Therefore, beams of lead and gold

https://doi.org/10.1017/9781009290753.001 Published online by Cambridge University Press

ions are made to collide with each other. The available energy in the center-of-momentum (CM) frame exceeds by far the rest energy of each participating nucleon. In a press release, in February 2000, the CERN laboratory has formally announced that it views the collective evidence obtained from seven relativistic nuclear collision experiments as being conclusive proof that some new form of matter has been formed:

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy-ion collisions at the SPS features many of the characteristics of the theoretically predicted quark–gluon plasma.

The study of highly excited and dense hadronic matter by means of ultra-relativistic nuclear collisions has been and remains a multidisciplinary area of research, which is subject to a rapid experimental and theoretical evolution. This research field is closely related both to nuclear and to particle physics, and, accordingly, this book encompasses aspects of these two wide research areas. It employs extensively methods of statistical physics and kinetic theory. Looking back at the early days, it was primarily the theoretical work on multiparticle production by E. Fermi [121] in the USA, and L. Landau [173, 175] in the USSR, which paved the way to the development in the early sixties [137, 140] of the statistical bootstrap model description of hadron production by R. Hagedorn. This approach was refined as the understanding of hadronic structure advanced, and ultimately it has been modified to allow for the possibility that individual, confined hadron-gas particles dissolve into a liquid of quarks and gluons, which we refer to as the QGP.

The multiparticle-production work was primarily the domain of particle physicists. However, since the early seventies interest in nuclear 'heavy-ion' (not fully stripped heavy atoms) collision experiments at relativistic energies had been growing within the nuclear-physics community. The initial experimental program was launched at the Lawrence Berkeley Laboratory, LBL, at Berkeley, USA, and at the Joint Institute for Nuclear Research, JINR, in Dubna, USSR.

At the LBL, a transport line was built to carry heavy ions from the heavy-ion accelerator HILAC to the BEVATRON which was made famous by the discovery of antiprotons in the early fifties. This BEVALAC facility permitted the acceleration of nuclear projectiles to about* $1A$ GeV/c. Lighter projectiles,

* We follow the convention of presenting the beam energy or momentum per nucleon in the nucleus thus: $200A$ GeV implies a projectile with the total energy $200 \times A$ GeV, or momentum $200 \times A$ GeV/c, where A is the number of nucleons in the projectile. We rarely differentiate between the units of mass [GeV/c^2], of momentum [GeV/c], and of energy [GeV], in the relativistic domain of interest to us in this book. This corresponds to the commonly used convention which sets the units of time such that $c = 1$.

which could be completely ionized and had more favorable charge over mass ratios, were accelerated to above $2A$ GeV/c. At the JINR in Dubna, a similar program of research with an acceleration capability restricted to lighter ions has been developed. More recently, another heavy-ion accelerator complex, the SIS (SchwerIonenSynchrotron), of comparable energy to BEVELAC, has been erected at the Gesellschaft für Schwerionenforschung laboratory, GSI, in Darmstadt, Germany. About the time the more modern SIS started up, the BEVELAC closed down in 1993. The energy scale $\mathcal{O}(\infty)$ GeV per nucleon yields compressed nuclear matter at few times normal nuclear density, and yields final-state particle (spectral) 'temperatures' at or below 100 MeV, conditions which are generally considered inadequate for elementary quarks and gluons to begin to roam freely in the reaction volume.

The success of the initial heavy-ion experimental program, specifically the demonstration of the possibility of studying the properties of compressed and excited nuclear matter, gave birth to the research programs at the BNL and CERN. Much of this interest has been driven by the hope and expectation that, within the reach of existing elementary-particle-accelerator facilities, one may find the point of transition from the hadronic gas (HG) phase of locally confined nucleons and mesons to the new QGP phase in which color-charged quarks and gluons could propagate.

The first oxygen beam at $60A$ GeV was extracted from the Super Proton Synchrotron (SPS) accelerator at CERN and met the target in the late autumn of 1986, about the same time as the BNL started its experimental program at the Alternate Gradient Synchrotron (AGS) accelerator with a $15A$-GeV silicon-ion beam. Very soon thereafter, the energy of the SPS beam could be increased to $200A$ GeV and a sulphur-ion source was added. In order to study the relatively large volumes and longer lifetimes expected in dense matter formed in collisions of the heaviest nuclei, an upgrade of the SPS injector system was approved, which, as of 1994, allowed one to accelerate lead (^{208}Pb) ions to $158A$ GeV. At the BNL, a gold (^{197}Au)-ion beam with energy up to $11A$ GeV became available at that time. The smaller beam energy per nucleon of the heavier Pb ions compared with that for sulphur reflects their smaller ratio of particle charge to particle mass, given a fixed magnetic field strength used to bend the beam into a circular orbit in an accelerator.

Today, we are redirecting our efforts toward new experimental facilities. At the BNL, the Relativistic Heavy Ion Collider (RHIC), completed in 1999 with colliding nuclear beams at up to $100A$ GeV, will dominate the experimental landscape for the foreseeable future. It is allowing the exploration of an entirely new domain of energy, ten times greater than that of CERN-SPS. The Large Hadron Collider (LHC) project set in the 27-km CERN-LEP tunnel comprises an important heavy-ion program at energies about a factor of 30 greater than those of the RHIC. As this book goes to press, the expectation is that the experimental data from the LHC will become available in 2007.

In this book, our objective is to offer both an introduction and a perspective on the recent accomplishments and near-term aims of this rapidly developing field. The material derives from our research work, including several reviews, summer courses, and graduate lecture series that we have presented during the past 20 years. The selection of material and emphasis represents our personal experience in this rather wide interdisciplinary field of research, that today cannot, in its entirety, fit into a single volume.

We assume that the reader is familiar with quantum mechanics, special relativity, and statistical physics, and has been introduced both to nuclear and to particle physics. However, we recapitulate briefly as needed the essential introductory elements from these fields. We begin with a 70-page overview, followed by more extensive treatment of the core of our personal research experience, and mention other domains of research as appropriate.

No book is complete and this book is no exception. We will not address in depth many interesting areas of active current research. We treat the two particle intensity interferometry measurements superficially, and have not discussed the elliptical flow measurements which point to early thermalization. We do not explore the theoretical models which interpret suppression of charmonium in terms of QGP, and only key experimental results from this wide research area are shown. We do not discuss the production of photons and dileptons, since this goes beyond the scope of this book, and also in consideration of the inherent difficulties in isolating experimentally these QGP signatures. Instead, we have put a lot of effort into a detailed introductory presentation of hadron physics, as the title of this book announces.

We are hoping that our text can serve both as a reference text for those working in the field and a class text adaptable for a graduate course. One of us (J. R.) has tried out this presentation in the Spring 2001 semester at the University of Arizona. This experience further refined our presentation. Doubtless, later editions will build upon practical experience of how to handle this very diverse material in a classroom. Rather than conventional homework exercises, we leave in the text topics for further research, *'We will not discuss further in this book . . . ,'* which students can address in class presentations.

We have updated the contents by incorporating advances made up to October 2001, including a selection of run 2000 RHIC results. Most of the material we present has not yet been covered in any other monograph. Complementary books and reports that we found useful are the following.

1. *The QCD Vacuum, Hadrons and the Superdense Matter.* World Scientific, Singapore (1988). E. V. Shuryak presents an early view of the structure of the QCD vacuum.
2. *Finite-Temperature Field Theory.* Cambridge University Press (1989). J. Kapusta offers a lucid introduction to the theoretical aspects of QCD and hot quark–gluon matter, an area that has since developed rapidly.

3. *Thermal Field Theory.* Cambridge University Press (1996). M. Lebellac presents a modern introduction which complements and updates the text of J. Kapusta cited above.
4. *Vacuum Structure and QCD Sum Rules.* North Holland, Amsterdam (1992). M. A. Shifman develops a more comprehensive view of the vacuum structure and presents applications of the sum-rule method.
5. *Particle Production in Highly Excited Matter.* Plenum Press, New York (1993), editors H. H. Gutbrod and J. Rafelski. This volume comprises several comprehensive introductory and survey articles pertinent to interpretation of data.
6. *Introduction to Relativistic Heavy Ion Collisions.* J. Wiley and Sons, New York (1994). In this text, L. P. Csernai emphasizes the transport phenomena in the process of collision and presents applications of matter flow models, including an analysis of the LBL, GSI and Dubna energy ranges, these subjects are not covered in depth in this book.
7. *Introduction to High Energy Heavy-Ion Collisions.* World Scientific, Singapore (1994). C.-Y. Wong emphasizes the role of the parton structure in the collision, considers model dynamics of color strings and the associated pair production mechanisms, and addresses among physical observables more comprehensively the electromagnetic probes of dense hadronic matter.
8. *Bose–Einstein Correlations and Subatomic Interferometry.* John Wiley, Chichester (2000). R. Weiner presents a detailed and technical discussion of the HBT particle-correlation method used to study the space–time geometry in heavy-ion collisions and related topics. Our book offers a short introduction to this monograph.
9. *Quark–Gluon Plasma.* World Scientific, Singapore, Volumes I and II (1990 and 1995) editor R. Hwa. Useful collections of articles on a variety of topics, contributed by hand-picked authors.
10. *Hot Hadronic Matter: Theory and Experiment.* Plenum Press, New York (1995), editors J. Letessier, H. H. Gutbrod, and J. Rafelski. This volume, dedicated to Rolf Hagedorn, comprises in particular a comprehensive survey of the bootstrap model of confined hadronic matter.
11. Proceedings of *Quark Matter* meetings held about every 18 months have in recent years been published in *Nuclear Physics* A. These proceedings present regular comprehensive updates of the experimental results, speckled with a mostly random assortment of theoretical contributions.
12. Proceedings of *Strangeness in Hadronic Matter* have in recent years been published in *Journal of Physics* G. These volumes comprise a comprehensive survey of the strongly interacting heavy flavor probes of phases of hadronic matter.
13. A very useful reference is the bi-annual reissue of the *Review of Particle Physics*, published as separate issues of *Physical Review* D, alternating with

the *European Physical Journal* and accessible online.

A closely related area of research is the study of the properties of quantum chromodynamics by numerical methods within the lattice-gauge-theory approach. We can barely touch this huge research field in this book. Some standard texts are the following.

14. *Quarks, Strings, and Lattices.* Cambridge University Press (1983), by M. Creutz.
15. *Quantum Fields on the Computer.* World Scientific, Singapore (1992), by M. Creutz.
16. *Quantum Fields on a Lattice.* Cambridge University Press (1994), by I. Montvay and G. Münster.
17. Proceedings of *Lattice* meetings, published in *Nuclear Physics*, are the best places to find the most recent results.

The publisher has used its best endeavors to ensure that the URLs for external websites referred to in this book are correct and active at the time of going to press. However, the publisher has no responsibility for the websites and can not guarantee that a site will remain live or that the content is or will remain appropriate.

We would like to thank our friends and colleagues who over the years helped us reach a better understanding of the material addressed in this book: we thank in particular Drs Mike Danos (Chicago and Washington, deceased), Hans Gutbrod (GSI), Rolf Hagedorn (CERN), Berndt Müller (Duke University), and Emanuele Quercigh (CERN and Padua).

This volume is dedicated to Helga Rafelski. Helga has been a companion from day one in the field of relativistic heavy-ion collisions; her presence at the finale will be sorely missed.

Jean Letessier and Johann Rafelski, Paris and Tucson, November 2001.