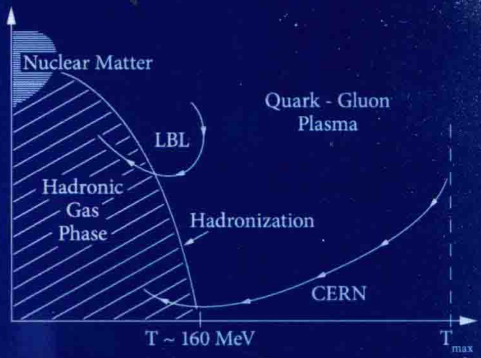

Johann Rafelski *Editor*

Melting Hadrons, Boiling Quarks

From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN

With a Tribute to Rolf Hagedorn

Springer Open

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ISBN 978-3-319-17544-7 ISBN 978-3-319-17545-4 (eBook)
DOI 10.1007/978-3-319-17545-4

Library of Congress Control Number: 2015938584

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN

Foreword

This book fulfills two purposes which have been neglected for a long time. It delivers the proper credit to a physicist, Rolf Hagedorn, for his important role at the birth of a new research field, and it describes how a development which he started just 50 years ago is closely connected to the most recent surprises in the new experimental domain of relativistic heavy ion physics.

These developments, focused on the first 20 years 1964–1983, are faithfully and competently described in this book, prepared by Johann Rafelski, a close collaborator and co-author of Hagedorn. Its contents include much of the material they developed in close collaboration, including little known and even secret manuscripts.

I got to know Rolf Hagedorn in the 1960s when I did my first experiment at CERN. In contrast to many other theorists working at that time often on abstract and fundamental problems, Hagedorn was accessible to an experimental physicist. He explained to me his main ideas concerning the heating up of strongly interacting matter in high energy collisions in a way easily understandable for an experimentalist. The concept that the energy content of strongly interacting matter could increase without surpassing a certain temperature was matured in the head of Hagedorn over several years. It was refined and finally found its definite formulation in the form of the Statistical Bootstrap Model (SBM).

Of course, along this path he recognized that the energy content can only be increased without increasing the temperature if new degrees of freedom become available. As to their nature, at first Hagedorn could only speculate. Quarks and gluons were not yet known and the theory of strong interactions QCD which could justify the new phase of matter, a quark-gluon plasma, did not exist. But as these new concepts arose they were incorporated into Hagedorn's description of hot and dense nuclear matter.

On the experimental side, in the 1970s and 1980s, the study of heavy ion reactions grew out of the nuclear physics and eventually became an interdisciplinary field of its own that is presently achieving new peaks. Hagedorn can rightly be considered as one of the founding fathers of this field, in which the 'Hagedorn Temperature' still plays a vital role.

The rapid progress was due not only to such new theoretical ideas, but also to experiments at increasing energies at laboratories like Brookhaven National

Laboratory in the USA, Dubna in Russia, and CERN in Europe. At CERN difficulties arose in the 1980s, because in order to build LEP at a constant and even reduced budget, it became necessary to stop even unique facilities like the ISR collider at CERN. Some physicists considered this an act of vandalism.

In that general spirit of CERN physics program concentration and focus on LEP it was also proposed to stop the heavy ion work at CERN, and at the least, not to approve the new proposals for using the SPS for this kind of physics. I listened to all the arguments of colleagues for and against heavy ions in the SPS. I also remembered the conversations I had with Hagedorn 15 years earlier. In the end, T.D. Lee gave me the decisive arguments that this new direction in physics should be part of the CERN program. He persuaded me because his physics argument sounded convincing and the advice was given by somebody without a direct interest.

I decided that the SPS should be converted so that it could function as a heavy ion accelerator, which unavoidably implied using some resources of CERN. But the LEP construction and related financial constraints made it impossible to provide direct funds for the experiments from the CERN budget. Heavy ion physicists would have to find the necessary resources from their home bases and to exploit existing equipment at CERN.

This decision was one of the most difficult to take since contrary to the practice at CERN, it was not supported by the competent bodies. However, the reaction of the interested physicists was marvelous and a new age of heavy ion physics started at CERN. After a series of very successful experiments at the SPS, it is reaching a new zenith in the ALICE experiment at the LHC, which is mainly devoted to heavy ion collisions. Other LHC experiments (ATLAS and CMS) are also contributing remarkable results.

Since the first steps of Hagedorn and his collaborators, a long path of new insights had to be paved with hard work. The quark-gluon plasma, a new state of matter, was identified at last in the year 2000. This new state of matter continues to surprise us: for example, at the newly built RHIC collider at BNL, it was determined that at the extreme conditions produced in high energy collisions, nuclear quark-gluon matter behaves like an ideal liquid.

I remember Hagedorn as a lively colleague fully dedicated to physics but also fond of nature and animals, especially horses. He was original, and able to explain his novel ideas and in doing this he was laying the foundations that had led to the development of the study of nuclear matter at extreme conditions at CERN.

At first, Hagedorn's research interests were somewhat outside the mainstream and he could not find many colleagues to join his efforts. However, with remarkable persistence, he followed up his ideas and it is very sad that he could not see the main fruits of his concepts during his lifetime. How happy would Rolf Hagedorn have been if he could have learned what wonderful new world of nuclear matter at extremely high temperatures came out of his relatively simple and original ideas he formulated 50 years ago!

Geneva, Switzerland and Hamburg, Germany Herwig Schopper

Preface

Half a century ago, Rolf Hagedorn pioneered the field of research that this book describes: the interpretation of particle production in hadronic interaction in terms of statistical and thermal methods. While several before him, including E. Fermi and L. Landau, provided seminal contributions, Hagedorn was the first to devote his career to the subject, and to recognize the pivotal importance of the hadronic mass spectrum which led him to propose the Hagedorn temperature.

The appearance of the Hagedorn Temperature governing elementary hadronic interactions and particle production has been and remains a surprise. It could be that a full understanding of the Hagedorn temperature hides within the vacuum structure and the related quark-confinement mechanism, or, that it is still beyond our current paradigm of the laws of nature.

When our understanding was evolving, ideas were developing so quickly that there was no time to enter the cumbersome process of assembling ongoing work into refereed papers. The conference reports were often the only place where novel work was published, building progress on earlier presentations. Therefore many of the steps taken in creating this knowledge may have not been seen by the following scientific generation. Some of the evolving insights supersede earlier work which today's generation uses in their research, an example being the precise form of the Hagedorn mass spectrum. The republication here of these pivotal reports is therefore of scientific as well as historical interest.

In the timeline of the subject, there were two pivotal milestones. The first milestone occurred in 1964/1965, when Hagedorn, working to resolve discrepancies of the statistical particle production model with the experimental *pp* reaction data, produced his "distinguishable particles" paper. Due to a twist of history, this work is published here for the first time; that is, 50 years later. Hagedorn then went on to interpret the observation he made. Within a time span of a few months, he created a model of how the large diversity of strongly interacting particles could arise, based on their clustering properties, and in the process invented the Statistical Bootstrap Model.

The second milestone followed a decade later when we spearheaded the development of an experimental program to study 'melted' hadrons, and the boiling quark-gluon plasma phase of matter. The diverse roots of this program go back to the mid-1970s, but the intense theoretical and experimental work on the thermal properties of strongly interacting matter, and the confirmation of a new quark-gluon plasma paradigm started in 1978 when the SBM mutated to become a model for melting nuclear matter. This development motivated the experimental exploration in the collisions of heavy nuclei at relativistic energies of the phases of matter in conditions close to those last seen in the early Universe.

This volume has three parts. In the first part through personal recollections and historical documents, the developments culminating in the discovery of quark-gluon plasma are described, focused often on the role of Rolf Hagedorn in making this happen. It would be, however, inappropriate to present in this part only the scientific side. I have included testimonials about Hagedorn, a man of remarkable character.

The second part contains the original pivotal documents that describe the emergence of the Hagedorn temperature concept, and the Statistical Bootstrap Model as a new scientific field, paving the way for the understanding of the dissolution of hadrons into quark-gluon matter. The third part is devoted to the heavy ion collision path which led to the new paradigm of locally deconfined, hot quark-gluon plasma phase of matter, and strangeness as its observable. Quark-gluon plasma is the primordial stuff filling the Universe before matter as we know it was created.

This volume then provides the reader both a scientific and a historical perspective on melting nuclei and boiling quarks; on Rolf Hagedorn; and of how CERN, despite its initial disinterest, became the site where this new physics happened. Looking back, I can say that events in Fall 1964–Spring 1965 marked the beginning of the path to quark-gluon plasma discovery, which CERN announced as a "New State of Matter" in February 2000.

Rolf Hagedorn was the person with whom I interacted most intensely in these formative years of the field. I thank other senior, contemporary, and junior theorists directly or indirectly involved in our effort: Peter Carruthers, John W. Clark, Michael Danos, Walter Greiner, Joseph Kapusta, Peter Koch, Jean Letessier, István Montvay, Berndt Müller, Krzysztof Redlich, Helmut Satz, and Ludwik Turko. Their role is acknowledged in individual chapters. This being a book about, and with Rolf Hagedorn, he is the main focus.

Acknowledgments

I thank Victoria Grossack for constant, competent editorial support; Dr. Stephen Lyle for essential input into latex composition of the volume; CERN for sponsoring this work as a full open access publication, released under a creative commons license; Springer and in particular Dr. Christian Caron for his interest in, and guidance given to this project; and the US Department of Energy, Office of Science, Office of Nuclear Physics under award number DE-FG02-04ER41318 for support of my research activities.

Tucson, AZ, USA and Geneva, Switzerland Johann Rafelski
Winter 2014/2015

Acronyms

An effort is made in this volume to avoid excessive use of acronyms. However, when appropriate we follow the use in original articles of the following universally recognized abbreviations which have acquired proper name character.

Laboratories

BNL	Brookhaven National Laboratory, Long Island, New York
CERN	Derived from French language, *Conseil Europén pour la Recherche Nucléaire*, and maintained as the proper name for the *International Particle Physics Laboratory* located across French-Swiss Border near to Geneva
Dubna	International laboratory in Russia named after the location, providing beams of near relativistic heavy ions
GSI	German acronym for "Gesellschaft für Schwerionenforschung", translates as Center for Heavy Ion Research, at Darmstadt suburb Wixhausen close to Frankfurt
LBNL	Lawrence Berkeley National Laboratory; earlier name LBL
LPI	(Moscow) Lebedev Physical Institute

Accelerators, Experiments

AFS	Axial Field Spectrometer, an ISR experimental area 1977–1982
AGS	Alternate Gradient Synchrotron, used today as injector for RHIC at BNL, formerly a fixed target relativistic heavy ion source
ALICE	LHC experiment dedicated to study of QGP
Bevalac	Two accelerators at LBL connected with transfer line, delivering a beam of near relativistic heavy ions at LBL
ISR	Intersecting Storage Ring, the first hadron collider ever built, located at CERN
LEP	Large Electron–Positron collider was housed in the same tunnel as the LHC today
LHC	Large Hadron Collider
NAxy	NA refers to the experimental 'North Area' located in France, formerly the CERN-II campus, while 'xy' is a sequential number like 35, 49, 61, etc.

PS	Proton Synchroton, the first high energy particle accelerator at CERN, served as injector to ISR, remains the injector of SPS and thus LHC
PHENIX	One of two 'large' experiments at RHIC, see also STAR
RHIC	Relativistic Heavy Ion Collider
SPS	Super Proton Synchroton, an accelerator ring used today mainly as injector to LHC, but still providing heavy ion beams for fixed target experiments
STAR	One of two 'large' experiments at RHIC, see also PHENIX
WAxy	WA refers to the main CERN campus experimental 'West Area' while xy is sequential number like 85, 94, 97, etc.

Scientific Abbreviations

AA	Nucleus–nucleus, used as in 'heavy ion collision' between nuclei of nucleon number *A*
BE	Bootstrap Equation
BES	Beam energy scan: RHIC experimental program where RHI collisions in a wide energy range are explored, reaching to lowest accessible energy
BeV	Old for 'GeV' when a 'billion' was used in sense of 'giga'
CM	Center of mass or, in relativistic context, center of momentum
fm	10^{-15} meter named after Enrico Fermi, nearly the radius of the proton
GeV	Giga (10^9) electron Volt, a particle physics unit of energy about 1.07 times energy equivalent of the proton mass
HG	Hadron gas: same as HRG, often used in this simplified name form
HRG	Hadron (also, equivalently, Hagedorn) resonance gas
LQCD	Lattice-QCD as in numerical solution of QCD represented on a lattice space-time
MeV	Mega (10^6) electron Volt, there are a 1,000 MeV in a GeV, see above
pA	Proton–nucleus, used as in 'collision' with a nucleus of nucleon number *A*
pp	Proton–proton, used as in 'collision between'
RHI	Relativistic heavy ion—typically 'collisions', distinct from RHIC, the collider
QCD	Quantum chromo-dynamics
SBM	Statistical Bootstrap Model
QGP	Quark-gluon plasma
SHM	Statistical Hadronization Model
T_{H}	Hagedorn temperature, T_0 in Hagedorn's and other contemporary work

Other Abbreviations

DG	The CERN Director General is often referred to as 'DG'
SPIRES	'Stanford Physics Information Retrieval System'; bibliographic data base about literature in the field of HEP (High Energy Physics) and related areas, originating at SLAC (Stanford Linear Accelerator Center)

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Part I

Reminiscences: Rolf Hagedorn *and* Relativistic Heavy Ion Research

edited by Johann Rafelski

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