Chapter 33
Melting Hadrons, Boiling Quarks

Johann Rafelski

Abstract The events presented in this book happened more than three decades ago. At that time we did not know how long it would take for the experimental program to come to be, and to make the discovery happen. Looking back, and looking at the present I can say that a vast majority of physicists studying relativistic heavy ion collisions agree today that the new quark-gluon plasma phase has been discovered and the discovery of more than a decade ago has been confirmed by the more recent results obtained at LHC. Given this circumstance, as a final word, I answer a few pertinent questions which I have heard often as related directly to the contents of this book—there are many other questions each answer generates.

33.1 The Concepts: Hadron Side

What is Hagedorn Temperature?

Hagedorn temperature $T_\mathrm{H} \simeq 1.8 \times 10^{12}\,\mathrm{K}$ is the maximum temperature at which matter can exist in the usual form. At $T > T_\mathrm{H}$ all individual material particles dissolve into the quark-gluon plasma. This transformation can occur at a lower temperature in the presence of dense nuclear matter. At densities an order of magnitude greater than the nuclear density this transformation probably can occur near to, or even at, zero temperature.

The value of T_H is measured by the way of the exponential growth of the hadron mass spectrum,

$$\rho(m) \propto m^{-a} \exp(m/T_\mathrm{H}). \tag{33.1}$$

T_H is thus uniquely defined independent of the question, if the conversion of matter into quark-gluon plasma is a sharp boundary, or a continuous transformation. The

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J. Rafelski (✉)
Department of Physics, The University of Arizona, Tucson, AZ 85721, USA

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index ‘a’ of the pre-exponential factor determines the nature of the transformation, see Table 23.1.

T_{H} is not a maximum temperature in the Universe. A further heating of the quark-gluon plasma ‘liquid’ can and will continue. We understand today T_{H} as the boiling point of a hot gas made of hadrons, i.e. Hadron Gas (HG), dissolving into the quark-gluon plasma (QGP), a liquid phase made of Debye screened color-ionic quarks and gluons.

What is the Statistical Bootstrap Model?

SBM is based on the hypothesis that the exponential in particle mass growth of the density of hadron states generates a state of matter in which practically every strongly interacting particle produced is distinguishable—one way to think about this situation is to omit in the statistical evaluation the Boltzmann pre-factor $1/n!$. The SBM relies on the model hypothesis of which the most prominent is, see Eq. (20.4)

$$\frac{\log \rho(m)}{\log \sigma(m)} \underset{m\to\infty}{\longrightarrow} 1\,, \tag{33.2}$$

where $\sigma(m)$ is the density of states of the system, from which the shape of the exponential mass spectrum $\rho(m)$, Eq. (33.1) emerges. It is important to note the relation to Eq. (33.1) which thus characterizes $\sigma(m)$, and keep in mind that Hagedorn temperature and SBM are two separate ideas.

The pre-exponential power index a in Eq. (33.1) is dependent on additional technical details, see Hagedorn’s discussion in Chap. 25, below Eq. (25.16) on page 292. By 1972 in a Lorentz-covariant SBM a value $a = 3$ emerges, replacing the value $a = 2.5$ that Hagedorn considered in 1965, see Chap. 20. The compressibility of the finite size hadron fireballs embedded in dense matter plays an important role producing other values of a discussed in Chap. 21: For incompressible hadrons of finite size one finds $a = 7/2$, while allowing compressibility leads to $a > 7/2$. How the value of a controls the singular behavior near phase boundary is shown in Table 23.1 on page 258.

SBM can evolve with our understanding of the strongly interacting matter and provide a deeper understanding of the results of lattice-QCD: for example introducing strange quark related scale into characterization of the hadron volume, or making baryons more compressible as compared to mesons in consideration of the interaction scale of QCD. In this way one can embrace in detail the current emerging lattice-QCD paradigm predicting a critical point at finite baryon density and a phase transition for higher baryon density.

What is Hadron Resonance Gas?

While SBM produces the shape of the mass spectrum $\rho(m)$, this is a description that includes averaging of the hadron spectrum features. This can be avoided: given the availability of computers of ever greater power, it is opportune to employ an experimentally known spectral composition including all observed hadrons as explicit partial fractions. This is the Hadron (equivalently, Hagedorn) Resonance Gas (HRG), represented by a discrete sum, see Sect. 7.4.

The emphasis here is on 'resonances', reminding us that all hadrons, stable and unstable, must be included. Hagedorn went to great length to justify how the inclusion of unstable hadrons, i.e. resonances, accounts for the dominant part of the interaction between all hadronic particles. His theoretical insight can be tested today by comparing HRG results with lattice-QCD. One finds good agreement, see Chaps. 7 and 21: within 10 % precision we have ab-initio confirmation that Hagedorn developed a properly working model of strongly interacting particles for $T < T_{\mathrm{H}}$. I believe, based on my own tedious study of the experimental particle yields and fireball properties within the SHM (see next), that the experimentally available discrete hadron mass spectrum is sufficient to achieve accurate description of physical phenomena for $T < 145\,\mathrm{MeV}$ at a precision level that exceeds the numerical precision of lattice-QCD results.

Still, there is something that can be done better: not all 'high' mass hadron resonances are known, with the current experimental limit implying that 'high' means about twice the proton mass. The physical relevance of such experimentally undiscovered Hagedorn states depends on the temperature of the system. Thus for higher values of T in the direct vicinity of T_{H}, such additional heavy resonances could play a significant role in the comparison of lattice results with the HRG model.

What is the Statistical Hadronization Model?

The statistical hadronization model (SHM) was invented to characterize, using Fermi-Hagedorn statistical particle evaporation methods, how a blob of primordial matter falls apart into individual hadrons. The SHM is in essence a complete and careful implementation of the Fermi-Hagedorn picture of particle production using the observed discrete hadron mass spectrum.

The SHM analysis relies on the hypothesis that a hot fireball will 'hadronize', populating all available phase space cell proportional to their respective size. This is the Fermi hypothesis which is now implemented using the semi-grand-canonical Hagedorn method. In the present day implementation all known exact (baryon number for example) and approximate (entropy) conservation laws can be respected.

This analysis of particle production allows the inference of both the statistical canonical parameters as well as the extensive and intensive microcanonical physical properties of the fireball source. Importantly, among the observables we note the entropy content and strangeness content of the emerging multiplicity of hadronic particles. These properties originate at a far earlier fireball evolution stage compared to the hadronization process itself. Therefore performing a SHM analysis of all hadrons produced we obtain a deeper look into the history of the expanding QGP fireball.

33.2 The Concepts: Quark Side

Why are Quarks Confined?

Quark confinement can be seen as an expression of the incompatibility of quark and gluon color-electrical fields with the vacuum structure. This feature was inherent in the work on quark confinement by Ken Wilson [1]. A clear statement of how this mechanism works, with a description of confinement of color charge, is seen for the first time in the September 28, 1979 lecture by T.D. Lee [2]. Quark confinement within a bound state with other quarks is explained as result of a transport property of the vacuum state surrounding us, and is not a direct consequence of the nature of an inter-quark force.

This understanding of confinement is convenient for the understanding of the quark-gluon plasma as a domain in space in which this vacuum structure is dissolved, and chromo-electric field lines can exist.

With their color field lines expelled from the vacuum, quarks can only exist in colorless cluster states: mesons $q\overline{q}$ and baryons qqq (and antibaryons $\overline{qqq}$). These are bubbles with the electric field lines contained in small space domain.

To make the mechanism of confinement in lattice-QCD visible we can pose the question; what is the interaction energy between a heavy pair of a quark and an antiquark? Such a particle pair interacts in terms of color-Coulomb force. Such a force can be for $T > T_{\mathrm{H}}$ similar to the normal electric-Coulomb $1/r$ force when the pair is in a global colorless state. For $T < T_{\mathrm{H}}$ the color field lines are, however, confined. When we place heavy quarks relatively far apart, the field lines are according to above squeezed into a cigar-like shape where the field occupied volume grows linearly with long axis of the cigar. The expected heavy quark potential will therefore have more linear than Coulomb $1/r$ character. Potential shape can be studied as a function of quark separation and of temperature, demonstrating how the potential properties change when deconfinement sets in [3, 4].

What is the Quark Bag Model?

A popular model implementation of quark-confinement is the so-called quark-bag model where by imposing boundary conditions we find quark wave functions in a localized bound state. This model works akin to the localization of quantum states in an infinite square-well potential. Since there have been quite a few variants of the quark-bag model I present in qualitative terms the main common ideas. A key new ingredient is that the domain occupied by quarks and their chromo-electrical fields has a higher energy density called bag constant $\mathscr{B}$: the deconfined state is the state of higher energy compared to the conventional confining vacuum state. Variants of such a model including a contributing "surface energy" are not viable phenomenologically.

The physical volume size V_h of a deconfined domain containing quarks forming a hadron 'h' arises from the balance of the vacuum energy $V_\mathrm{h}\mathscr{B}$ with the quark energy $\propto n/V_\mathrm{h}^{1/3}$ inside the bag. n is the number of valance quarks and antiquarks. Optimization of the total energy reveals an optimum size for each hadron $V_\mathrm{h} \propto \mathscr{B}^{-3/4}$. The larger is $\mathscr{B}$, the smaller and more compressed are hadron volume bubbles. In such a simplified model with just one scale parameter $\mathscr{B}$, the mass of each hadron can be written as being proportional to the particle volume: $M_\mathrm{h} = 4V_\mathrm{h}\mathscr{B}$. Knowledge of the hadronic size of the proton (a ball of radius 1fm) allows an estimate of $\mathscr{B}$.

The growth in energy of the quark bound state with the volume occupied by the field means that as a 'kicked' quark attempts an exit, as described in above discussion on confinement, pulling its field lines in a cigar-shaped geometry. As result there is a linearly rising attachment energy as function of the length of the cigar-shaped field lines. Ultimately, one can expect that the field line connection snaps, producing a quark-antiquark pair. Instead of a free 'kicked' quark, a colorless meson escapes from the colorless bound state that remains colorless. The field lines connecting the quark to its source, along with the modification of the vacuum that arise, are called a 'QCD string'.

This explanation of quark confinement as a confinement of the color-electrical field lines takes us to the question: how can there be a vacuum structure that expels color-electric field lines? Can we invoke as a justification the present day results of lattice-QCD computations? If you attempt a search on-line you will be mostly disappointed. This is so because lattice-QCD produces values of static observables, and not interpretation of confinement in terms of moving quarks and dynamics of the color-electric field lines.

What Does Quark-Gluon Plasma Mean Precisely?

Quark-Gluon Plasma (QGP) in the contemporary use of the language is a nearly free gas of quarks and gluons at thermal (kinetic) and close to chemical (abundance) equilibrium. Even today not everybody likes this 'QGP' name, as an example see Chap. 9. Léon Van Hove wrote a report in which he refers in title to "QGP, also called Quark Matter".

Let us look within lattice-QCD at strongly interacting matter in the domain of temperature which is large compared to Hagedorn temperature, yet not beyond the range of experiments that can be conducted today, $T \simeq 4 \times T_{\mathrm{H}}$. We look at results of references seen in Chaps. 7 and 21, such as the behavior of the pressure which follows the Stefan-Boltzmann law,

$$P_{\mathrm{QCD}} = ST^4, \qquad S = g_{\mathrm{QCD}} \frac{\pi^2}{90} \tag{33.3}$$

S is the QCD Stefan-Boltzmann constant, and g_{QCD} describes all effectively massless 'radiation' particles which can be excited at temperature T. g_{QCD} includes $2_s \times 8_c = 16$ gluons and $2_s \times 2_p \times 3_c \times 3_f \times 7/8|_{\mathrm{F}} = 31.5$ u, d, s-quarks, where indices stand for: s=spin (=2), c=color (=3, or =8), p-particle and antiparticle (=2), f-flavor (=3), and F-Fermi as compared to Bose particle reference in the Stefan-Boltzmann constant S.

Based on perturbative thermal, QCD properties, we expect and find a 10–20 % reduction in $g_{\mathrm{QCD}} \simeq 40$ instead of 47.5 due to effects of interaction in $\mathcal{O}(\alpha_s/\pi)$. α_s is the QCD energy scale dependent coupling constant, which in the domain of T we consider is about $\alpha_s \simeq 0.5$.

Given that lattice-QCD is a correct description of strongly interacting particles, we can conclude that the state of strongly interacting matter at $T \simeq 4T_{\mathrm{H}}$ is composed of the expected number of nearly free quarks and gluons, and the count of these particles emerges exactly as expected in results of lattice-QCD. We can say that in this numerical work, QGP emerges to be *the phase of strongly interacting matter which manifests its physical properties in terms of nearly free dynamics of practically massless gluons and quarks.* The 'practically massless' is inserted also for gluons as we must remember that in dense matter all color charged particles including gluons acquire an effective in medium mass.

As temperature decreases towards and below T_{H} , the color charge of quarks and gluons literally freezes, and for $T < 0.8T_{\mathrm{H}}$ the properties of strongly interacting matter are now fully characterized by a HRG, see Chaps. 7 and 21. As these results of lattice-QCD demonstrate, the modern meaning of "quark-gluon plasma" is a phase of matter comprising color charged particles (gluons and quarks) that can move nearly freely so as to create ambient pressure close to the Stefan-Boltzmann limit. The properties of QGP that we check for are thus:

1. kinetic equilibrium—that is a meaningful definition of temperature;
2. dominance by effectively massless particles assuring that $P \propto T^4$;
3. both quarks and gluons must be present in conditions near chemical (yield) equilibrium with their color charge 'open' so that the count of their number produces the correctly modified Stefan-Boltzmann constant of QCD.

How do we connect this simple result to experiment? The path to measuring P in plasma and for that matter the local energy density ε goes via the dynamics of the expansion of the QGP phase. It is important to note that the smallness of the QCD interaction effects that one sees in the behavior of $P(T)$ indicates that the color-ionic charges are screened; the viscosity entering flow models should be, in relative terms, small. Thus we expect that a QGP blob formed at a high value of $T \gg T_{\mathrm{H}}$ will expand in a way similar to a gas of non-interacting quarks and gluons, but with a reduced by interaction value of g_{QCD}.

How Did the Name "QGP" Come into Use?

Quite often in physics names attached to important insights appear late and even sometimes attribute the discovery to the wrong person. The situation is similar with the naming of hot interacting quark-gluon matter as QGP: we call QGP today what appeared in many early articles under a different name 'quark matter', while yesterday QGP used to denote something else, a Feynman parton gas.

In my memory, the use of "QGP" to describe the strongly interacting quark-gluon interacting thermal equilibrium matter was adopted following the title of a paper by Kalashnikov and Klimov [5] of July 1979. However, let me stress that the work by Kalashnikov-Klimov [5] did *not* invent QGP, neither in the content, and the name already existed

- We see the key results of Kalashnikov-Klimov in a year earlier, July 1978, work of Chin [6] presented under the name "Hot Quark Matter" *and* including hot gluons and their interaction with quarks and with themselves, which is the important pivotal element missing in many other papers.
- Kalashnikov-Klimov may have borrowed the term from another work, of March 1978, by Shuryak [7]. Shuryak at that time also used 'QGP' in his title addressing *pp* collisions as a source of photons, dileptons and charmonium. With time one notices Shuryak's *pp* work cited in the modern *AA* QGP meaning context. This was also done in some of our citations both by Hagedorn and myself.

Why is Quark-Gluon Plasma of Interest?

Several fundamental questions come together in the study of the deconfined phase of matter, QGP:

- All agree that QGP was the Big-Bang stuff that filled the Universe before matter formed. The experimental exploration of the QGP properties solidifies our models of the Big Bang when the Universe was younger than 20 microseconds. We learn about the material content of the Universe and what happened near the end of the quark Universe era.
- In relativistic heavy ion collisions the kinetic energy of ions feeds the quark population in the QGP phase. These quarks later turn into material particles. This means that we study experimentally the mechanisms that lead to the conversion

of energy into matter. In an as yet unknown way, this could lead to a better understanding of the stability of matter and conversion of matter into energy.

- While as noted above, the mass of quarks is believed to originate in the Higgs field, the mass of nucleons, a ‘bag’ of three confined quarks is about 40 times larger than the sum of constituent quark masses. Nucleons dominate the mass of matter by a factor 2000. For this reason, the origin of the mass of matter is recognized to be caused by the confinement of quarks, compressed to a relatively small, hadron volume—this confinement mass effect dominates the Higgs effect by a large factor [8, 9]. Therefore, the vacuum structure which causes confinement of color is responsible for the inertia of matter. We can hope to learn how to use this deep insight in the future.
- In the standard model there are three families of particles which duplicate in essence all their properties, except for their mass-generating interaction with the Higgs field. They are thus distinguished only by three different sets of elementary particle masses. At present we do not have a good explanation why this is so.

  There have been few experiments possible to study this situation since in experiments involving elementary particle collisions, we deal with a few if not only one pair of newly created second, or third family at a time. A new situation arises in the QGP formed in relativistic heavy ion collisions. QGP includes a large number of particles from the second family: the strange quarks, and in fact also, the yet heavier charmed quarks; and from third family at the LHC also bottom quarks.

  The new ability to study a large number of these second and third generation particles present together in a different vacuum structure of QGP could help answer the riddle about the meaning and origin of the three particle families. “Could” means that a proposal has not emerged on how to approach this fundamental question.

33.3 Quark-Gluon Plasma and Relativistic Heavy Ion Collisions

How Did RHI Collisions and QGP Come Together?

In October 1980, I answered this question as follows, see Chap. 27, [21]: “The possible formation of quark-gluon plasma in nuclear collisions was first discussed *quantitatively* by S.A. Chin: Phys. Lett. B **78**, 552 (1978); see also N. Cabibbo, G. Parisi: Phys. Lett. B **59**, 67 (1975).”

I now have second thoughts about this answer. The work by Cabibbo and Parisi, though pointing to the need to develop SBM to include melting of hadrons, does not mention or allude to nuclear collisions directly or indirectly. And, the paper by Chin, of July 1978, in its Reference [7] grants the origin of the idea to Chapline and Kerman [10], manuscript of March 1978.

The contents of the never-published Chapline-Kerman's manuscript is qualitative. The authors did not pursue further development of their idea; I note that a year later Chin and Kerman presented the idea of strangelets [11], cold drops of quark matter containing a large strangeness content. This proposal will anchor the resources of the BNL-AGS program for many years. A few years later Chapline considers the possibility of 'warm' high baryon density quark matter being produced in RHI collisions, which the experiments did not confirm.

Here some partial regrets: an 'idea' paper equivalent to [10] introducing bootstrap of hot hadron matter could have been written by Hagedorn and myself in October 1977. But, as already discussed in Chap. 1, Hagedorn would never write such a paper without working out a good model. After 10 months of further effort we wrote a 99 page long paper [12], as well as a shorter version, presented in Chap. 23.

How and What Happens When QGP is Created in the Laboratory?

The reaction path into QGP in some early work has been a line placed in the temperature-baryon density plane, such as the one shown in Fig. 32.2 on page 403, with an arrow pointing from a hot thermal hadron phase into the QGP domain. For RHI collisions capable of forming QGP, such a picture can only apply if a mechanism of entropy production exists at hadron collision level that creates the thermally equilibrated hadron phase. While new particles are formed, this state dissolves into QGP.

This process requires conversion of directed motion energy into locally equilibrated matter. Moreover, the system proceeds via a non-equilibrium stage where neither the particle abundance nor their spectra are close to conditions that are associated with the phase diagram properties. Thus a locally equilibrated matter emerges first amongst quark and gluon degrees of freedom. Presentation in the phase diagram of a RHI collision entrance path into QGP domain is thus not appropriate.

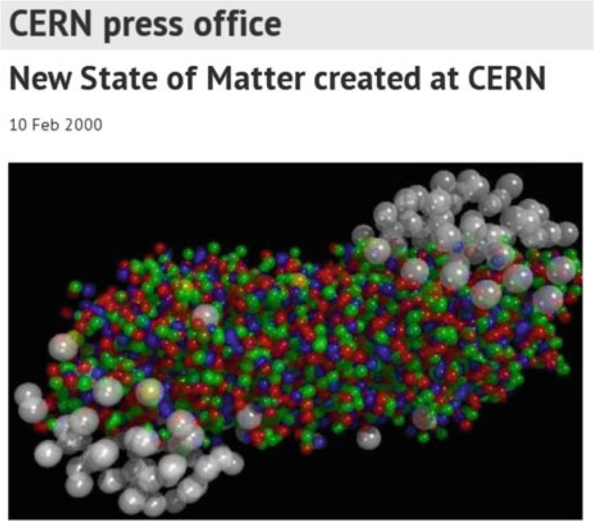
In fact, for very high RHIC and LHC energies all scattering processes occur at quark-gluon (parton) level. Thus there is no connection whatsoever with models of hadron-hadron scattering that sometimes decorate in an explanatory way the AA collision process. At much lower energies, near to the presumed threshold of QGP formation, the reaction path at least in part involves hadron based processes described within kinetic non-equilibrium approaches. The question one may wonder about in this case is how Hagedorn could interpret hadron production, introducing his limiting temperature.

"Why the Hadronic Gas Description of Hadronic Reactions Works" is the title of a work suggesting an explanation long ago [13]: it is the formation of nearly equilibrated QGP that is, partonic gas, and the evaporation of hadrons from QGP fireball that produces the near equilibrium hadron particle abundances observed. I believe this is practically the case for all strong interaction reaction processes, including pp and pA (proton-Nucleus) scattering, aside of AA nucleus-nucleus (heavy ion) collisions, all of these differ only in the degree of equilibration that is achieved.

The present consensus about the formation of an equilibrium state characterized by a high entropy density contents in relativistic heavy ion collision at RHIC and LHC is that it is much more likely to be produced in the context of parton collisions. Among the first to address a parton based entropy production quantitatively within a kinetic collision model was Klaus Geiger [14, 15], see Fig. 14.2 on page 111. Klaus built computer cascade models at parton level, and studied thermalization as a collision based process which opens a Pandora box of questions in regard to decoherence of investigated processes. Thus more than 20 years later a search and exploration of fast entropy generating mechanism properly described within QCD continues, see for example [16].

When and Where was QGP Discovered?

Both CERN and BNL have held press conferences describing their experimental work. In Fig. 33.1 a screenshot shows how CERN advertised its position in February 2000 to a wider public. The document for scientists agreed to by those representing the seven CERN experiments read: "A common assessment of the collected data



CERN press office

New State of Matter created at CERN

10 Feb 2000

Fig. 33.1 The press release text: "At a special seminar on 10 February 2000, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely" leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, ... 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."

At the April 2005 meeting of the American Physical Society, held in Tampa, Florida a press conference took place on Monday, April 18, 9:00 local time. The public announcement read: At RHIC "...two beams of gold atoms are smashed together, the goal being to recreate the conditions thought to have prevailed in the universe only a few microseconds after the Big Bang, so that novel forms of nuclear matter can be studied. At this press conference, RHIC scientists will sum up all they have learned from several years of observing the world's most energetic collisions of atomic nuclei. The four experimental groups operating at RHIC will present a consolidated, surprising, exciting new interpretation of their data." The participants at the conference obtained "Hunting for Quark-Gluon Plasma" report, of which the cover in Fig. 33.2 shows the four BNL experiments, which reported on the QGP physical properties that have been obtained at BNL.

33.4 Hadrons and Quark-Gluon Plasma

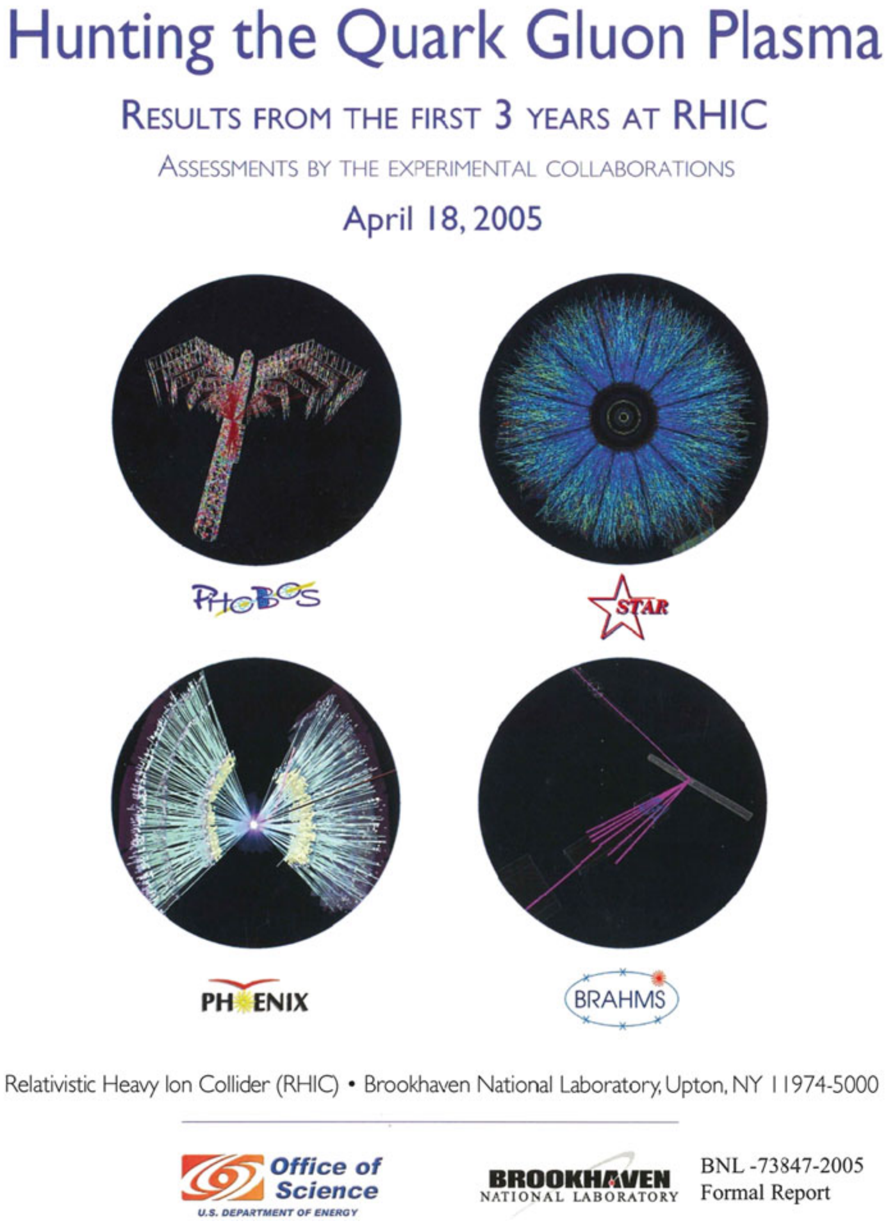
What Controls Kinetic Energy Conversion into Material Particles?

Particles emerging in hadronization of QGP carry entropy. In the temporal sequence of events, entropy contents must increase. Conversely, the final yield of particles produced is thus dependent on how much entropy will be created when heavy ions collide. Most of the entropy production is, when considered in quantitative fashion, related to the process of color deconfinement and thermalization of quarks and gluons in QGP.

Entropy is produced in the processes that occur when partons collide forming dense matter. These mechanisms continue at first when the system expands. The massless light quark and gluon abundances all grow, substantially. Thus at least in the beginning the dense matter fireball explodes in a non-adiabatic fashion, forming additional entropy in the process of the creation of new particle populations, such as strange quark pairs.

Once local thermal and chemical equilibrium is achieved, the explosive flow of QGP, the micro-bang, should be largely adiabatic, not much different from the picture that emerges in the study of the Big-Bang QGP dynamics in the early Universe. The main difference between the big- and micro-bangs is that in the laboratory experiments the time frame in which dense matter exists is so short that the electromagnetic and weakly interacting particles remain far from equilibrium.

In this adiabatic expansion involving dilution of particle density and adiabatic cooling of temperature thermal energy is transferred into the energy of the kinetic



Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

BNL -73847-2005
Formal Report

Fig. 33.2 The cover of the BNL-73847-2005 Formal Report prepared by the Brookhaven National Laboratory, on occasion of the RHIC experimental program press conference April 2005. The cover identified the four RHIC experiments flow of matter. This, as well as the potential radiation effects reduce the temperature of QCD matter fireball, ultimately leading to the freezing of quarks and gluons back into hadrons. This latter process is described in the Statistical Hadronization Model described earlier.

All of the entropy produced in this time line of QGP formation and hadronization turns at the end into a hadronic matter-antimatter, meson, particle gas, just as was the case in the evolution of the early Universe. A remarkable outcome of the QGP formation is that by way of the formation of a large entropy content when breaking color bonds and deconfining quarks and gluons we convert the kinetic energy of the colliding nuclei into abundantly produced entropy that needs to emerge at the end in the form of material particles.

What is Special About Heavy Quarks?

Strangeness

In order to produce the large abundance of strange quark pairs that can be present in QGP, the initial collisions of partons do not suffice. One can see this by considering the strangeness yield as a function of reaction energy and size of QGP formed: the relative population of strangeness grows as the collision volume increases and/or the energy increases. Strange quark pairs: s and antiquarks $\bar{s}$, are for most part produced after QGP formation, in processes called gluon fusion [17] illustrated in the center of Fig. 33.3, see Sect. 31.2. Processes based on light quark collisions contribute fewer

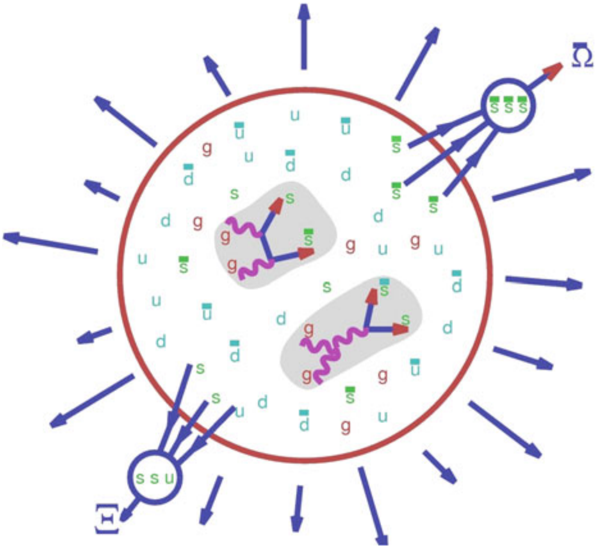


Fig. 33.3 Multistrange (anti)baryons as signature of QGP, see text for further discussion

$s\bar{s}$-pairs by nearly a factor 10. Thus, the abundance of strangeness is considered a signature of the formation of a thermal gluon medium.

The fireball of QCD matter, driven by its internal pressure, changes rapidly and with this the rates of production and reannihilation of massive quarks change. In the early stage it is likely that a sequence of chemical equilibration processes is present, with gluons being first to equilibrate in their number and momentum distribution, and then gluon based processes driving the equilibration of quarks, first light to later, heavy.

Once produced, strangeness evolves with light $(u, \bar{u}, d, \bar{d})$ quarks and gluons g until the time of hadronization, when the remaining particles seed the formation of hadrons observed in the experiment. In QGP, s and $\bar{s}$ can move freely and their large abundance leads to unexpectedly large yields of particles with a large s and $\bar{s}$ content, as is illustrated exterior of the QGP domain in Fig. 33.3.

Strange Antibaryons

In regard to strange antibaryon signature: in the 1982 discussion of the possible and forthcoming CERN SPS experiments I said [18], see Sect. 31.4:

> "…we should search for the rise of the abundance of particles like Ξ, $\overline{\Xi}$, Ω, $\overline{\Omega}$, and ϕ, …such experiments would uniquely determine the existence of the phase transition to the quark-gluon plasma.…Strangeness-based measurements have the advantage that they are based on the observation of a strongly interacting particle $(s, \bar{s}$ quark) originating from the hot plasma phase; these are much more abundant than the electromagnetic particles (dileptons or direct photons)."

Léon Van Hove, the former DG (1976–1980), characterized the strange antibaryon situation *after* the 1982 presentation as follows [19]:

> *In the "Signals for Plasma" section:* …implying (production of) an abnormally large antihyperon to antinucleon ratio when plasma hadronizes. The qualitative nature of this prediction is attractive, all the more so that no similar effect is expected in the absence of plasma formation.

These remarks became the intellectual cornerstone of the experimental strangeness program carried out at the CERN SPS in the last decade of the twentieth century.

Production and Annihilation of Flavor

The initial on-impact production of charm c, $\bar{c}$ and yet heavier bottom quark pairs $b, \bar{b}$ increases with AA collision energy. From some collision energy on, dependent on the heavy quark mass, the initial production yields thus corresponds to an abundance which exceeds the chemical equilibrium yield of heavy quark pairs at the later hadronization condition of the QGP fireball. This happens because the ratio of heavy quark mass to the hadronization temperature enters in the exponential, and the mass of charmed (and bottom) quarks is much larger compared to the final temperature at which QGP fireball breaks up into hadrons. I expect that there is enough charm produced at LHC to allow that during evolution of the QGP fireball charm yield undergoes the thermal pair annihilation processes decreasing in yield down towards the chemical equilibrium abundance.

After noting this anomalous charm behavior, one wonders if to a smaller measure a similar above chemical abundance yield can occur also for strangeness: if the QGP formed in the *AA* high energy collision is very hot, thermally produced strangeness reaches its highest abundance at a transient high temperature condition in the QGP fireball. Later, as QGP expands and cools, strangeness pair yield is above chemical equilibrium, just as charm is. The difference between strangeness and charm is that for strangeness both production and later annihilation is by thermal in-plasma reaction processes. Once above chemical equilibrium, strangeness in QGP is decreasing towards chemical equilibrium. Depending on dynamical evolution details, strangeness can hadronize from a state above QGP chemical equilibrium.

The final state abundance of all heavy quark flavors: strangeness, charm and yet heavier bottom quark pairs $b, \bar{b}$ is thus a part of the ongoing investigation of the time evolution of a QGP fireball.

Was the Predicted Strange (Anti)baryon Enhancement Found?

SPS Results

Given the quark combination reactions shown in Fig. 33.3 that create multistrange baryons and antibaryons, these particles are naturally a sensitive probe of the hadronization strangeness density. Experiments explored the production of multi strange nucleons—'Cascades' $\Xi^-(ssd)$ and 'Omegas' $\Omega^-(sss)$ and, importantly, their antiparticles, the multi-strange anti-nucleons $\overline{\Xi}, \overline{\Omega}$. The study of single strange mesons—kaons $\mathrm{K}^+(u\bar{s})$, $\mathrm{K}^-(\bar{u}s)$, and single strange nucleons—the Lambda particles $\Lambda^0(sud)$ set a comparison base-line.

The studies in *AA* collisions at the CERN-SPS Ω'-spectrometer, see Sect. 15.3 thus measured the production of higher strangeness content baryons and antibaryons, as compared to lower strangeness content particles, Ξ/Λ and $\bar{\Xi}/\bar{\Lambda}$. These early SPS experiments clearly confirmed the QGP prediction in a systematic fashion, as we see in the compilation of the pertinent results in Fig. 33.4, see [20].

In these experiments WA85 and WA94 the sulfur ions S with $200A$ GeV hit stationary laboratory targets, S, W (tungsten), respectively, with reference date from *pp* (AFS-ISR) and *p* on S shown for comparison. The Ξ/Λ and $\bar{\Xi}/\bar{\Lambda}$ ratio enhancement rises with the size of the reaction volume measured in terms of target *A*, and is larger for antimatter as compared to matter particles. This agrees very well with qualitative model predictions [18], Chap. 31 and their quantitative model consideration [21], much of this work was carried out with Berndt Müller, Fig. 33.5.

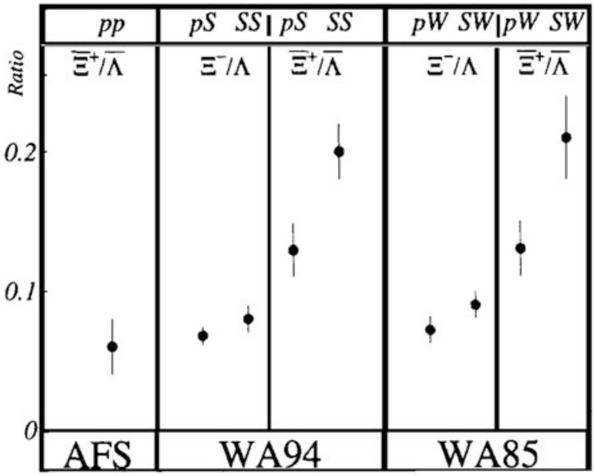


Fig. 33.4 Results obtained at the CERN-SPS Ω'-spectrometer for Ξ/Λ-ratio in fixed target S-S and S-Pb at 200 *A* GeV/*c*; results from compilation in [20]

Fig. 33.5 Berndt Müller (*left*) with Johann Rafelski work on hadronization of QGP in 1984/85, the Physics Reports article [21]. *Image credit: Johann Rafelski and University of Cape Town*

When a thermal QGP fireball domain is not formed, the production of such complex multistrange (anti)baryons is less probable for two reasons:

1. When new particles are produced in color string breaking process, strangeness is known to be produced less often by a factor 3 compared to lighter quarks.
2. The generation of multistrange content requires multiple such suppressed steps.

Thus the conclusion is that with increasing strangeness content the production by string processes of strange hadrons is progressively more suppressed.

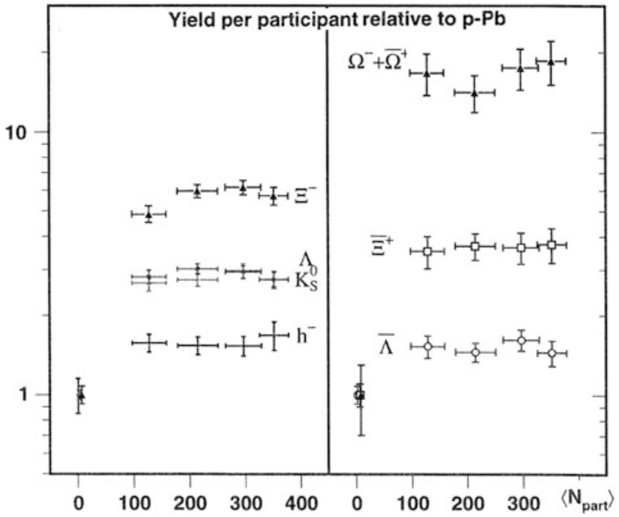


Fig. 33.6 Results obtained at the CERN-SPS Ω'-spectrometer for multi-strangeness enhancement at mid-rapidity $|y_{CM}| < 0.5$ in fixed target Pb–Pb collisions at $158A$ GeV/c at CERN SPS as a function of the mean number of participants $\langle N_{part} \rangle$, from [22]

Conversely, comparing pp, pA to AA absolute yield results, the enhanced production of higher strangeness content baryons and antibaryons in AA collisions increases with the particle strangeness content. To make this comparison fairly, one normalizes the yields to be per unit of hadronization volume measured in terms of the number of collision participating nucleons. The number of 'participants' $\langle N_{part} \rangle$ is obtained from geometric models of reaction based on energy and particle flows.

The results obtained for the top SPS energy Pb (lead) beam of $156A$ GeV are shown in Fig. 33.6. On the right are considered particles made only of quarks and antiquarks that are created in the collision. On the left some of the particle valence quarks can be from matter brought into the reaction volume. The number of participants is large, greater than 100, a point to remember. The particles made entirely from newly created quarks are up to 20 times more abundant. This enhancement falls with decreasing strangeness content and increasing contents of valence quarks which are brought into collision. The results at yield ratio '1' provide the error measure for the pA reference measurement.

All these results are in excellent agreement with the deconfined QGP fireball as the source of strange baryons and antibaryons. These results provided key evidence for the formation of a new state of matter at the CERN-SPS energies, which CERN announced in a press release in February 2000. Much has been learned about the QGP fireball properties from ongoing analysis of these and other related hadron production results [24–28].

RHIC and LHC Confirmation

Some of the above presented discoveries are now nearly 20 years old. They have been confirmed by further results obtained at SPS, at RHIC, and at the LHC. The present day experimental summary is shown in Fig. 33.7. We see results obtained by the collaborations:

SPS NA57 for collision energy $\sqrt{s_{\mathrm{NN}}} = 17.2\,\mathrm{GeV}$ (lighter open symbols);
RHIC STAR for collision energy $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ (darker open symbols);
LHC Alice for collision energy $\sqrt{s_{\mathrm{NN}}} = 2760\,\mathrm{GeV}$ (filled symbols).

These results span a range of collision energies that differ by factor 160.

Comparing results of Fig. 33.7 with those seen in Fig. 33.6 we note that $\langle N_{\mathrm{part}}\rangle$ is now on a logarithmic scale: the results of Fig. 33.6 which show that the enhancement is volume independent are in Fig. 33.7 compressed to a relatively small domain on the right in both panels. The new SPS results seen in Fig. 33.7 are in agreement with the earlier SPS results shown in Fig. 33.6.

The rise of enhancement which we see in Fig. 33.7 as a function of the number of participants $2 < \langle N_{\mathrm{part}}\rangle < 80$ reflects on the rise of strangeness content in QGP to its chemical equilibrium abundance with an increase in volume and thus lifespan of QGP fireball. It is not surprising that the enhancement at SPS is larger than that

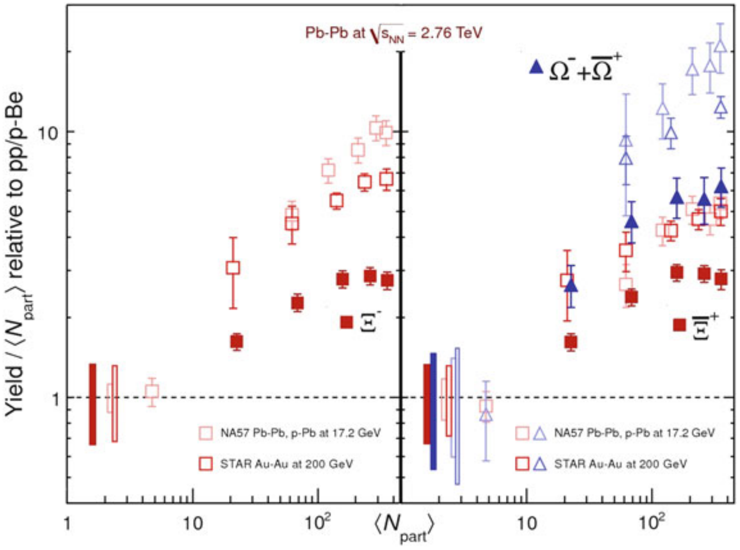


Fig. 33.7 Enhancements of Ξ^-, $\overline{\Xi}^+$, $\Omega^- + \overline{\Omega}^+$ in the rapidity range $|y_{\mathrm{CM}}| < 0.5$ as a function of the mean number of participants $\langle N_{\mathrm{part}}\rangle$: LHC-ALICE: full symbols; RHIC-STAR and SPS-NA57: open symbols. The LHC reference data use interpolated in energy *pp* reference values. Results at the dashed line (at unity) indicate statistical and systematic uncertainties on the *pp* or *p*Be (at SPS) reference. Error bars on the data points represent the corresponding uncertainties for all the heavy-ion measurements. Results presented and compiled in [23]

seen at RHIC and LHC, considering that the reference yields play an important role in this comparison. Especially the high energy LHC *pp* reactions should begin to create space domains that resemble QGP but do not yet achieve the degree of chemical strangeness equilibration that would erase the enhancement effect entirely.

Detailed analysis of the RHIC and LHC *AA* particle production abundance results shows that the source of strange baryons and antibaryons is a deconfined QGP fireball which hadronizes at a common physical condition [29]. This establishes that in a large range of collision energies the final hadron abundance is sourced in the same fireball with a main and practically only difference being the volume size.

Is There a Threshold in Energy and Size for QGP Formation?

Dynamics and Deconfinement

Our study of properties of hot nuclear matter assumes chemical equilibrium abundance of all strongly interacting particles, including those that are quite heavy. In the SBM approach there are very few of each kind, but there are many, many different types of particles. For each particle there is an equilibration relaxation time. The heavier the particle is, the more time is needed to produce it. Thus it is not guaranteed that the theoretical result about thermal equilibrium properties of the hot hadronic matter is a true image of the dynamical RHI collision situation.

The smaller the size of colliding nuclei, the shorter is the collision time. Thus in collisions of small size objects such as *pp* or light nuclei, one cannot presume that at relatively low collision energy a complete chemical equilibration is achieved. As nucleon number *A* increases, for large nuclei, the situation changes. However, should the hadro-chemical equilibrium be established late in the collision, the hadron dissolution into the deconfined QGP phase will have only a fleeting presence and thus leave few if any signatures. In such ‘just beyond’ deconfinement reactions of great importance are signatures that are based on strong interactions, as these are more likely to appear.

An important additional observation is that particle production processes are more effective with increasing collision energy. Therefore the chemical equilibration is achieved more rapidly at higher energy. This was the main reason why QGP search experiments started at the highest available energy where QGP is both more easily produced, and, in terms of more rarely produced particles, more easily detected. This said, the question about threshold of QGP production remains.

Where are Thresholds of Deconfinement?

The above qualitative discussion suggest that thresholds are expected as a function of collision energy and reaction volume size. The volume can be controlled by creating categories of the ‘violence’ of collisions which are associated with collision offset between centers of nuclei and/or value of A of the nuclei colliding. This is the participant number $\langle N_{\rm part} \rangle$.

Thus in principle for each reaction energy studied, one can explore a range of reaction volumes and compare the results by looking at observables such as strangeness. This type of data is under consideration both at the SPS at CERN (see Chap. 11) and at RHIC at BNL (see Chap. 14). A study of head-on Pb–Pb collisions as a function of energy at SPS did produce by 2010 tantalizing hints of an energy threshold to new phenomena [30] in an energy range also accessible to RHIC.

What makes the search for a threshold difficult is a likely change, as a function of both reaction energy and reaction volume, of the *probability* to enter the QGP phase. Since experiments in general ‘trigger’ their detector on interesting looking events in a process one would call ‘maximum bias’, the variation of this probability can be compensated in part by trigger procedures which are often specific to the particular approach taken by the experimental group.

In Chap. 11 discontinuities as a function of collision energy in the K^+/π^+ particle yield ratio and the inverse slope parameter of the $m_\perp$ spectra of K^-, see Fig. 11.1 are interpreted as the onset of deconfinement. We see a local maximum near to 30 A GeV, that is at 3.8+3.8 GeV, $\sqrt{s_{\rm NN}} = 7.6$ GeV collider energy collisions in both quantities. Both of these behavior ‘thresholds’ are to some degree mirrored in the much smaller pp reaction system. This indicates that a qualitative change in the production mechanism of strange particles occurs in a wide range of reaction volume.

An analysis of the SPS AA global particle production results shows that the fireball content in strangeness per entropy s/S nearly saturates at this $\sqrt{s_{\rm NN}} = 7.6$ GeV energy threshold [28], as is shown in Fig. 33.8. This means that both strangeness and entropy above threshold grow with energy in same manner; one can argue this signals activation of gluon and quark degrees of freedom, a point made in Chap. 11.

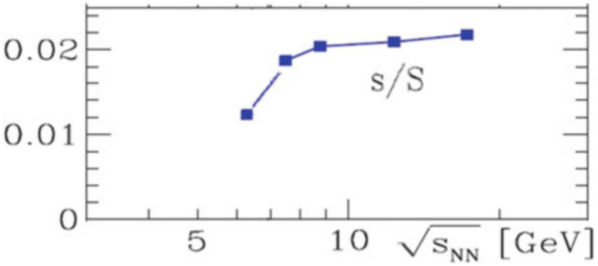


Fig. 33.8 Fireball thermal energy content divided by strange quark pair content as function of collision energy, update of results [28]

Fig. 33.9 1978: Rolf Hagedorn (*on right*) toasts to work accomplished. *Photo: JR*

This shows that while the formation of QGP has been clearly achieved, the work on the characterization of the relation of phase diagram and experimental conditions has just begun. Two new accelerator complexes (FAIR at GSI and NICA at Dubna) should improve experimental access to these questions in the future. This effort continues today the tradition begun 50 years ago, when Hagedorn Temperature was invented. We can toast, see Fig. 33.9, to 50 more years of transforming advances in the study of 'hot' strong interactions.

33.5 Conclusions

This report barely touches the surface of the physics program that has emerged in the past 17 years of hard work. By showing a few qualitative and quantitative pictures I have aimed to illustrate how the interest in *Melting Hadrons and Boiling Quarks* morphed into a comprehensive experimental program addressing strangeness observable of QGP. In a nutshell, the theoretical and experimental highlights are:

- (Multi) strangeness enhancement from QGP fireball formed in AA collisions is natural and was predicted.
- All SPS, RHIC and LHC data clearly shows it consistent with predictions.
- At LHC energy the particle multiplicity and thus space-time volume of the reaction increases strongly; therefore even pp data show gradual approach to strangeness equilibration.

– For large AA colliding nuclei the onset of new physics with collision energy occurs early, permitting an intense experimental exploration of the physical properties of the deconfined state in the coming decade. These final remarks are complemented by the full account presented under the same title (Melting Hadrons, Boiling Quarks) in format of a Review in the European Physical Journal A (2015).

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Erratum to:
Chapter 6: The Tale of the Hagedorn Temperature

J. Rafelski (ed.), *Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN*,
DOI 10.1007/978-3-319-17545-4_6

Fig. 6.2 has been inserted incorrectly. Correct Fig. 6.2:

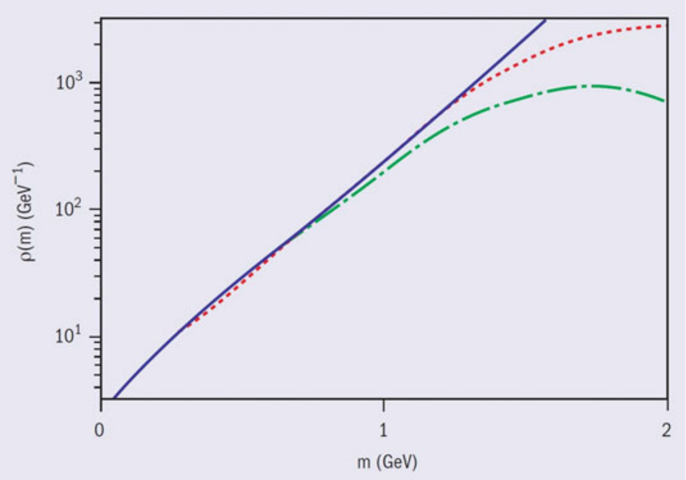

Fig. 6.2 The smoothed mass spectrum of hadronic states as a function of mass. Experimental data: *long-dashed green line* with the 1,411 states known in 1967; *short-dashed red line* with the 4,627 states of mid 1990s. The *solid blue line* represents the exponential fit yielding $T_{\mathrm{H}} = 158\,\mathrm{MeV}$. Depending on the preexponential factor, a range $T_{\mathrm{H}} = 150 \pm 15\,\mathrm{MeV}$ is possible. *Picture: CERN Courier September 2003 p. 30*

The online version of the original chapter can be found under
DOI 10.1007/978-3-319-17545-4_6

J. Rafelski (ed.), *Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN*,
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