Part II
The Hagedorn Temperature
edited by Johann Rafelski

Contributions by:

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Part II addresses properties of hot hadronic gas (HG) matter and the proposal and characterization of the phase transformation between HG and quark-gluon plasma (QGP).

The opening Chap. 16 is a long-lost review, appearing for the first time in English. It describes the meaning of limiting (Hagedorn) temperature T_{H}, the Statistical Bootstrap Model (SBM), and its role in the Big Bang and Universe evolution. Chapter 16 can be read by a general science-versed reader. Hagedorn's comprehensive technical 1995 retrospective of the experimental and theoretical developments that compelled introduction of T_{H} and SBM follows in Chap. 17.

Chapter 18 is a commentary on Chap. 19, Hagedorn's first unpublished 1964 paper introducing T_{H} and the exponentially growing mass spectrum $\rho(m)$. Chapter 20 presents the experimental 1968 data for $\rho(m)$, and Chap. 21 offers a contemporary discussion of this central result. Chapter 22 is Hagedorn's unpublished 1972 guide to SBM literature.

Chapter 23 is a 1979 unpublished conference paper which presents SBM in its covariant form, introducing finite sized hadrons, and allowing for finite baryon density characterized by a chemical potential. This work shows the transformation from hadron gas to a collapsed single fireball drop that we call QGP today.

This phase transformation is made mathematically more precise in the following Chap. 24. This is Hagedorn's 1981 unpublished resolution of a critisism of Chap. 23 as extended with the concept of the available volume, discussed further in the following Chap. 27. Chapter 25 is Hagedorn's 1984 retrospective about development of the SBM leading on to our work on the phase transition to quark-gluon plasma. Hagedorn explains in plain language and resolves many questions that arise in the study of the material of this book. Noteworthy for Part II are the two paragraphs below Eq. (25.16) which discuss the relation of the phase limit temperature with a limiting temperature.

A short quote from Chap. 16 explains this further: Hagedorn draws the parallel between boiling hadronic matter and boiling water: "…with increasing temperature, it becomes ever easier for a molecule to free itself from the liquid, and when the temperature approaches the boiling point, it is so easy for them to leave, they all want out and actually escape in a rapid manner. They absorb all the heat made available and leave the molecules still remaining behind no energy to increase their temperature." Hagedorn places emphasis on the fact that water cannot get hotter but vapor in principle, could. However the 1968 view was: "…boiling HG matter can never overcook, *because it is the supplied energy itself* which materializes and so ensures that more new particles are always being born. Therefore there can never arise the process corresponding to the continued heating the water vapor. …**$\mathbf{T_{H} = 1.8 \times 10^{12}}$ K is the highest ever possible temperature** in a stationary thermodynamic equilibrium."

This position evolved with the development of the nuclear bootstrap model for the gas phase, incorporating a finite hadron volume, see Chap. 23. With the rise of QGP as the new phase of matter, the meaning of T_{H} expands to be the phase transformation condition. The new phase, QGP, can be heated—quark and gluon tempeature rises without limit, $T > T_{\mathrm{H}}$.

Chapter 16
Boiling Primordial Matter: 1968

Rolf Hagedorn

Abstract This introductory article presents in popular language how the view of the early Universe was evolving through 1968 under the influence of than new and recent insights about the thermodynamic properties of strongly interacting matter (by JR, editor).

16.1 The Large and the Small in the Universe

Even though no one was present when the Universe was born, our current understanding of atomic, nuclear and elementary particle physics, constrained by the assumption that the Laws of Nature are unchanging, allows us to construct models with ever better and more accurate descriptions of the beginning. We begin to understand the composition and abundance distribution of nuclei, and we understand the origin of the energy which drives the Sun and countless other stars. We would have never understood these things if we had not advanced on Earth the fields of atomic and nuclear physics.

To understand the great, we must descend into the very small. The objects, which will be discussed here, are incomprehensibly different in their size. In our daily lives a centimeter-sized object is a visible and reasonable magnitude; our direct experience ranges from "very thin"—a sheet of cellophane (10^{-3} cm)—to one hundred meters (10^4 cm); below and above these limits we no longer experience lengths directly through our senses, but indirectly with the assistance of our intellect—for example we imagine 100 km as one hour on the freeway. Even

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with these tricks we can only go so far, because in order to express how small an elementary particle is and how large the currently observable part of the Universe is, we must use numbers that are again beyond our direct comprehension. There are as many protons in a centimeter as there are for example centimeters in the diameter of Earth's solar orbit, and as another example consider the many Earth orbit's diameters needed to reach from here to the furthest visible spiral nebula—that is to say, somewhere between 10^{13} and 10^{14}.

Who can comprehend the number 10^{13}? With an effort I can have a feeling for one million, 10^6: a million teaspoons of water is about one cubic meter. But even 10^9—a billion—is difficult. Do you want to be a billionaire? Put aside a Swiss Franc every second for 32 years—then you'll be one. One million years yields 3×10^{13} s. String protons together, one each second—in a million years you'll have a chain barely 3 cm long; string together centimeter-sized pearls, one each second, and in a million years the chain will reach from here to the sun. Lay together an Earth orbit every second, and after a couple million years you will reach the furthest visible spiral nebula (or to be precise, where that spiral nebula was a couple billion years ago, when its light started in our direction). And a last example, which we all know: on a distant island is a diamond mountain, and every hundred years a bird sharpens its beak on the mountain. When the mountain has been whetted away, the first moment of eternity will be finished. Mont Blanc would be whetted away after 10^{40} s (the Milky Way is only 10^{17} s old!) and for just as long must one lie proton next to proton—one each second—to reach the furthest spiral nebula.

After this attempt, to make the incomprehensible more comprehensible, I propose my assertion:

> *In order to explore the enormously gigantic (*10^{14} *diameters of the earth's orbit), we must apply our knowledge of the extremely small (*10^{-13} *cm).*

In large things the Universe follows the laws of macrophysics: mechanics, electrodynamics, thermodynamics, relativity and hydrodynamics. For most part we encounter conditions that differ vastly from those surrounding us. They are more akin to those present in a nuclear experiment carried out at a cosmic scale. How can the inner structure of matter—the extremely small—be the building principle of the Universe, determining for the large part the emergence of galaxies and stars and the course of their lives? All this originates and depends nevertheless on these so unusual circumstances to which matter is subjected—or perhaps one should say, conventional conditions, a statement allowing for the fact that the conditions under which *we* live are extraordinary.

Under these circumstances one can anticipate that each new step in understanding the extremely small develops new relationships in the extremely large and leads us further on the way, which we hope, succeeds in bringing us to a new theory capable to explain simultaneously the functioning of the Universe in both the very large and the very small.

The most recent step into the very small began a few years ago, and it leads today to few if any consequences for our conceptual understanding of the Universe; I believe, however, that these will come soon. With the last step I am referring to the field of high energy physics. Those who prefer precise wording might criticize the use of the expression “last step” because it could be easily misunderstood: namely as the last possible instead of the latest accomplished, as I meant to say here.

But there is no mistake in expression. I meant both and especially the last possible step. Instead of an error of style it has to do with a hypothesis, which is being described by this lecture. It appears that we have reached, in elementary particle physics a completely new paradigm, a kind of a terminal situation, in which the question about the composition of matter receives an unforeseen and satisfying answer. This is actually surprising, because we still can’t overcome the old difficulties. Whenever someone says to me, that he has now found the true atom, the building block of all matter, I always ask him, then what is this thing made from? One can just read Kant, to see in what sort of cul-de-sac that leads. And now I claim that high energy physics—perhaps!—offers a final solution to this dilemma? I do not want to be misunderstood: first, I am making a claim, which is not accepted by all of my colleagues, and second, I do not claim that we are about to understand everything about elementary particles. But this new approach seems—at least from a particular perspective—to offer us the view, which could be used to take the picture.

The New Situation: Multiparticle Production in High Energy Physics

I want to show you first why the situation is new.

The question, “How is matter created?” is a challenge for scientists studying nature. This also invites them to take ‘it’ apart, to study the building blocks and the forces binding these building blocks together, to apply the already known laws of physics as much as possible, to postulate new laws only when unavoidable and to attempt to bring everything together consistently. The importance of conceptual theoretical insight is that this lets us understand how the whole may be more than the sum of the parts, remembering that the first and the last word is spoken by experiment. To study this question, this is what the experiment dictates: break apart particles into their building blocks and measure the forces acting between them that do so for sub building blocks, then break down the sub sub building blocks and again study the forces and so forth, without end. Without end?

We want to follow this continuing decomposition and pay attention to how much energy we must use, in order to break down a given material into its components. The “new situation” will become clearest when we compare the requisite energy with the total energy that is stored within the given material.

> *Relativity teaches us in that a piece of material with mass m contains the energy equivalent* $E = mc^2$ *(c is the speed of light).*

This proposition has been confirmed experimentally. The energy $E = mc^2$ is enormously large in comparison to familiar energy scales. We will see that soon.

We consider some everyday matter—some cooking salt—and break it down into its elementary building blocks and with each step compare the energy released in the decomposed material to the energy in the material as a whole. So let's take a piece of cooking salt (NaCl), about the size of a fist. How do we decompose it? First we let it fall to the Earth; with a hard floor and a falling distance of about a meter, it breaks into about a hundred smaller pieces—but those splintered pieces are still cooking salt. In order to break apart the smallest piece of salt—a molecule of NaCl—into sodium Na and chloride Cl elements, we must turn to chemical processes.

For centuries, the futile efforts of alchemists demonstrated that one could not go beyond the decomposition of NaCl into Na and Cl. The belief set in that atomic elements are truly the indivisible elementary building blocks. Yet the question remained: why are there 90 different atomic species? If they are different, then their structures must be different, so they must have subparts.

Soon we found a way to break elements apart too: one throws them on the floor—but this time somewhat harder—or rather one bombards them with very fast projectiles. From this we learned that atoms are composed of three different building blocks: protons and neutrons, which are the nuclear building blocks, and electrons, which are needed to create the atomic shells. The very weakly bound electrons are responsible for chemical processes, for which the tightly bound nuclei can have nothing in common—hence the failure of alchemy. Only the energy rich projectiles, which modern particle accelerators shot at the nuclei being studied, enabled these nuclei to be broken apart. When this was accomplished, one attempted the next step, breaking apart the nucleons (the shared name for protons and neutrons, which are similar to each other) with a collision using another nucleon—and this approach failed—but in a way suggesting that something fundamentally new happened.

Now we turn to take a look at a chart which shows what fraction of the energy is required to break mater down into components:

- Mechanical decomposition of a cooking salt crystal into fragments by letting it fall from a height of one meter: 1×10^{-16} of the total energy of the crystal.
- Chemical decomposition NaCl→Na+Cl: 7×10^{-10} of the total energy of a NaCl molecule.
- Nuclear decomposition Na→23 nucleons: 8×10^{-3} of the total energy of the Na-nucleus.
- Decomposition of the nucleon? 5× the total energy does not suffice!

These numbers show how enormous the binding forces become, when the decomposed objects become smaller. To achieve the chemical binding energy of the cooking salt crystal I need to throw it 7,000 km high (assuming that Earth's gravity remains the same). However, the energy in the nuclei is still ten million times higher—and yet this is but barely 1 % of its total stored energy as shown in $E = mc^2$.

With so comparatively tiny—albeit growing—fractions of the total energy, we can break down all the known substances into their electron and nucleon building blocks.

It was foreseeable that one would have to bombard the nucleon with an even larger fraction of its total energy in order to get the nucleon to break down into its components. Therefore we have built high energy particle accelerators and smashed nucleons together with higher and higher energies so that now, at the most recently built Soviet accelerator (70 GeV) we are not achieving just a fraction, but five times the energy $E = mc^2$ contained in a nucleon.

The nucleons remain intact!

When the highest energy cosmic rays hit an atom, the collision energy up to a few hundred times greater than that in the nucleon is achieved—and so far there is no evidence that this will break apart the nucleons. Just the opposite. In such experiments a large number of new material particles including even nucleons (and antinucleons) are created. Most of these newly generated particles are certainly unstable—they decay in an unbelievably brief time, nevertheless slowly enough, that one can experiment with them.

I do not want to go now into the detailed properties of these particles nor to describe the astounding way in which their properties can be classified in a simple scheme. What this scheme suggests is that the nucleons as well as all the other newly formed material particles are composed of only a few fundamental building blocks, the so-called quarks. Quarks have never been observed as free particles and might not exist in this form. These insights have been described in a manner understandable for non-specialists in many other popular-scientific articles, thus I do not dwell further on this matter.

My objectives are different. First, I will try to make clear that the above finding suggests that something radically new is really present; and second, let me explain why I believe that we are in a 'final' situation, which nevertheless does not signify an ending of our search for the ultimate building blocks of matter.

First: imagine that through decomposing and decomposing and decomposing, the matter is finally pushed to small, incredibly hard spheres, say the size of a pea, which can neither be destroyed nor differentiated from each other in any manner. We collide such spheres onto one another and thereby expend energies that were greater than the mass energy of the spheres. However, instead of breaking up, they divided into four such peas (including an anti-pea)—*each just as big, just as heavy and just as hard as the two originals*—therefore two brand new peas were created. In the process appeared also a lot of splinters and sparks of a previously unknown material, all of which almost instantly shattered with a bang and disappeared, while adding some more peas to the type of peas described above. Such a situation should be correctly viewed as a new phenomenon.

For physicists this was not however unexpected: relativity and quantum physics have long taught that energy and mass are equivalent and can spontaneously change into each other; set energy free with an impact, it can reappear as matter, subject only to the constraint that the amount of energy is greater than the mass energy equivalent $E = mc^2$ of the particle to be generated. Other conservation laws such as that of baryon number deserve mention here as well.

Black Body Radiation

I now need to introduce another concept that has played an influential role by undermining classical physics. This idea forced Planck to postulate the quantum hypothesis initiating a radical conceptual change which culminated in the formulation of quantum theory. Arguably, there has not been anything of comparable importance discovered since. I present to you "Black Body Radiation".

If you place a completely empty box—a cavity—in a heat bath of temperature T, it does not remain empty; it fills with electromagnetic radiation, whose spectral distribution, i.e. the composition of different wavelengths (radio waves, heat, light, ultraviolet light, X-rays), is described accurately by Planck's radiation law. This spectral distribution is a function of temperature; in fact, we measure temperature of very hot and/or far and distant bodies (stars), by studying the radiation spectral distribution. Aside of the spectral distribution dependence on the temperature, the intensity of the radiation is also temperature dependent. Namely, the total radiated energy is proportional to T^4. Or said differently, the way I prefer: the temperature is proportional to the fourth root of the radiation energy content. When the temperature just doubles, the radiation energy is increased 16 times.

From daily life experience, by and large, (that is, apart from chemical and phase changes, such as melting, boiling), we are accustomed to thermal energy being approximately proportional to temperature increases; that is, 16 times the thermal energy also means 16 times the temperature. This is because heat is nothing more than the random motion of molecules and that, as their number (usually) remains constant, all energy supplied again finds itself as heat and the temperature increases proportionally: temperature is defined as a measure of the average kinetic energy per molecule. However, in the radiation field—also called photon gas—the number of "molecules," that is to say, the number of photons, is not at all constant: ever more and more of them are created as the temperature is increased, as I supply ever more energy. This larger number of photons, many more than were originally available, must share the newly supplied energy; therefore each photon takes only a minor portion for itself, than it would have received, had their number been constant. The temperature = average energy per photon rises more slowly than in the case of constant particle number; in consideration that a large part has just been invested in the creation of new photons. In a more careful evaluation we find the Stefan–Boltzmann law which I introduced, the temperature is proportional to the fourth root of energy density: $T = \text{Const.} \times \sqrt[4]{E}$

What does this have to do with our indestructible nucleons and the newly created particles?

All we need is to generalize the concept of black body radiation: who says that the radiation must consist only of photons? There is no law in physics prohibiting material particles forming from radiation. In fact, relativity and quantum theory claim it outright: if $E \geq mc^2$, a particle of mass m can arise spontaneously (there are certain constraining conservation laws, but in principle this detail changes nothing). So if we increase the temperature of our box on and on, it is inevitable that in principle within the cavity particle radiation of any sort of matter (and antiparticles) sometimes occur. Admittedly, the probability of finding a particle of mass m, decreases extremely rapidly with increasing mass (that is, exponentially).

Considering very high energy collision processes quantitatively one finds that the newly created particles have just the same energy and angular distribution, which they would have if they were emitted by a black body source of a very high temperature as first argued by Enrico Fermi. Although not of immediate interest in our present context, the black body radiation cavity source is also in motion. As argued, we can measure the source temperature by generalizing the Planck's radiation law to include the radiation of material particles. To each Planck's spectral energy distribution corresponds a certain temperature value T. All we need to do is to measure the energy spectral distribution of the newly generated particles in a given collision process to learn which temperature was reached in the collision between the two projectiles.

By this procedure we can deduce the temperature that prevailed during the incredibly short collision time (10^{-23}) s in the incredibly small domain of space (10^{-13}) cm—in the time (10^{-23}) s the light travels the distance (10^{-13}) cm. Using the same method we can make an equally reliable statement about the temperature of the surface of Sirius or in the interior of a blast furnace. As the collision energy is a multiple of the mass energy of the colliding particles, it is not surprising that the temperatures measured in these collisions far surpass all the temperatures known on Earth and in the sky above. Created daily at CERN in billions of collisions these temperatures are of the order 10^{12} K. To imagine this number, consider this: a furnace that becomes hotter by one degree every second, would bring water to a boil in 1.5 min; and after 1.5 h it will be as hot as the surface temperature of the sun; after a year we would reach the interior temperature of the Sun but only after 100,000 years would we reach the temperature of which we speak in high energy physics!

16.2 Highest Temperature = The Boiling Point of Primordial Matter?

I claim that it is not surprising that the temperature seen in high energy collisions is that high—in fact, one would have expected it to be much higher and in particular that it should grow with the energy of the colliding particles. Namely, as one knows from the black body radiation law—and that is what we are dealing with here—temperature should grow at about the fourth root of the energy. Instead, it remains a simple constant, apart from some not yet quite understood exceptions. More precisely, as the particle collision energy grows, the temperature T_0 approaches a finite limit of 1.8×10^{12} K corresponding to 160 MeV.

It appears that this fact is extremely significant indicating that in the decomposition of matter, we have reached an unexpected end, which is, nevertheless, not an end.

Namely: the temperature of ordinary black body radiation only grows with the fourth root of energy, that is, relatively slowly, because a large part of the available energy is used to produce new photons instead of being used to increase the temperature. Considering the case of material particle black body radiation present in high energy physics we have available not only photons but all new types of particles. Each type of particle demands a part of the available energy. Each particle component needs this energy to participate fully. The more such particle fractions are present, that is the more different *types* of such "elementary particles" are present—the less energy that can be vested in each type of component and thus less energy remains available to raise the temperature.

In fact today there are many different types of particles that can be produced in a high energy collision—-one already knows about 100 new "elementary particles"—and all these have distinct mass. Thus we are led to, and we need to characterize the concept of the mass spectrum. To this end I would like to introduce a seemingly absurd but valid comparison, namely books. There are many different titles, each with a fixed price (if two have the same price, one can introduce another distinguishing property). In this approach let me compare the book title with a particle type, and book price with particle mass; the print number with the probability of finding this sort of particle. Even without looking at the content of the books we can generate a spectral price distribution by asking: how many books are there in each price interval (such as between Fr 10 and Fr 11 or between Fr 31.50 and Fr 36.75). Similarly, one can arrange the various types of elementary particles without considering their individual properties—by specifying how many species there are in each mass interval. This distribution we call mass spectrum, just as one speaks of the price distribution counting books.

Clearly, the radiation equilibrium within our black body source will now depend on material particle mass spectrum. The more different particle types there are, the less is the temperature rise given the same input energy. The precise terms "mass spectrum" and "radiative equilibrium in cavity" permit a precise mathematical treatment of the problem.

The outcome is that if the mass spectrum of the participating "elementary particles" increases immensely strongly and in a very specific way, the temperature may never grow beyond a pre-established limiting value. This limiting temperature T_0 emerged as a characteristic constant in the mathematical description of the mass spectrum: each equal length mass steps $\Delta m = 2.4 \times T_0$ moving up the mass spectrum, brings into the picture ten times more new types of particles as compared to all previous steps taken together. It is said that the mass spectrum grows exponentially as e^{m/T_0}.

This we can verify experimentally: in high energy experiments for a temperature characterized by the limiting value T_0 one would further experimentally observe new types of "elementary particles" that can be sorted into a mass spectrum from which it is possible to read off the constant T_0 again. Of course it is possible to study a small mass spectrum domain of the low-mass to mitigate the effect that for the larger masses few particles are produced: that is, in our book example at high price only "Limited Editions" are produced, which limits the printed number of copies; this reduction is again exponential. One finds in such a study:

> *The nearly fully known mass spectrum grows in exactly the way that is required for the existence of a limiting temperature, and the constant T_0 is numerically consistent with the upper bound of the temperatures measured in high energy collisions.*

Now, a few limiting temperatures are familiar to us from our daily lives, perhaps the best known being the boiling point of water: no matter how hot I make the stove, at normal atmospheric pressure water boils at exactly 100 °C. Why? Because all of the additional heat energy is used to lift water molecules out of the liquid. Generally, any additional energy is divided between two competing mechanisms: increase in temperature, and evaporation. Since molecules do not have a sharp temperature controlled energy but a distribution, some can cross over from liquid into vapor at practically any temperature. However, with increasing temperature, it becomes ever easier for a molecule to free itself from the liquid, and when the temperature approaches the boiling point, it is so easy for them to leave, they all want out and actually escape in a rapid manner. They absorb all the heat made available and leave the molecules still remaining behind no energy to increase their temperature.

The limiting temperature appears in the high-energy collisions in analog fashion. You have only to replace the words "leave the liquid" with "make the leap from non-being into being." To make this transition a particle of mass m needs the energy $E = mc^2$, and when there are as many different particle types as described above, then the all-particle birth rate will eventually be so great with increasing temperature, and the many required mc^2 amounts will use up all energy supply such that already-born particles will have nothing left to increase their common temperature. Because of this analogy I speak of "boiling primordial matter."

Of course, once all the water has evaporated, additional energy will further increase the temperature of the steam. Moreover, all the water can boil away, given that a fixed amount of water has a fixed number of molecules. Our boiling primordial matter can never overcook, *because it is the supplied energy itself* which materializes and so ensures that more new particles are always being born. Therefore there can never arise the process corresponding to the continued heating the water vapor.

> *If these considerations are correct: that is, we were not lured by nature into a trap of following the correspondence between the experimental limiting temperature T_0 and the shape of the growing mass spectrum (which in principle can never be ruled by these experiments), then $T_0 = 1.8 \times 10^{12}\,K$ is the highest ever possible temperature in a stationary thermodynamic equilibrium. Occasional exceedances of T_0 likely correspond to the familiar phenomenon of superheating leading to an increased boiling point.*

16.3 Is the Question About the “Final Building Block” Meaningless?

There is the final question that remains: suppose, that everything were correct; there is an infinite number and an exponential mass spectrum of new types of particles and a corresponding limiting temperature—what does that have to do with the here presented end situation, which nevertheless does not mean an end? Here we enter into a theoretical construction wherein one abstracts a general rule from a limited number of experimental data, which is then tentatively postulated as a universal principle. This introduces us to the usual practical circumstance of theoretical physics: we have a model whose other properties are analytically derived using established methods of mathematics and the assumptions that generally apply to the already known laws of nature. In this way we obtain experimentally testable predictions as derived from known or later verifiable behavior. Agreement of these predictions with the facts is necessary, but not sufficient, to ensure that the theoretical model is correct. This applies especially to the model I will now describe.

In order to introduce the model in words, I will characterize the situation far less exactly than the technical tools of theoretical physics would allow me to do this. I proceed in this way as I seek at all cost to avoid technical jargon.

In a high-energy collision new material particles are copiously produced (events with a multiplicity of a hundred or more have been observed). In our terminology, these particles emerge from the collision-produced boiling primordial matter. In a certain and physically quite precise sense they were all contained in this piece of boiling primal matter. Taking one of these newly generated particles under the microscope (which is not easy: lifespan $\simeq 10^{-23}$ s), we observe that it behaves itself as boiling primordial matter; namely it can decay further into many particles. The greater its mass, the greater is this tendency. Such a particle with a large mass thus has a dual nature: on the one hand, it can be used as an “elementary particle” contributing to radiative energy equilibrium, on the other hand it can itself create other “elementary particles” which contribute to the radiative energy equilibrium. Seen from this perspective, none of these produced particle types can be viewed as an elementary particle, given that other particles can emanate from any of the produced particles, which are again no more elementary since each can be simultaneously created out of the other, and in this way all these particles have undetermined building block composition.

Nothing in this picture changes if one day quarks should be confirmed as the primordial building blocks. In our approach they would play a preferential role, being the stuff from which “everything is built.” As an aside, it is the virtue of our approach that the statement “composed of” does not characterize the number and the character of the fundamental building blocks. The composition and nature of the source of produced particles can remain cloaked in mystery; it can remain undetermined.

The model aims to overcome the limited number of presently known types of particles by continuing the observed behavior of the mass spectrum at low mass to higher mass, (where we experimentally know nothing yet). Once this is done, much of what follows can be found ready to use in textbooks of statistical thermodynamics. The surprising extrapolation result is:

> The mass spectrum grows in exactly the manner (exponential) as is required for the presence of an absolute maximum temperature.

With this the circle closes:

- The property of the new "elementary particles" is that each is simultaneously in ever-changing ways being created from all the others,
- with the tremendously (exponentially) increasing mass number distribution of different types of such "elementary particles",
- leading to the existence of a "boiling point" for primordial matter.

These three seemingly different things are actually different manifestations of a single underlying physics principle—provided that you take any one of these three as a general postulate valid beyond the currently experimentally studied range.

A theoretical model, such as this one, which is introduced as a postulate, where the behavior is extrapolated to infinity from the finite domain that is known, cannot be proved. Its consistency, its formal simplicity and the fact that its detailed quantitative predictions agree in the currently accessible experimental range, makes it interesting and credible until further notice. Should it be correct, then the old question of the ultimate constituents of matter disappears all by itself: this issue merges into the endless circle. Let's return to the analogy we developed with books: there is no "elementary book" from which all others are made. Yet when two books collide with each other violently enough, many new are produced—and each contains every other somehow in itself.

Before answering the last question: what does all this have to do with the "evolution of matter?" I offer a few remarks.

(a) The situation described is typical of the physics of strong interactions, involving all nucleons and other particles responsible for the mediation of the nuclear forces. The electron is in this context irrelevant. The reason is that in such a short collision only the strong interactions can participate in formation of radiation equilibrium. There is no time for the electro-magnetic and weak forces to act; before they awake and can respond, everything is as if the collision had happened a few million years earlier.

(b) The model described here relies on a speculation which posits what should happen for infinitely large particle masses by extrapolating what is observed at finite particle masses. There is another approach founded in similar yet very different more technical concept, namely the extrapolation towards stable "elementary particles", i.e. nucleon, mesons (stable under strong interactions). We attempt a description in which each such elementary particle emerges simultaneously from all the others: this is our so-called "Bootstrap-Theory," originating in the well-known "Baron Münchhausen" bootstraps. The gentleman is trying to pull himself out of the swamp by yanking on his own hair. Despite this analogy I think our particle bootstrap model is in principle correct—it's practically the same model as the one I introduced above. However, it has, I believe, due to a technical defect, so far not functioned quite right: one has usually introduced only the few lowest mass particles in self-consistent bootstrap circles; the more stable particles one takes, the better the particle bootstrap should function, so all stable particles need to be included, after this is done there can no longer be an objection. On the lighter side, we recall that only when Münchhausen has yanked very strongly at his hair, was he able to move, and then not only himself, but taking with him the swamp, and the Earth—the whole world.

(c) It is noteworthy that in the realm of today's particle physics (or High Energy Physics—we have seen that these two terms mean the same) no evidence is found that the existing principles of relativity and of quantum theory need to be corrected or extended in any way; even though we are in a new situation.

(d) After my report, it might seem as if the end of elementary particle physics has come. However, what I have presented arises from speculative hypothesis. And even if everything were correct, we would not come to an end, but find ourselves at a new beginning: in all the above considerations only strong interactions were considered, and not in terms of particular form of forces, but only in terms of the ever-changing composition of the "elementary particles," and we have never spoken about their individual characteristics—therefore our conclusions were completely independent of all these additional known particle properties. Thus we have described the average behavior, the statistical behavior. But the main focus of high energy physics is precisely on all these more detailed individual properties of the new particles and the forces acting between them. And there is the question, why *these* forces? In this regard we stand at a new beginning.

(e) Many physicists still believe in the possibility of exploring deeper and further to ever more elementary building blocks. One must follow this line experimentally and cannot be misled by intellectually satisfying speculation into believing that the scientific question is settled.

(f) I have tried to describe everything in everyday language, in words, that we physicists use, when we talk about such things at tea. To you, the reader, everything must look very mysterious, especially the claim that each "elementary particle" in different ways has been created from all the others. Take it to be 'as-if-speech', as a blurry image of what can be formulated much more precisely with the help of mathematics or technical jargon.

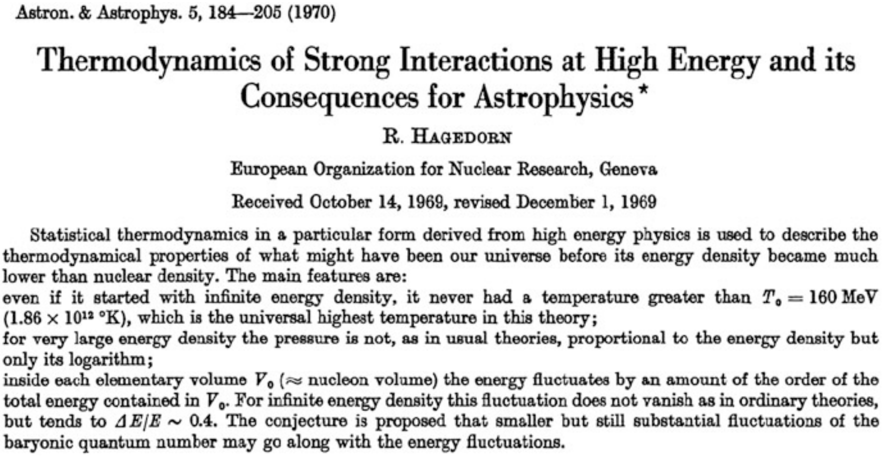
With this report I also, as an aside, hope I have made you understand why we high energy physicists yearn so much for the next European 300-GeV accelerator, which will now probably be built.

Possible Consequences in the Large?

What does this all have to do with the creation of matter? At least a few theories about the beginning of the Universe assume a Big Bang, that is to say a creation explosion. Following previous ideas—based on traditional black body radiation—the Universe began with infinite energy density, with energy density proportional to the pressure, and infinitely high temperature. Under such extreme conditions, traditional black body radiation no longer remains, but rather the conditions are found akin to the high-energy collisions of nucleons. And then when strongly interacting matter is present the temperature cannot be infinite, but only about 10^{12} K, and the pressure is not anymore proportional to the energy density but only proportional to its logarithm. This is a different scenario of the beginning of the Universe than was previously thought. A beginning is seen in experiments at CERN, where a proton melts with another for 10^{-23} s into boiling primordial matter. Moreover, it cannot be excluded that even entire stars consist of boiling primordial matter.

We can wonder if this Big Bang, the origin of everything, including the beginning of time is an equally unsatisfactory assumption as is the existence of the very final building blocks of matter. Just as you can ask: and how did that building block come about?, so you can ask: and what was before Big Bang? How did it happen? We do not know. Maybe we will find one day that this question in a similar way is irrelevant as—possibly—the one about the final building blocks.

I close with an anecdote: on the bulletin board of a German university the following could once be read among lecture announcements: *Tuesdays 9–11 AM, free for all discussion session about the structure of the Universe—only for the advanced. signed X.* We will, alas, always be beginners (see Fig. 16.1).
In 1992 a Summer School took place that united experts and students working on hadron production and quark-gluon plasma in laboratory and cosmology. The meeting was organized by G. Belletini, H.H. Gutbrod and J. Rafelski with the principal sponsor being the NATO Scientific Affairs Division. Next page presents in abridged format the meeting poster.



Astron. & Astrophys. 5, 184—205 (1970)

Thermodynamics of Strong Interactions at High Energy and its Consequences for Astrophysics*

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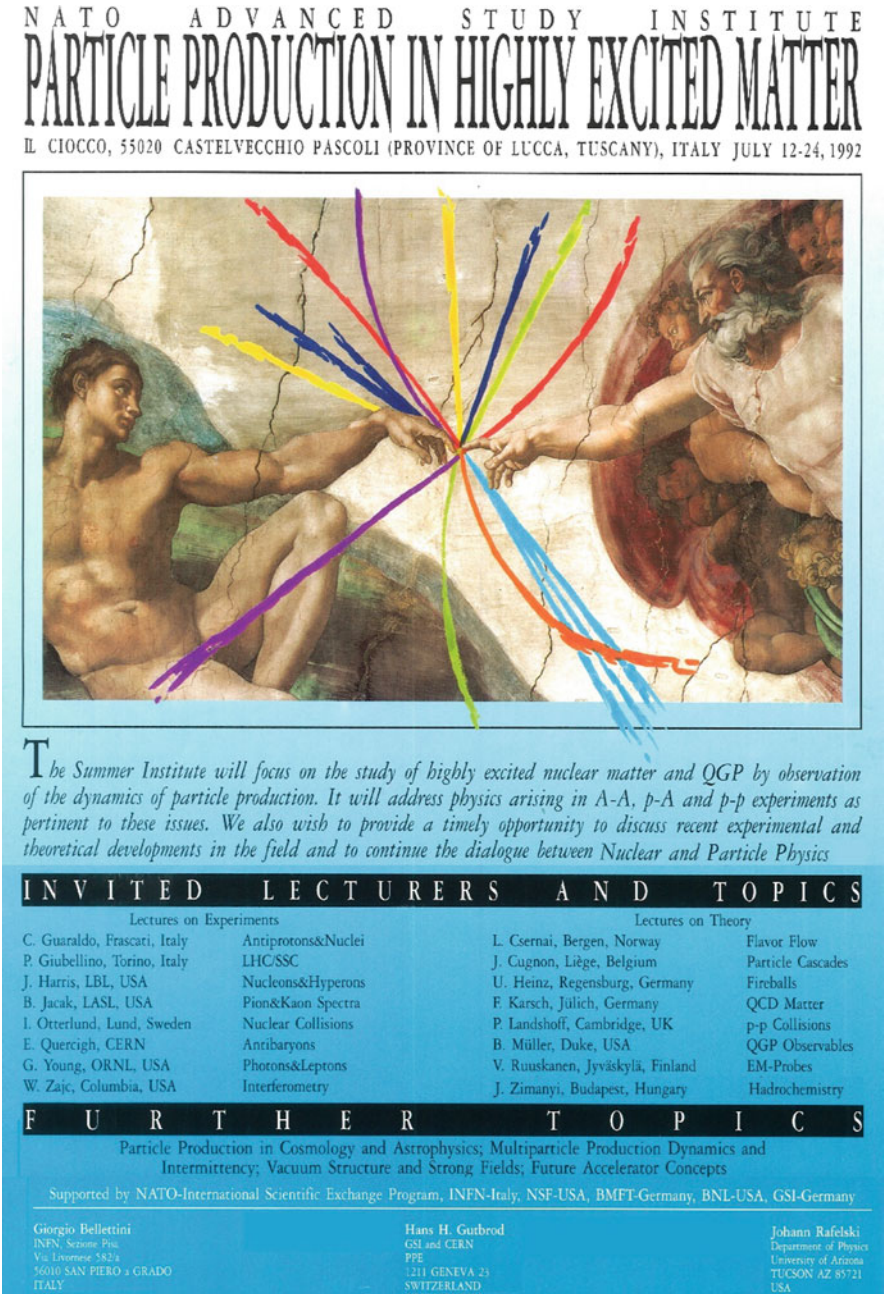
Received October 14, 1969, revised December 1, 1969

Statistical thermodynamics in a particular form derived from high energy physics is used to describe the thermodynamical properties of what might have been our universe before its energy density became much lower than nuclear density. The main features are:
even if it started with infinite energy density, it never had a temperature greater than $T_0 = 160$ MeV (1.86×10^{12} °K), which is the universal highest temperature in this theory;
for very large energy density the pressure is not, as in usual theories, proportional to the energy density but only its logarithm;
inside each elementary volume V_0 ($\approx$ nucleon volume) the energy fluctuates by an amount of the order of the total energy contained in V_0. For infinite energy density this fluctuation does not vanish as in ordinary theories, but tends to $\Delta E/E \sim 0.4$. The conjecture is proposed that smaller but still substantial fluctuations of the baryonic quantum number may go along with the energy fluctuations.

Fig. 16.1 Within a year of this popular level lecture, Hagedorn presented a scientific account of his views as shown here (Astron. & Astrophys. **5** 184–205 (1970)). In doing this he contributed decisively to the establishment of the 'Hot Big Bang' as the standard cosmological model. The recognition of the phase boundary between boiling-quark and melting-hadron primordial universe arrived a decade later



NATO ADVANCED STUDY INSTITUTE

PARTICLE PRODUCTION IN HIGHLY EXCITED MATTER

IL CIOCCO, 55020 CASTELVECCHIO PASCOLI (PROVINCE OF LUCCA, TUSCANY), ITALY JULY 12-24, 1992

The Summer Institute will focus on the study of highly excited nuclear matter and QGP by observation of the dynamics of particle production. It will address physics arising in A-A, p-A and p-p experiments as pertinent to these issues. We also wish to provide a timely opportunity to discuss recent experimental and theoretical developments in the field and to continue the dialogue between Nuclear and Particle Physics

INVITED LECTURERS AND TOPICS

Lectures on Experiments	
C. Guaraldo, Frascati, Italy	Antiprotons&Nuclei
P. Giubellino, Torino, Italy	LHC/SSC
J. Harris, LBL, USA	Nucleons&Hyperons
B. Jacak, LASL, USA	Pion&Kaon Spectra
I. Otterlund, Lund, Sweden	Nuclear Collisions
E. Quercigh, CERN	Antibaryons
G. Young, ORNL, USA	Photons&Leptons
W. Zajc, Columbia, USA	Interferometry

Lectures on Theory	
L. Csernai, Bergen, Norway	Flavor Flow
J. Cugnon, Liège, Belgium	Particle Cascades
U. Heinz, Regensburg, Germany	Fireballs
F. Karsch, Jülich, Germany	QCD Matter
P. Landshoff, Cambridge, UK	p-p Collisions
B. Müller, Duke, USA	QGP Observables
V. Ruuskanen, Jyväskylä, Finland	EM-Probes
J. Zimanyi, Budapest, Hungary	Hadrochemistry

FURTHER TOPICS

Particle Production in Cosmology and Astrophysics; Multiparticle Production Dynamics and Intermittency; Vacuum Structure and Strong Fields; Future Accelerator Concepts

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