Boiling Quarks, Melting Hadrons

Department of Physics, The University of Arizona
Tucson, AZ

June 2, 2015
Boiling Quarks, Melting Hadrons
1964/65: Two new fundamental ideas

- Quarks $\rightarrow$ Standard Model of Particle Physics
- Hagedorn Temperature $\rightarrow$ New State of Elementary Matter

Topics today:

1. 50 years ago – Melting hadrons: birth of hadronic matter
2. 35 years ago – Boiling quarks: hadrons dissolve into quarks at Hagedorn Temperature $T_H$
3. 15 years ago – Quark-gluon plasma discovery
4. Today – Searching telltales of QGP in the Universe
Particle production

Hagedorn 1960-1964: Fermi-Landau fireballs produce too few pions – need distinguishable particles → Hagedorn limiting $T$

A new kind of thermodynamical model for strong interactions at high energies is proposed. We start from the fact that strong interactions produce so many possible particle states (from $S^r$ over its resonances to nucleons, strange particles and their resonances, up to highly excited "fireballs") that in an actual process each of these states practically never occurs more than once. We use this in order to treat the very first instant of a high-energy collision by statistical thermodynamics of a system of an illimited number of distinguishable particles. The model shows surprising properties: there exists a universal highest possible temperature $T_0$ of the order of 150-200 MeV (corresponding to $\approx 10^7$ K), which governs all high-energy processes of strongly interacting particles, independent of the actual energy and independently of the particle number, from cosmic ray jets down to elastic scattering.

I have written and distributed this paper too early. The logical difficulty mentioned on p. 41 has been removed as follows and the result is disappointing:

1) if $\rho(n)$ grows faster than exponentially, $\log Z$ diverges for all $T > 0$. No thermodynamics is possible.
within a few months

R. Hagedorn
CERN - Geneva

\textbf{ABSTRACT}

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For \( n \to \infty \) these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a elegant: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which...". This principle, which could be called "asymptotic bootstraps", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

\[ \rho(x) \sim \text{const}.x^{-5/2} \exp(-x/T_0). \]

\( T_0 \) is a remarkable quantity: the partition function corresponding to the above \( \rho(x) \) diverges for \( T \to T_0 \). \( T_0 \) is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.g. form factors, etc.). There is experimental evidence for that, and then \( T_0 \) is about 150 MeV ( \( \approx 10^{12} \text{ MeV} \)). With this value of \( T_0 \) the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.
SBM = Statistical Bootstrap Model

A macroscopic system

with total energy $E$
given volume $V$
density of states $\sigma(E,V)$

compress

with total energy $m$
self-confined to its
natural volume $V(m)$
density of states $\rho(m)$

Idea yields exponential mass spectrum
Exponential mass spectrum defines $T_H$

\[ a = -3 \]
From \textit{pp} to \textbf{elementary matter}

SN collapse at origin of the long standing interest in ultra-high density ‘nuclear’ matter, quark matter stars proposed: D. D. Ivanenko, D. F. Kurdgelaidze: “Hypothesis concerning quark stars,” Astrophysics \textbf{1}, 251 (1965). \textbf{Lab:} Presumption that when big nuclei collide matter is \textbf{compressed} prevails till Hagedorn-Montvay-JR (1978) show that energy flows into production of particles akin to the \textit{pp} case. \textbf{This is how hadronic matter differs from all other forms of matter.}
Hagedorn Temperature $T_H$

Singular point of partition function

Valedictorian Lecture 1994
Boiling quarks

THE ROOTS:

- Cold quark matter in diverse formats: 1965 →
- Hot interacting QCD quark-gluon plasma: 1979 →
- Formation of QGP in relativistic nuclear (heavy ion collisions) 1979 →
- Experimental signatures: Strange antibaryons 1980 →
- Materialization of QGP: 1982 →
  Statistical Hadronization Model (SHM)
Cooking strange quarks → strange antibaryons
Prediction: 1980 JR; 1982 JR, Berndt Müller; 1986 P. Koch, BM, JR; Present day results
**PARTICLE YIELDS: INTEGRATED SPECTRA**

Particle yields allow exploration of the source bulk properties in the co-moving frame – collective matter flow dynamics integrated out. This avoids the dynamical mess:

Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.
(FERMI) STATISTICAL HADRONIZATION MODEL (SHM)
Very strong interactions: equal hadron production strength irrespective of produced hadron type particle yields depending only on the available phase space

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER

  Experiments report event-average rapidity particle abundances, model should describe an average event

- Canonical phase space: sharp number of particles
  ensemble average energy $E \rightarrow T$ temperature
  $T$ could be, but needs not to be, a kinetic process temperature

- Grand-canonical – ensemble average energy and number of particles: $N \rightarrow \mu \leftrightarrow \Upsilon = e^{(\mu/T)}$
The first 20 years: 1962-1982

35 years ago: boiling quarks

Quarks and the Universe

Examples: data (LHC)
AGS, SPS, RHIC bulk properties

Johann Rafelski
Wigner Colloquium, June 2, 2015

Boiling Quarks, Melting Hadrons
QGP+ Statistical Hadronization Model
=Hadron Gas Abundances without Hadron Gas

Why the hadronic gas description of hadronic reactions works: the example of strange hadrons

Received 28 August 1985

P. Koch and J. Rafelski
Institute of Theoretical Physics and Astrophysics, University of Cape Town, Rondebosch

1. Introduction

The observation that soft multihadron production ($p_T < 1$ GeV) shows many features of an underlying statistical reaction mechanism has inspired Hagedorn's Statistical Bootstrap [1,2] long before anything about quantum chromodynamics (QCD) was known. But since QCD has been accepted as the underlying gauge field theory of strong interactions, it seems today rather 'old-fashioned' to treat high energetic hadronic collisions in the framework of phenomenological statistical models. A contrary understanding may be adopted following the present discussion. Our point of view is that the transitory formation of a quark–gluon plasma-like state is the prerequisite in order that statistical models can be used. The number of accessible states in hadronic reactions may be many times larger than a naive hadronic phase space counting indicates and a statistical description may indeed also be necessary in order to describe the hadronic interactions. The whole hadronic reaction
At a special seminar on 10 February, 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.

Preeminent signature: Strange antibaryon enhancement
9AM, 18 April 2005; US – RHIC announces QGP
Press conference APS Spring Meeting

Preeminent signature: honey that flows
The objective is to understand the properties of the quark-gluon plasma, to write a few pages on the history of our universe.

Wow! Then you will become rich and famous!!

Oh, I doubt it! We are just doing what you have done by following the rabbit... satisfying human curiosity... From our results, we can learn for example how the matter of the early universe evolved.

"We"? But who is 'we'? We are about 1000 researchers, engineers, technicians and students from all over the world. For years, we have been working hard to design and build the ALICE experiment. This is an exciting period; but even more exciting will be when we cook the soup... speaking of soup, would you like to join our party? I can introduce you to my colleagues.
Today new question:

<table>
<thead>
<tr>
<th>Big-Bang</th>
<th>Micro-Bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \approx 30 \mu s$</td>
<td>$\tau \approx 5 \times 10^{-23} s$</td>
</tr>
<tr>
<td>$N_B / N \approx 10^{-10}$</td>
<td>$N_B / N \approx 0.001$</td>
</tr>
</tbody>
</table>
Do we see QGP in the sky?

Photons freeze-out around 0.25 eV and today they make up the \( T_\gamma = 0.235 \text{ meV} \) \( (2.7^\circ \text{ K}) \) Cosmic Microwave Background (CMB). The CMB is one of the anchors of observational cosmology. Could CMB connect to early Universe QGP era? Let us search the web!

*Image: ESA and the Planck Collaboration*
Stunning graphics! But nothing addressing the question. Thus we (Jeremiah Birrell and JR) tried to remedy the situation.
Result: time evolution of the energy density composition

- Dark Energy
- Dark Matter
- Hadrons
- $e^\pm$
- $\gamma$
- $\nu$
- $\mu^\pm$
- $\tau^\pm$
- $\pi$, $K$, $p+n$, $\Delta, Y$, $\eta f_0$, $\rho + \omega$, $b$, $c$, $u/d/s$, $c$

$T_{\text{recomb}}$, $T_{\text{BBN}}$, $T_{\nu}$, $T_{\text{QCD}}$

J. Birrell & J. Rafelski (2014/15)

Boiling Quarks, Melting Hadrons
Input into the image

- FRW Cosmology
- Disappearing Particles: Degrees of Freedom and Reheating
- Our contributions: connecting the Eras
  - From the beginning to QGP hadronization
  - Matter-antimatter annihilation era
  - Onset of neutrino free-streaming
  - Big-Bang nucleosynthesis and disappearance of practically all matter \((e^+e^-\text{ annihilation})\)
  - Emergence of free streaming dark matter, baryons follow
  - Photon Free-streaming – Composition Cross-Point
  - Dark Energy Emerges – vacuum energy
FRW Friedmann–Lemaître–Robertson–Walker (FRW) cosmology assumes a) Homogeneous and b) Isotropic Einstein Universe, metric:

\[ ds^2 = g_{\mu\nu} dx^\mu dx^\nu = dt^2 - a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2(\theta) d\phi^2) \right] \]

\[ a(t) \] determines the distance between objects at rest in the Universe frame (comoving). Skipping \( g^{\mu\nu} \rightarrow R^{\mu\nu} \)

\[ G^{\mu\nu} = R^{\mu\nu} - \left( \frac{R}{2} + \Lambda \right) g^{\mu\nu} = 8\pi G_N T^{\mu\nu}, \quad T_{\mu\nu} = \text{diag}(\rho, -P, -P, -P) \]

Definitions: Hubble parameter \( H \) and deceleration parameter \( q \):

\[ H(t) \equiv \frac{\dot{a}}{a}; \quad q \equiv -\frac{\text{acceleration}}{H^2} = \frac{\ddot{a}}{H^2} \frac{1}{a}, \quad \Rightarrow \dot{H} = -H^2(1 + q). \]

Two dynamically independent Einstein equations arise: eliminate \( G \) and get

\[ q = \frac{1}{2} \left( 1 + 3 \frac{P}{\rho} \right) \left( 1 + \frac{k}{\dot{a}^2} \right). \]

Flat \((k = 0)\) metric is favored in the \( \Lambda \)CDM analysis by PLANCK (arXiv:1303.5076v1502.01589).
Degrees of Freedom – disappearing particles
adiabatic Universe with comoving entropy conserved:
The effective number of entropy degrees of freedom, $g_S^*$, defined by:

$$S = \frac{2\pi^2}{45} g_S^* T^3 \gamma a^3.$$ 

For ideal Fermi and Bose gases

$$g_S^* = \sum_{i=\text{bosons}} g_i \left( \frac{T_i}{T\gamma} \right)^3 f_i^- + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left( \frac{T_i}{T\gamma} \right)^3 f_i^+. $$

$g_i$ are the degeneracies, $f_i^\pm$ are (known) functions valued between 0 and 1 that turn off the various particle species as the temperature drops below their mass. Entropy redistributed among coupled dof’s → reheating: e.g. when $e^+e^-$ annihilated only $\gamma$ reheated, already free-streaming neutrino temperature lower by factor

$$R_\nu = (4/11)^{1/3} = 0.714.$$
Degrees of freedom as function of $T_\gamma$

Ideal gas approximation is not valid during QGP phase transition and equation of state from lattice QCD must be used [1]. At and above 300 MeV non-rigorous matching [2] with perturbation calculations may impact result.

[2] Mike Strickland (private communication of results and review of thermal SM)
Checking the ‘contents’ of the Universe

Cosmic neutrino background (CNB) contributes to dynamics of expansion influencing temperature fluctuations in CMB

- ‘Effective’ number of neutrinos – measurable – is defined comparing the relativistic energy density to the energy density of one SM neutrino flavor, with the standard $e^+e^- \rightarrow \gamma's$ photon reheating ratio $R_\nu = (4/11)^{1/3}$ allowed for.

$$N_\nu \equiv N_{\text{eff}} \equiv \frac{\rho_r}{\frac{7}{120} \pi^2 (R_\nu T_\gamma)^4}.$$ 

- Planck satellite: $N_\nu = 3.36 \pm 0.34$ (CMB no priors) and $N_\nu = 3.62 \pm 0.25$ (CMB + $H_0$) [1].

In latest release $\delta N_\nu \simeq 0.3 \pm 0.25$.

Is the understanding of neutrino freeze-out accurate?

- The computed best value is $N_\nu = 3.046$ (some flow of $e^\pm$-pair into $\nu$) [1]. Only drastic changes in neutrino properties and/or physical laws can change this value noticeably [2].

- Consistent $\delta N_\nu > 0$ – is there ‘Darkness’ content in the Universe? New relativistic particles in the early Universe modify $N_\nu$ fractionally, see e.g. [3].

Are there additional dark degrees of freedom

Darkness Candidates

a) ‘True’ Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work.

b) Super-WI neutrino partners. Connection to deconfinement not straightforward.

Massive $m > \mathcal{O}(\text{eV})$ sterile $\nu$ not within ‘Darkness’ context. Mass must emerge after CMB decouples, $m < 0.25$ eV. Allowing higher ‘sterile mass’ requires full reevaluation of many steps in the analysis including key elements we do not control (PLANCK CMB fluctuations).
Quark–gluon plasma as the possible source of cosmological dark radiation

Jeremiah Birrell, Johann Rafelski

Abstract

The effective number of neutrinos, $N_{\text{eff}}$, obtained from CMB fluctuations accounts for all effectively massless degrees of freedom present in the Universe, including but not limited to the three known neutrinos. Using a lattice-QCD derived QGP equation of state, we constrain the observed range of $N_{\text{eff}}$ in terms of the freeze-out of unknown degrees of freedom near to quark–gluon hadronization. We explore limits on the coupling of these particles, applying methods of kinetic theory, and discuss the implications of a connection between $N_{\text{eff}}$ and the QGP transformation for laboratory studies of QGP.
Hadron and QGP Era

- QGP: from electro-weak mass emergence down to phase transition at $T \approx 150\text{MeV}$ Energy density dominated by QCD (quarks and gluons) but photons, neutrinos, $e^\pm$, $\mu^\pm$ need to be remembered
- $2 + 1$-flavor lattice QCD equation of state must be used [1]
- u,d,s lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115\text{MeV}$
- Hadrons included: pions, kaons, eta, rho, omega, nucleons, delta, Y
- Hadron pressure matching lattice-QGP and a few resonances is discontinuous but hard to notice.

Left pane: Increase in $\delta N_{\text{eff}}$ due to the effect of $1, \ldots, 6$ light Goldstone boson DoF ($g_s = 1, \ldots, 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. Right pane: Increase in $\delta N_{\text{eff}}$ due to the effect of $1, \ldots, 6$ light sterile fermion DoF ($g_s = 7/8 \times 1, \ldots, 7/8 \times 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. The horizontal dotted lines: $\delta N_{\text{eff}} + 0.046 = 0.36, 0.62, 1$. Vertical dotted lines: $T_c = 142 - 163$ MeV.
Limits on Couplings: 
Goldstone Boson limit in laboratory

**Laboratory setting:** Chemical equilibrium abundance of Darkness is achieved in the short lifespan of QGP formed in laboratory heavy ion collisions if

\[ G_{\text{Darkness}}^{-1/2} \simeq 170 \text{ MeV} \]
\[ G_{\text{WI}}^{-1/2} = 300 \text{ GeV}. \quad (1) \]

The appearance of a coupling on the order of the QCD scale is consistent with the intuition about the interaction strength that is required for particles to reach chemical equilibrium in laboratory QGP experiments. However, could such particles be excluded already by experiment?
HOWEVER: Activation of QCD Scale Interactions by $T$

QGP activation: Missing Energy in RHI Collisions

- **Breakup**: Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.

- **Continuous emission**: Darkness stops interacting at the QGP surface – escapes freely during the entire lifespan of the QGP. This Dark-radiation loss proportionally largest for long-lived QGP

→ Does energy in/out balance in large $AA$ collision systems beyond threshold of QGP formation?

- **Experiment**: A systematic exploration of the energy balance as function of $\sqrt{s}$ and $A$ at energies near to QGP formation threshold: $=$ NA61 experiment..
QGP Phase Transition Accentuated?

- We recall that lattice-QCD results show a gradual transformation of the QGP into hadrons consistent with the absence of a phase transition.

- However, Darkness as above introduced contributes to the pressure internal to QGP, yet not in the external region – free streaming. This should sharpen the QGP phase boundary surface.

- This impacts model of QGP flow and formation azimuthal asphericity \([1,2]\) (particle \(v_2\)). Darkness thus has indirect, dynamical effect on the flow of QCD matter.

---

Summary

- 50 years ago particle production in $pp$ reactions prompted introduction of Hagedorn Temperature $T_H$; soon after recognized as the critical temperature at which matter surrounding us dissolves into its different fundamental phase of quarks and gluons – QGP.

- Laboratory work confirms QGP and leads the way to an understanding of the properties of the Universe below the age of $18 \mu s$.

- A first links between observational cosmology and hadronization stage of the Quark Universe is found: Released Darkness could be a new component pushing the Universe apart.

- Laboratory effort: a search for missing energy in connection to dynamics of hadronization near to phase boundary as function of $\sqrt{s}$ with energy imbalance increasing with $A$. 