Exploring the QCD Phase Diagram with Strangeness

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1964/65: Two new fundamental ideas

- Quarks → Standard Model of Particle Physics
- Hagedorn Temperature → New State of Elementary Matter

Merging in 1979/80 into Quark-Gluon Plasma

Topics today:
1. From Hagedorn temperature to heavy ion collisions
2. Strangeness
3. QGP discovery buzz
4. SHM data analysis
5. Phase diagram and the horn
Hagedorn exponential mass spectrum: boundary of a new phase of matter

**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 $s \to \infty$ 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 bootstrap", 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:

$$\rho(s) \sim \text{const} \times s^{-5/2} \exp\left(\frac{s}{T_0}\right).$$

$T_0$ is a remarkable quantity: the partition function corresponding to the above $\rho(s)$ diverges for $s \to T_0$. $T_0$ 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 ($\approx 10^{12}$ eV). 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.

Johann Rafelski, Thursday, October 13, 2016, Exploring the QCD Phase Diagram through Energy Scans (INT-16-3)
Experimental mass spectrum defines $T_H$

To fix $T_H$ in a limited range of mass need prescribe value of $a$ obtained from SBM. In 1978 we noted that at $T_H$ sound velocity vanishes. This creates another way of fixing $T_H$ both in experiment and in lattice QCD and when this is done, the critical power $a$ is also determined.
From $T_H$ to RHI collisions

Strangeness

Quark-gluon plasma discovery buzz

SHM data analysis

Phase diagram and the horn

Hagedorn Temperature $T_H$

Singular point of partition function

$$Z_1(\beta, V) = \int \frac{2V_{\mu\nu} P_{\mu}^n}{(2\pi)^3} \tau(p^2) e^{-\beta \mu \rho^\mu} d^4p$$

Inserting $1 = \int \delta_0(m^2 - p^2) dm^3$

Replacing $\tau(m^2) dm^2$ by $\rho(m) dm$

$$Z_1(\beta, V) = \frac{V_{\mu\nu}}{2\pi^3} \int m^2 \rho(m) K_2(m\beta) dm$$

$$Z_1(\beta, V) \sim C \int_M m^{3/2 - a} e^{-(\beta - \beta_0)m} dm + C.$$
Melting Hadrons, Boiling Quarks: From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN. With a Tribute to Rolf Hagedorn
By Johann Rafelski (ed.)
Springer
The statistical bootstrap model (SBM), the exponential rise of the hadron spectrum, and the existence of a limiting temperature as the ultimate indicator for the end of ordinary hadron physics, will always be associated with the name of Rolf Hagedorn. He showed that hadron physics contains its own limit, and we know today that this limit signals quark deconfinement and the start of a new regime of strong-interaction physics.

This book is edited by Johann Rafelski, who was a long-time collaborator with Hagedorn and took part in many of the early conceptual developments of the SBM. It may perhaps be best characterised by pointing out what it is not. It is not a collection of review articles on the physics of the SBM and related topics, which could be given to newcomers as an introduction to the field. It is not a collection of reprints relativistic heavy-ion programme at CERN that took place in the early 1980s. It starts with his thoughts about a possible programme of this kind, presented at the workshop on future relativistic heavy-ion experiments, held at the Gesellschaft fuer Schwerionenforschung (GSI). It also includes the draft minutes of the 1982 CERN SPC meeting, and some early works on strangeness production as an indicator for quark–gluon plasma formation, as put forward after many years by Rafelski.

The book is undoubtedly an ideal companion to all those who wish to recall the birth of one of the main areas of today’s concepts in high-energy physics, and it is definitely a well-deserved credit to one of the great pioneers in their development.

Flrhtjof Karsch, Bielefeld University, Germany.
Research time-line: Quarks $\rightarrow$ QGP formation in RHICollision

- **Cold quark matter in diverse formats from day 1: 1965**
  D.D. Ivanenko and D.F. Kurdgelaidze, *Astrophysics* 1, 147 (1965)
  *Hypothesis concerning quark stars*

- **Interacting QCD quark-plasma: 1974**
  *Quarkium: a bizarre Fermi liquid*

- **Formation of quark matter in RHI collisions: 1978**
  Conference talks by Rafelski-Hagedorn (CERN)
  Unpublished document (MIT web page) Chapline-Kerman

- **Hot interacting QCD QGP: 1979 (first complete eval!)**
  J. Kapusta, *Nucl. Phys. B* 148, 461 (1979)*QCD at high temperature*

- **Formation of QGP in RHI collisions 1979-80**
  CERN Theory Division talks etc Hagedorn, Kapusta, Rafelski, Shuryak

- **Experimental signature:**
  **Strangeness and Strange antibaryons 1980**
  Rafelski (with Danos, Hagedorn, Koch (grad student), Müller

- **Statistical materialization model (SHM) of QGP: 1982**
  Rafelski (with Hagedorn, Koch(grad student), Müller
First strangeness signature 1980: ratio of $\bar{s}/q$ in $\Lambda/\bar{p}$

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\frac{\bar{s}}{q} = \frac{1}{2} \left( \frac{m_{s}}{T} \right)^{2} K_{2} \left( \frac{m_{s}}{T} \right) e^{\frac{e^{3}T}{3}}$$

The function $x^{2}K_{2}(x)$ is, for example, tabulated in Ref. 15. For $x = m_{s}/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/q > 5$. As $T \to 0$ there are about as many $\bar{u}$ and $\bar{d}$ quarks as there are $\bar{s}$ quarks.

Johann Rafelski, and Rolf Hagedorn, “From hadrons to quark matter II,” *Statistical mechanics of quarks and hadrons* proceedings of Bielefeld, August 24-31, 1980 / edited by Helmut Satz

Cooking strange quarks $\rightarrow$ strange antibaryons
A first meeting September 1988 with RHI data

it Hadronic Matter in Collision, Tucson, September 1988 – in the picture Wit Busza, Marek Gazdicki, Roy Glauber, Mark Gorenstein, Hans Gutbrod, Berndt Muller, Stanislaw Mrowczynski, Emanuele Quercigh, Chris Quigg, Jan Rafelski, Gena Zinoview, and many more, and some who are in our memory: Peter Carruthers, Mike Danos, Maurice Jacob, Bob Thews, Leon VanHove.
From $T_h$ to RHI collisions

Strangeness

Quark-gluon plasma discovery buzz

SHM data analysis

Phase diagram and the horn

Joint MG+JR S+S analysis paper 1994: features $\frac{\Lambda}{\bar{p}}$

$\frac{\Lambda}{\bar{p}}$-ratio near midrapidity in proton-proton, minimum bias proton-nucleus and central nucleus-nucleus collisions at 200 GeV per nucleon as a function of the rapidity density of negatively charged hadrons at midrapidity.

Chemical freeze-out conditions in central S-S collisions at 200 $A$ GeV

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Strangeness and QCD Phase Diagram
Largest medium effect: Strange antibaryons
Origin: Strangeness density at hadronization high strangeness abundance doubled

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Relevance: Cosmology Connection to Relativistic Heavy Ion Collisions

- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

Theory connects RHI collision experiments to Universe
The Universe Composition Changes

dark energy matter radiation $\nu, \gamma$ leptons hadrons

$\Rightarrow$ Different dominance eras
Global view on many properties observed

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.
CERN RHI experimental SPS program spans a wide range of observables
9AM, 18 April 2005; US – RHIC announces QGP
Press conference APS Spring Meeting

New signatures show today a flow and quench smooth from SPS to RHIC to Alice: There is one and the same deconfined state of quarks and gluons
LHC-Alice enters:

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.
From $T_H$ to RHIC collisions  
**Strangeness**  
Quark-gluon plasma discovery buzz  
**SHM data analysis**  
Phase diagram and the horn

(FERMI-KOPPE) **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: SINCE

- **Hagedorn**: Large number of particles: use ensemble average energy $E \rightarrow T$ AND

- With hesitance use in $pp$ collisions of ensemble average over particles $N \rightarrow \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

- **Rafelski-Danos**: (PLB 97, 279 (1980)) canonical suppression when particle numbers (strangeness) small

Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra. IMPLEMENTATION: SHARE G. Torrieri et al, Comput. Phys. Commun. 167, 229 (2005), ibid 175, 635 (2006) ibid 185, 2056 (2014)
QGP+ Statistical Hadronization Model
= Hadron Gas Abundances without Hadron Gas

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

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 'oldfashioned' 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...
Data analysis 2003-2008 as a function of $\sqrt{s_{NN}}$ and $A$

Left: Energy dependence; Right: Centrality dependence

Interest in (thermal) energy cost of strangeness pair $E/s$ as it should show appearance of a more effective strangeness production reaction mechanism. See EPJA 35, 221 (2008) & PRC 72, 024905 (2005), ibid 73, 014902 (2006)
AGS, SPS, RHIC bulk properties $\rightarrow$ Fit to ALICE data

Strangeness and QCD Phase Diagram
COMPARISON ACROSS ENERGY
SPS-RHIC-LHC: SHM PARAMETERS

\[ T \text{ [MeV]} \]
\[ \chi_\text{q} \]
\[ \mu_\text{B} \text{ [MeV]} \]
\[ \chi_\text{s} \]

\( \sqrt{s} \text{ [GeV]} \)

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Strangeness and QCD Phase Diagram
Consistency with Lattice-QCD

Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, $T$-SHM is the QGP source temperature, there cannot be full chemical equilibrium.
Strangeness enhancement: relative to entropy $s/S$

Relative $s/S$ yield measures the number of relaxed active degrees of freedom and the degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{g_s}{2\pi^2} T^3 \left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) \left(\frac{g_s n_f}{6}\right) \mu_q T \sim \frac{1}{35} = 0.029$$

much of $O(\alpha_s)$ interaction effect largely cancels out, estimate of effect raises ratio $s/S \to 1/31 = 0.0323$. Now introduce QGP nonequilibrium

$$\frac{s}{S} = \frac{0.03 \gamma_s^{QGP}}{0.4 \gamma_G + 0.1 \gamma_s^{QGP} + 0.5 \gamma_q^{QGP} + 0.05 \gamma_q^{QGP} (\ln \lambda_q)^2} \to 0.03 \gamma_s^{QGP}.$$
Two phases

**Marek’s Discovery: The HORN is doing well today**

Evidence of drastic change in matter properties – far from equilibrium hadrons turn at the peak into a quark-gluon plasma ball in near equilibrium. Use of non-equilibrium physics essential in understanding the Horn and understanding the threshold of QGP formation.
Use of nonequilibrium and the rôle of $s/S = \text{strangeness/multiplicity}$

To describe the horn we need $\gamma_q \neq 1$

Looking at the fit $\chi^2$ we see that between 20 and 30 GeV results favor that $\gamma_q$ jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The individual fits relevant to understanding how the horn is created have good quality - see $P$%. 

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Interaction measure/trace anomaly

SHM measured trace anomaly for LHC-Alice, fit results as function of centrality. The top band obtained with $\gamma_q > 1$, bottom lines assuming $\gamma_q = 1$, correspond to a hadron resonance gas (HRG) value. Right: Lattice QCD trace anomaly as function of a temperature parameter from, Borsanyi 2013 Loc. Cit.
Our future: exploration of the phases of QGP in $T, \mu_B$

![Graph showing the QCD phase diagram with regions for LHC, RHIC, SPS, FAIR, and the transition between Hadron Gas and QGP.](image)
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 the fundamental phase of quarks and gluons – the QGP.

▶ Global effort to discover QGP - followed. I speak for my expertise: Strangeness played a pivotal role, confirmed; QGP consistency. Some people will keep arguing mainly for lack of information: . . .

▶ . . . overall there is little doubt that the totality of evidence is evidence for a Strange-rich QGP phase of primordial matter; each small item in the long list can be explained in some other way but all of the list emerges in a simple new paradigm.

▶ In near future fixed target program at RHIC using well developed detectors can scan baryon rich deconfined phase of matter. Discoveries will determine where the field goes.