Strangeness Production and Quark Gluon Plasma Properties

September 22, 2011, SQM2011–Krakow, Poland

A historical perspective: The formation and study of strangeness rich quarkgluon plasma offers opportunity to explore the enigmatic aether, the quantum vacuum structure subject to strong interactions, and to probe the nature of the Universe 30 microsecond after the big-bang. Strangeness is intimately connected to gluons, the specific agents that characterize quantum chromodynamics, the theory of strong interactions. The fate of strangeness following on quark-gluon plasma break-up offers us a unique opportunity to investigate how matter was created in the early Universe, and to study strangeness rich matter in the lab. This talk aims to both show what we learned today after 30 years of effort, and where we are heading tomorrow.

Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318

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Four Pillars of QGP/RHI Collisions Research Program

RECREATE THE EARLY UNIVERSE IN LABORATORY:

Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about $30 \mu s$ after big bang.

QGP-Universe <u>hadronization</u> led to nearly matter-antimatter symmetric state, the later ensuing matter-antimatter annihilation leaves behind as our world the 10^{-10} matter asymmetry.

STRUCTURED VACUUM-AETHER (Einsteins 1920+ Aether/Field/Universe)

The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum from <u>hadronic matter</u> ground state to <u>quark matter</u> ground state, and finding the changes in laws of physics.

ORIGIN OF MASS OF MATTER –(DE)CONFINEMENT

The confining quark vacuum state is the origin of 99.9% of mass, the Higgs mechanism applies to the remaining 0.1%. We want to show that the quantum zero-point energy of confined quarks is the mass of matter. To demonstrate we 'melt' the vacuum structure setting quarks free.

ORIGIN OF FLAVOR

Normal matter made of first flavor family (u, d, e, ν_e) . Strangeness rich quark-gluon plasma the lonly laboratory environment about one-third filled with 2nd family matter (s, c, μ, ν_{μ}) – potential to unravel the secret of flavor.

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Stages in the evolution of the Universe



Aether 1920

Albert Einstein at first rejected æther as unobservable when formulating special relativity, but eventually changed his initial position, re-introducing what is referred to as the 'relativistically invariant' æther. In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, L. Kostro, Apeiron, Montreal (2000). he writes:

It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities.



In a lecture published in May 1920 (given on 27 October 1920 at Reichs-Universität zu Leiden, addressing H. Lorentz), published in Berlin by Julius Springer, 1920, also in Einstein collected works: In conclusion:

... space is endowed with physical qualities; in this sense, therefore, there exists an æther. According to the general theory of relativity space without æther is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this æther may not be thought of as endowed with the quality characteristic of ponderable media, as (NOT) consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

Reminder: Three Generations of Matter

In QGP we excite Generation II – opportunity for new physics?



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Challenge:QGP has fleeting presence in laboratory Discover / Diagnosis / Study properties at 10^{-23} s scale

- Diletpons and photons: weakly coupled probes report all of history of collision, including the initial moments (!) – hampred by a large background of decaying hadrons
- J/Ψ suppression: one measurement, ongoing and evolving interpretation
- \bullet Jet suppression: in essence demonstration of radiation reaction at critical acceleration.
- Dynamics of quark matter flow: demonstrates presence of collective quark matter dynamics
- Strange strongly interacting probes provide image of the last few-fm/c of QGP expansion/hadronization:
 - Strangeness to entropy ratio enhancement (decepest probe)
 - Strange antibaryon enhancement (hadronization model, remote sensing)
 - Strange resonances (after life of matter)
 - Heavy flavor (c, b) with strangeness (towards flavor riddle) censored

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Relativistic Heavy Ions - the Beginning

Developments at CERN

G. COCCONI ion Européenne pour la Recherche Nucléaire, Geneva, Switzerland

, a group belonging to the Proton Synchrotron Division is preparing a two-year study on polarized beam and light-ion acceleration in the raft will be ready at the beginning of 1975). Injection into the PS of s becoming compatible with that of ordinary protons because, within npletion of the new linac will leave free the 50-MeV linac that is now into the PS. Another incentive for this project is that at CERN there of transferring the particles accelerated in the PS to the intersecting SR) and eventually to the 400-GeV superconducting PS. This enubly the scope of the experimental program. In Table 1 are given the present considered realistic for the PS and the ISR for fully stripped s have yet been made for the acceleration of heavy ions. If approved t could lead to usable beams before 1980.

Table 1 Luminosity of Fully Stripped Nuclei in PS and ISR PS ISR [equiv. lab $E \leq 2000(q/e)^2/A$ GeV] (≤28q/e GeV) Luminosity, cm⁻² sec⁻¹ Interaction rate, sect, cm² Particles/pulse -25.51012.5 1031 105.5 -25.5 1010 1027 101.5 101.5 -24.5 109.5 1026 -24 109 1025 101 nance.



I arrive at CERN in September 1977 as Theory Fellow. Stay under 3 years, work to create the Relativistic Heavy Ion Program at CERN and learn high-T strong interactions: statistical bootstrap and QCD.

QUARKM. TTER--NUCLEAR MATTER

The fusion of constituents of protons and neutrons -- quarks -to quarkmatter is expected to form a new phase of nuclear matter. Based on our recent theoretical work this is expected to occur at temperature and density accessible to experimental study.

Fachbereich Physik der Johann Wolfgang Goethe-Universität Frankfurt am Main

Einladung

zu der öffentlichen Antrittsvorlesung des Herrn

Prof. Dr. Johann Rafelski

über das Thema

"Quarkmaterie – Kernmaterie"

Das Verschmelzen der Bestandteile der Protonen und Neutronen – der Quarks – zur Quarkmaterie, einer neuen Phase der Kernmaterie wird aufgrund von neuesten theoretischen Ar¹⁻ten in einem experimentell zugänglichen Druck und Temperaturbereich erwartet.

am Mittwoch, dem 18. Juni 1980, 17 Uhr c. t.

im Hörsaal des Instituts für Angewandte Physik

Frankfurt am Main, Robert-Mayer-Straße 2-4

Die Vorlesung findet im Rahmen des Physikalischen Kolloquiums statt.

Der Dekan: Prof. Dr. Werner Martienssen

Quarkmatter and strangeness arrives in Frankfurt June 18, 1980

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Strangeness: A signature of QGP and Deconfinement

In order to observe properties of quark-gluon plasma we must design a thermometer, an isolated degree of freedom weakly coupled to the hadronic matter. Nature has, in principle (but not in praxis) provided several such thermometers: leptons and heavy flavours of quarks. We would like to point here to a particular phenomenon perhaps quite uniquely characteristic of quark matter; first we note that, at a given temperature, the quark-gluon plasma will contain an equal number of strange (s) quarks and antistrange (\ddot{s}) quarks, naturally assuming that the hadronic collision time is much too short to allow for light flavour weak interaction conversion to strangeness. Thus, assuming equilibrium in the quark plasma, we find the density of the strange quarks to be (two spins and three colours):

$$\frac{s}{V} = \frac{\overline{s}}{V} = 6 \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{p^2 + m_s^2}/T} = 3 \frac{T_0 m_s^2}{\pi^2} K_2 \left(\frac{m_s}{T}\right)$$
(26)

(neglecting, for the time being, the perturbative corrections and, of course, ignoring weak decays). As the mass of the strange quarks, m_s , in the perturbative vacuum is believed to be of the order of 280-300 MeV, the assumption of equilibrium for $m_s/T \sim 2$ may indeed be correct. In Eq. (26) we were able to use the Boltzmann distribution again, as the density of strangeness is relatively low. Similarly, there is a certain light antiquark density (\bar{q} stands for either \bar{u} or \bar{d}):

$$\frac{\bar{q}}{\bar{V}} \approx 6 \int \frac{d^3 \rho}{(2\pi)^3} e^{-|\rho|/T - \mu_1/T} = e^{-\mu_0/T} T^3 \frac{6}{\pi^2}$$
(27)

where the quark chemical potential is, as given by Eq. (3), $\mu_q = \mu/3$. This exponent suppresses the $q\bar{q}$ pair production as only for energies higher than μ_q is there a large number of empty states available for the q.

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



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



J. R. & R. Hagedorn, CERN-TH-2969, Oct.1980 From Hadron gas to Quark Matter

 $\bar{s}/\bar{q} \rightarrow K^+/\pi^+$, and strange antibaryons $\bar{s}/\bar{q} \rightarrow \bar{\Lambda}/p$ are proposed as signatures of deconfined QGP phase, matter-antimatter symmetry.

Chemical equilibrium in QGP is presumed in the argument.

First Challenge: Rolf Hagedorn, private communicationHow come equilibrium thermal particle abundance $n \propto e^{-m/T}$ production/annihilation rate $R \propto e^{-2m/T}$, this inconsistency needed to be understood to make the thermal equilibrium model work: "The Importance of theReaction Volume in Hadronic Collisions" J. Rafelski,& M. Danos, Print-80-0709,Sep 1980, Phys.Lett.B97:279,1980.

 Volume 97B, number 2
 PHYSICS LETTERS
 EDecember 1980

 THE IMPORTANCE OF THE REACTION VOLUME IN HADRONIC COLLISIONS

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 and

 Michael DANOS

 National Bureau of Standards, Washington, DC 20234, USA

 Received 10 October 1980

The pair production in the thermodynamic model is shown to depend sensitively on the (hadronic) reaction volume. Strangeness production in nucleus—nucleus collisions is treated as an example.



Fig. 2. Comparison of the quenching factors for hadronic and

One of the authors (J.R.) thanks R. Hagedorn for bringing the problem of the reaction volume to his attention, and for many discussions.

References

- R. Hagedorn and J. Ranft, Supp. Nuovo Cimento 6 (1968) 169;
- R. Hagedorn, Cargese Lectures in Physics, Vol. 6 (Gordon and Breach, New York, 1973).
- [2] R. Hagedorn, Lectures on the thermodynamics of strong interactions, CERN Report 71-12 (1971).
- [3] R. Hagedorn and J. Rafelski, Phys. Lett. 97B (1980) 136; Phys. Rep. to be published.



Mike Danos

Result generalized from U(1) conservation group (charge, strangenes, baryon number) to nonabelian compact group (isospin, color),

. "Quantum Gases With Internal Symmetry" L. Turko, CERN-TH-3082, May 1981. Phys.Lett.B104:153,1981.

Second Challenge: Biro-Zimanyi

230 書室

KFKI-1981-69.

It is clear from Fig.2 that the possible lifetime of quark-gluon plasma itself is far less than the time necessary for chemical equilibration between strange and non strange quarks.

An interesting feature of the relaxation time, \mathcal{T} , given in eq. (8) is that it does not depend on the density but on the temperature of the quark-gluon plasma ball only.

Finally we want to emphasize again that all of our considerations are based on the applicability of the <u>perturbative</u> QCD for the description of the plasma ball. Even in this case the relaxation time may change appreciably from the value given here if one uses other values for the rest mass of the strange quark and /or for the coupling constant. Here T is inversely proportional to α^2 and it shows a qualitatively exponential dependence on the strange quark, mass, as $\exp\left(\frac{2}{3} \mathrm{Ms}\right)$.

The authours are indebted to J. Kuti and V. Gribov for many enlightening and helpful discussions.



Nearly exactly 30 years ago, in late September 1981, preprint circulates claiming conversion of light quarks to strangeness is much too slow to achieve in QGP the desired chemical equilibrium.

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chemical equilibration time for gluons and light marks is found to be less than 10^{-31} and

Response: in QGP strangeness production by gluon fusion

In this moment of crisis I needed to find help fast and it so happened that Berndt Muller was willing to drop everything else to help. Serendipidity was on our side: I shared an office at CERN 1977-79 with Brian Combridge who invented the mechanisms of perturbative QCD charm production, showing glue based process dominated – Berndt and I used Brian's cross sections to compute the thermal invariant rates and prove that equilibration of strangenees in QGP is in experimental reach.

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Berndt Müller

,



The generic angle averaged cross sections for (heavy) flavor s, \bar{s} production processes $g + g \rightarrow s + \bar{s}$ and $q + \bar{q} \rightarrow s + \bar{s}$, are:

$$\bar{\sigma}_{gg \to s\bar{s}}(s) = \frac{2\pi\alpha_{\rm s}^2}{3s} \left[\left(1 + \frac{4m_{\rm s}^2}{s} + \frac{m_{\rm s}^4}{s^2} \right) \tanh^{-1}W(s) - \left(\frac{7}{8} + \frac{31m_{\rm s}^2}{8s} \right) W(s) \right]$$
$$\bar{\sigma}_{q\bar{q} \to s\bar{s}}(s) = \frac{8\pi\alpha_{\rm s}^2}{27s} \left(1 + \frac{2m_{\rm s}^2}{s} \right) W(s) \,. \qquad W(s) = \sqrt{1 - 4m_{\rm s}^2/s}$$

QCD resummation: running α_s and m_s taken at the energy scale $\mu \equiv \sqrt{s}$. USED: $m_s(M_Z) = 90 \pm 20\%$ MeV (perhaps too large since $m_s(1 \text{GeV}) \simeq 2.1 m_s(M_Z) \simeq 200 \text{MeV}$.

Perturbative production of strangeness works for SMALL enough $\alpha_s^{(4)}(\mu)$ An essential pre-requirement for the perturbative theory of strangeness production in QGP, is the relatively small experimental value $\alpha_s(M_Z) \simeq 0.118$, which has been experimentally established in recent years.



 $\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.1182$ (experimental point, includes the error bar at $\mu = M_Z$).

Had $\alpha_s(M_Z) > 0.125$ been measured instead of $\alpha_s(M_Z) = 0.118$ than our 1981/82 perturbative strangeness production approach would have been in question.

Thermal average of (strangeness production) reaction rates Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p_1}, T)$ to obtain average rate:

$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3 p_1 \int d^3 p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3 p_1 \int d^3 p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} \,.$$

Invariant reaction rate in medium:

$$A^{gg \to s\bar{s}} = \frac{1}{2} \rho_g^2(t) \left\langle \sigma v \right\rangle_T^{gg \to s\bar{s}}, \quad A^{q\bar{q} \to s\bar{s}} = \rho_q(t) \rho_{\bar{q}}(t) \left\langle \sigma v \right\rangle_T^{q\bar{q} \to s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \rho_{\bar{s}}(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{q}}, \quad A^{s\bar{s} \to gg, q\bar{q}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s} \to gg, q\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to gg, q\bar{s}} = \rho_s(t) \left\langle \sigma v \right\rangle_T^{s\bar{s}}, \quad A^{s\bar{s} \to$$

 $1/(1+\delta_{1,2})$ introduced for two gluon processes compensates the double-counting of identical particle pairs, arising since we are summing independently both reacting particles.

This rate enters the momentum-integrated Boltzmann equation which can be written in form of current conservation with a source term

$$\partial_{\mu}j^{\mu}_{s} \equiv \frac{\partial\rho_{s}}{\partial t} + \frac{\partial\vec{v}\rho_{s}}{\partial\vec{x}} = A^{gg \to s\bar{s}} + A^{q\bar{q} \to s\bar{s}} - A^{s\bar{s} \to gg,q\bar{q}}$$

Strangeness relaxation to chemical equilibrium Strangeness density time evolution in local rest frame:

$$\frac{d\rho_s}{d\tau} = \frac{d\rho_{\bar{s}}}{d\tau} = \frac{1}{2}\rho_g^2(t) \langle \sigma v \rangle_T^{gg \to s\bar{s}} + \rho_q(t)\rho_{\bar{q}}(t) \langle \sigma v \rangle_T^{q\bar{q} \to s\bar{s}} - \rho_s(t) \rho_{\bar{s}}(t) \langle \sigma v \rangle_T^{s\bar{s} \to gg, q\bar{q}}$$

Evolution for s and \bar{s} identical, which allows to set $\rho_s(t) = \rho_{\bar{s}}(t)$. characteristic time constant τ_s :



Dominant uncertainty: mass of strange quark (wide range indicated). Dotted - fixed value $\alpha_s = 0.6$ used in 1981/2



"Strangeness chemical equilibration in QGP at RHIC and CERN LHC" Jean Letessier, & Johann Rafelski Phys.Rev.C75:014905,2007. nucl-th/0602047 LHC differences to RHIC

• There is a significant increase in initial temperature and gluon occupancy γ_g to accommodate increased initial pre-thermal evolution entropy.

• There is a about twice longer expansion time to the freeze-out condition, since there is 4 times entropy content at similar hadronization T_h .

• There is over saturation of s/S, γ_s in QGP, and thus a much greater over-saturation in hadron phase space (for $T_h < 240 \text{ MeV}$)

NOTE: s/S measures chemical equilibration in QGP.

What happens with antistrange quarks?

PHYSICS REPORTS (Review Section of Physics Letters) 88, No. 5 (1982) 331–347. North-Holland Publishing Company UFTP-80-1982, Mar 1982. 26pp. Invited lecture given at 17th Rencontre de Moriond on Elementary Particle Physics, Les Arcs, France, Mar 14-26, 1982. Published in Phys.Rept.88:331,1982 (special volume edited by Maurice Jacob).

2. Formation and Observation of the Quark-Gluon Plasma*

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One can study how much more total strangeness is found in the quark-gluon plasma as compared to the hadronic gas phase. While the total yields are up to 5–7 times higher (again depending on some parameters) it is more appropriate to concentrate attention on those reaction channels which will be particularly strongly populated when the quark plasma dissociates into hadrons. Here in particular, it appears that the presence of quite rare multistrange hadrons will be enhanced, first because of the relative high phase space density of strangeness in the plasma, and second because of the attractive ss-OCD interaction in the $\bar{3}_c$ state and $\bar{s}s$ in the 1_c state. Hence one should search for an increase of the abundances of particles like $\Xi, \Xi, \Omega, \overline{\Omega}, \phi$ and perhaps for highly strange pieces of baryonic matter, rather than in the K-channels. However, it appears that already a large value for the \overline{A}/A ratio would be

PROCEEDINGS OF THE 6th HIGH ENERGY HEAVY ION STUDY AND 2nd WORKSHOP ON ANOMALONS

Lawrence Berkeley Laboratory, University of California June 28 – July 1, 1983

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	CECCION VIII. FINIAI CECCION

It was difficult to publish in refereed journals on strangeness. Quarks were exotic, QGP was $(exotic)^2$, and strangeness in QGP was $(exotic)^3$. First paper by Peter Koch(-Steinheimer) on statistical hadronization model took two years from submission in one journal to publication in another. In my private archive I keep the transparencies from the LBL 6th Heavy Ion Study where I presented individual particle vields, given the high strange and multistrange anti-baryon yield there was general laughter, my lecture termed a 'fantasy' and in proceedings pushed into "Exotica session" of the proceedings far below "anomalons".

On the Way to Experiment

Hadron Chemistry

"Strange hadron in hot nuclear matter" Peter Koch, Johann Rafelski, W. Greiner, (Frankfurt U.). Published in Phys.Lett.B123:151-154,1983.

Kinetic Theory of Strangness Production in Confined MatterStrange Antibaryon CHALLENGE

Time Evolution Of Strange Particle Densities In Hot Hadronic Matter. Peter Koch, Johann Rafelski, (Cape Town U.). UCT-TP 22/85, Dec 1984. 60pp. Published in Nucl.Phys.A444:678,1985.

Statistical Hadronization Model:

"Why the Hadronic Gas Description of Hadronic Reactions Works: The Example of Strange Hadrons." Peter Koch, Johann Rafelski, (Cape Town U.). UCT-TP-26-2-1985, Apr 1985. 50pp. Published in South Afr.J.Phys.9:8,1986.

Quark-Recombinant (with Fragmentation) Hadron Production:

"Strangeness in Relativistic Heavy Ion Collisions" Peter Koch, Berndt Muller, Johann Rafelski, (Cape Town U. & Frankfurt U. & Darmstadt, GSI) . GSI-86-7, UCT-TP-41-86, UCT-TP-29-1985, Feb 1986. 180pp. Published in Phys.Rept.142:167-262,1986.

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Pete Carruthers HADRONIC MATTIN IN COLLISION 1988

Tucson, Arizona, USA October 6-12, 1988

Editors: P. Carruthers & J. Rafelski

World Scientific

Strange Antibaryon CHALLENGE

Around mid 1985 Howell Pugh, in midst of preparation for CERN experiments, called me in Cape Town. Joe Kapusta has shown that hadronization of QGP took 50-100 fm/c. According to Miklos Guylassy the strange antibaryon enhancement could never happen since strange antibaryons would annihilate in Kapusta's mixed phase. "He (Miklos) thinks the entire strangeness topic was dead". And if so, the bet placed by the LBL nuclear science by Howell on me (both NA35 and NA36 were mainly strangeness experiments) was bad.

I explained that we just completed a Physics Reports(Koch-Müller-Rafelski, 142 (1986) 167) which finds just the opposite. But that work was one drop in an ocean of contrary thaught.

From this challenge was born the realization that

1) spectra of baryons and antibaryons emerging from QGP differ only by normalization, while annihilation in hadron based kinetic models differentiates spectra of baryons and antibaryons, which like in pp reactions would be totally different: matter-antimatter spectra distinguish hadronization models (mostly forgotten by chemical equilibrium wishful thinkers.

2) that the production of antibaryons occurs from a central rapidity fireball.

MATTER-ANTIMATTER SPECTRAL SYMMETRY

Recombination hadronization implies symmetry of m_{\perp} spectra of (strange) baryons and antibaryons also in baryon rich environment.

CONVERSELY: spectral matter-antimatter symmetry implies; A common matterantimatter particle formation mechanism, AND negligible antibaryon re-annihilation/re-equilibration/rescattering.

Today: a nearly free-streaming particle emission by a quark source into vacuum also required by other observables: e.g. HBT particle correlation analysis pointing to a short emission time and relatively small volume of pion source



Analysis Method 'Statistical Model' Invented 1991

Volume 262, number 2.3

PHYSICS LETTERS B

20 June 1991

Strange anti-baryons from quark-gluon plasma

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Received 5 April 1991

Experimental results on strange anti-baryon production in nuclear $S \rightarrow W$ collisions at 200.1 GeV are described in terms of a simple model of an explosively disintegrating quark-lepton plasma (QGP). The importance of the strange anti-baryon signal for the identification of the QGP state and for the diagnosis of its properties is demonstrated.

..., and similar for $\overline{\Sigma}^0$. Thus comparing spectra of particles within overlapping regions of m_{\perp} we find for their respective ratios

$$R_{\Xi} = \frac{\overline{\Xi^{-}}}{\Xi^{-}} = \frac{\lambda_{d}^{-1} \lambda_{s}^{-2}}{\lambda_{d} \lambda_{s}^{2}}$$
$$= \exp(-2\mu_{s}/T) \exp(-4\mu_{s}/T) . \tag{4}$$

$$R_{\Lambda} = \frac{\bar{\Lambda}}{\Lambda} = \frac{\lambda_{d}^{-1}\lambda_{u}^{-1}\lambda_{v}^{-1}}{\lambda_{d}\lambda_{u}\lambda_{v}}$$

$$= \exp[-2(\mu_{\rm d} + \mu_{\rm u})/T] \exp(-2\mu_{\rm s}/T) .$$
 (5)

Ignoring isospin differences for the moment. $\lambda_u = \lambda_d =: \lambda_q$, we obtain

$$R_{\Lambda} = (\lambda_{\Lambda}/\lambda_{\rm q})^2 R_{\rm E} \,. \tag{6}$$

In QGP we have $\lambda_{1} = 1$, $\lambda_{q} > 1$, while in equilibrated.

---- Which implies

 $\mu_q/T = 0.46 \pm 0.08$, $\delta\mu_q/T = 0.041 \pm 0.007$.

We can use this result, together with $\mu_{n}=0$ and eq. (8), to predict the key strange anti-baryon ratios expected from primordial QGP (where as discussed above, $0 < \gamma \le 1$ characterizes the approach to absolute chemical equilibrium of strangeness):

$$\Xi^{-}/\bar{\Lambda} = \bar{\Lambda}/p = \gamma_{1}.55 \pm 0.13 ,$$

$$\Xi^{-}/\Lambda = \Lambda/p = \gamma_{0}.64 \pm 0.05 ,$$

$$\overline{\Omega^{-}}/\overline{\Xi^{-}} = \gamma_{1}.61 \pm 0.13 ,$$

$$\Omega^{-}/\overline{\Xi^{-}} = \gamma_{0}.62 \pm 0.05 .$$

Comparing with the first results on these ratios eq. (3), we can extract a first estimate of strange phase space saturation: $\frac{1}{2}\gamma = 0.4 \pm 0.2$. Here we used the strange anti-barson ratio, to avoid the systematic

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Emanuele Quercigh

m_T [GeV]

Why is the slope of baryons and antibaryons the same?

SUDDEN hadronization without rescattering.

page

Central Rapidity Fireball and QGP



Conclusion: by early 1990's we have convincing evidence of QGP formation at SPS energy heavy ion collisions including S-S. First antibaryon enhancement result, 1990-94, SPS-NA35II EXCESS $\overline{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions. From Yiota Foka, PhD Thesis, Geneva University 1994.



Strangeness QGP

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Building a Community

FI

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Hans Gutbrod

Particle Production in Highly Excited Matter

Edited by Hans H. Gutbrod and Johann Rafelski

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Strangeness QGP

September 22, 2011, SQM2011

Life NEVER easy: "Strange Thing"

STRANGE THING

you make my plasma thing you make everything confusing After my lecture on evidence of QGP given the strange antibaryon data this poem was composed in Il Ciocco, and I see here some of those who had fun on Rafelski in 1992.



Peter and

Jan

1993 Begins my Paris-Period

Hagedorn urges me to team up with his Paris friends Letessier and Tounsi to manage the data flow. After many years but with about 100 papers, one Book-monograph, several proceedings, this was my longest running engagement! Viva Jean Letessier! We build togather analysis tools and models that sourced in fierce competition with Francesco Becattini, Jean Cleymans,



Francesco Becattini, Jean Cleymans, Krzysztof Redlich, creating the contents we discuss today much of the time. The collaboration widened with arrival of Giorgio Torrieri, and soon we embraced Krakow (Wojtek)² and got SHARE, more on that to come!





1995 Begins 'Real' SQM

Strangeness QGP

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Marek 1995 in Tucson. Grazyna, Marek, Joe 2003 in NC 2003.

From QGP to Hadrons: Statistical Hadronization Model

= recombinant quark hadronization, main consequence: enhancement of flavored (strange, charm, bottom) antibaryons progressing with 'exotic' flavor content. Anomalous meson to baryon relative yields. Proposed 25 years ago, see review See: P. Koch, B. Muller and J. Rafelski, Strangeness In Relativistic Heavy Ion Collisions, Phys. Rept. 142, 167 (1986), and references therein.



- 1. $GG \rightarrow s\bar{s}$ (thermal gluons collide) $GG \rightarrow c\bar{c}$ (initial parton collision) $GG \rightarrow b\bar{b}$ (initial parton collision) gluon dominated reactions
- 2. RECOMBINATION of pre-formed $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

Formation of complex rarely produced multi flavor (exotic) (anti)particles enabled by coalescence between $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks made in different microscopic reactions; this is signature of quark mobility and independent action, thus of deconfinement. Moreover, strangeness enhancement = gluon mobility.

STATISTICAL HADRONIZATION

Hypothesis (Fermi, Hagedorn): particle production can be described by evaluating the accessible phase space.

Verification of statistical hadronization:

Particle yields with same valance quark content are in relative chemical equilibrium, e.g. the relative yield of $\Delta(1230)/N$ as of K^*/K , $\Sigma^*(1385)/\Lambda$, etc, is controlled by chemical freeze-out i.e. Hagedorn Temperature $T_{\rm H}$:



$$\frac{N^*}{N} = \frac{g^* (m^* T_{\rm H})^{3/2} e^{-m^*/T_{\rm H}}}{g (m T_{\rm H})^{3/2} e^{-m/T_{\rm H}}}$$

Resonances decay rapidly into 'stable' hadrons and dominate the yield of most stable hadronic particles.

Resonance yields test statistical hadronization principles.

Resonances reconstructed by invariant mass; important to consider potential for loss of observability.

HADRONIZATION GLOBAL FIT: \rightarrow

SHM is FERMI MODEL with QUARK CHEMISTRY If QGP near/at chemical equilibrium prior to fast hadronization we expect that emerging hadron multiplicites to be governed by parameters of ABSOLUTE chemical non-equilibrium described by phase spae occupancy γ ; Boltzmann gas: $\gamma \equiv \frac{\rho(T,\mu)}{\rho^{eq}(T,\mu)}$

<u>DISTINGUISH</u>: hadron 'h' phase space and QGP phase parameters: micro-canonical variables such as baryon number, strangeness, charm, bottom, etc flavors are continuous, and entropy is almost continuous across phase boundary:

$$\gamma_s^{\rm QGP} \rho_{\rm eq}^{\rm QGP} V^{\rm QGP} = \gamma_s^{\rm h} \rho_{\rm eq}^{\rm h} V^{\rm h}$$

Equilibrium distributions are different in two phases and hence are densities:

$$\rho_{\rm eq}^{\rm QGP} = \int f_{\rm eq}^{\rm QGP}(p) dp \neq \rho_{\rm eq}^{\rm h} = \int f_{\rm eq}^{\rm h}(p) dp$$

Another RELATIVE equilibrium:

FOUR QUARKS: $s, \overline{s}, q, \overline{q} \rightarrow$ FOUR CHEMICA

γ_i	controls overall abundance	Absolute chemical	HG production
	of quark $(i = q, s)$ pairs	equilibrium	
λ_i	$=e^{\mu_i/T}$ controls difference between	Relative chemical	HG exchange
		*1*1 *	
	strange and light quarks $(i = q, s)$	equilibrium	

See Physics Reports 1986 Koch, Müller, JR

Example of counting hadronic particles

The counting of hadrons is conveniently done by counting the valence quark content $(u, d, s, ..., \lambda_q^2 = \lambda_u \lambda_d, \ \lambda_{I3} = \lambda_u / \lambda_d)$:

$$\Upsilon_i \equiv \Pi_i \gamma_i^{n_i} \lambda_i^{k_i} = e^{\sigma_i/T}; \quad \lambda_q \equiv e^{\frac{\mu_q}{T}} = e^{\frac{\mu_b}{3T}}, \quad \lambda_s \equiv e^{\frac{\mu_s}{T}} = e^{\frac{[\mu_b/3 - \mu_s]}{T}}$$

Example of NUCLEONS $\gamma_N = \gamma_q^3$:

$$\Upsilon_N = \gamma_N e^{\frac{\mu_b}{T}}, \qquad \qquad \Upsilon_{\overline{N}} = \gamma_N e^{\frac{-\mu_b}{T}};$$

 $\sigma_N \equiv \mu_b + T \ln \gamma_N, \qquad \sigma_{\overline{N}} \equiv -\mu_b + T \ln \gamma_N$

Meaning of parameters from e.g. the first law of thermodynamics:

$$dE + P \, dV - T \, dS = \sigma_N \, dN + \sigma_{\overline{N}} \, d\overline{N}$$

 $= \mu_b(dN - d\overline{N}) + T \ln \gamma_N(dN + d\overline{N}).$

NOTE: For $\gamma_N \to 1$ the pair terms vanishes, the μ_b term remains, it costs $dE = \mu_B$ to add to baryon number.

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Baryon to Meson Ratio

Ratios $\overline{\Lambda}/K_S$ and \overline{p}/π in Au-Au compared to pp collisions as a function of p_{\perp} . The large ratio at the intermediate p_{\perp} region: evidence that particle formation (at RHIC) is distinctly different from fragmentation processes for the elementary e^+e^- and pp collisions.

To describe recombinant yields: non-equilibrium parameters needed

- $\gamma_q \ (\gamma_s, \gamma_c, \ldots)$: $u, d \ (s, c, \ldots)$ quark phase space yield, absolute chemical equilibrium: $\gamma_i \to 1$ $\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_c^2} \cdot \left(\frac{\gamma_s}{\gamma_q}\right)^n$
- γ_s/γ_q shifts the yield of strange vs non-strange hadrons:

$$\frac{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})}{\bar{p}(\bar{u}\bar{u}\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\mathrm{K}^+(u\bar{s})}{\pi^+(u\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2}, \qquad \frac{\Omega(sss)}{\Lambda(sud)} \propto \frac{\gamma_s^2}{\gamma_q^2},$$

GROUND LAID FOR MORE FORMAL AND DETAILED APPROACH:

J. Rafelski, Arizona

Statistical Hadronization fits of hadron yields

Full analysis of experimental hadron yield results requires a significant numerical effort in order to allow for resonances, particle widths, full decay trees, isospin multiplet sub-states.

Kraków-Tucson (and SHARE 2 Montreal) collaboration produced a public package SHARE Statistical Hadronization with Resonances which is available e.g. at http://www.physics.arizona.edu/~torrieri/SHARE/share.html

Lead author: Giorgio Torrieri nucl-th/0404083 Comp. Phys. Com. 167, 229 (2005) nucl-th/0603026 Comp. Phys. Com. 175, 635 (2006)



Wojtek Broniowski

Wojtek Florkowski

Giorgio Torrieri

SHARE can do REMOTE SENSING: CRITICAL PRESSURE



SHARE (Statistical Hadronization with REsonsnces) non-equilibrium fit made with SPS and RHIC data as function of energy AND the physical properties obtained summing all fractional contributions of different particles. Fit made on request of Marek Gaździcki, who wanted to see what his 'horn' means (ca 2004). Impossible to publish for 2 years. (Thanks to Tamas Biro for resurrecting the arXiv paper).

QGP and **HG** comparison: strangness / entropy

We compare strangeness per entropy (particle multiplicity) in deconfined quarkgluon plasma with hadron gas at a common measured T (Inga Kuznetsova). We expect hadron phase space to be oversaturated if QGP was equilibrated.



Strangeness to entropy ratio $s/S(T; \mu_B = 0, \mu_S = 0)$ for the chemically equilibrated QGP (green, solid line for $m_s = 160$ MeV, blue dash-dot line for $m_s = 90$ MeV); and for chemically equilibrated HG (red, dashed). The excess of SPECIFIC strangeness not assured if QGP not chemically equilibrated. However, since QGP is a high entropy and strangeness density phase, in absolute terms, there is both entropy and strangeness excess ALWAYS when QGP is formed.

Conclusions

- Strangeness fingerprints properties of QGP and demonstrates deconfinement
- Strangeness experimental results fulfill all our expectations: resounding confirmation of fast hadronization of quark-gluon plasma. – steady rise of s/Swith energy and centrality, expected enhancement of multistrange hadrons and strange antibaryons
- This requires strange quark mobility. Enhanced source of entropy content consistent with initial state thermal gluon degrees of freedom, expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast breakup of QGP.
- Evidence for CHEMICAL equilibration of the QUARK-GLUON phase at RHIC
- We can use (strange) hadron yields to learn about QGP properties at hadronization – remote 'sensing'

Conclusions II



Who is on=in the photo?