Probing QGP properties with strangeness

Jan Rafelski
Department of Physics, The University of Arizona, Tucson, AZ 85721
Seminar at Wroclaw, June 29, 2018

Beginning with the CERN SPS experiments 30 years ago we search for the understanding of how energy becomes matter, that is we study the hadronization of primordial phase of matter, quark-gluon plasma. Today the ALICE is the experiment at the CERN LHC build predominantly to study this process. The key information is derived in study of multistrange hadrons which carry information both, about the process of matter production (hadronization) $E \Rightarrow mc^2$, as well as about earlier stages when entropy and strangeness are produced. Very recent results show that even a relatively small pp and pA collisions at the LHC energy-scale are creating the new quark-gluon plasma (QGP) phase of matter.

Background: 1992 NATO School Il Ciocco Poster

What is special with RHI collisions & Quark Gluon Plasma?

1. 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 20 μs after the Big-Bang.
2. PROBING OVER A 'LARGE' DISTANCE THE (DE)CONFINING QUANTUM VACUUM STRUCTURE
   The quantum vacuum, the present day relativistic æther, determines prevailing form of matter and laws of nature.
3. STUDY OF THE ORIGIN OF MATTER & OF MASS
   Matter and antimatter created when QGP 'hadronizes'. Mass of matter originates in the confining vacuum structure
4. PROBE ORIGIN OF FLAVOR
   Normal matter made of first flavor family $(d, u, e, [\nu_e])$. Strangeness-rich quark-gluon plasma the sole laboratory environment filled 'to the rim' with 2nd family matter $(s, c, [\mu, \nu_\mu]))$. and considerable abundance of b and even t.
5. PROBE STRONGEST FORCES IN THE UNIVERSE
   For a short time the relativistic approach and separation of large charges $Ze \leftrightarrow Ze$ generates EM fields 1000's time stronger than those in Magnetars; strongfields=strong force=strong acceleration

Phases of hadronic matter have roots in this room

受入
79-4-32
高工研図書室

Ref.TH.2605-CERN

THERMODYNAMICS OF NUCLEAR MATTER FROM THE STATISTICAL BOOTSTRAP MODEL

R. Hagedorn, I. Montvay and J. Rafelski

CERN -- Geneva

Lecture given at the
Workshop on Theoretical Physics
"Hadronic Matter at Extreme Energy Density",
Erice -- October 13-21, 1978

Ref.TH.2605
16 December 1978

ABSTRACT

We study the properties of nuclear matter within the framework of a modified and generalized statistical bootstrap model in which the volume of a fireball grows with its mass. We find that the such described nuclear matter can exist in two phases. In particular we consider in a numerical example the high temperature ($T \lesssim T_0 \approx 150$ MeV) regime of the gaseous phase with a density of less than ~ 0.75 of normal nuclear density.

Phase Transitions in the Statistical Bootstrap Model with an Internal Symmetry

K. Redlich and L. Turko
Institute of Theoretical Physics, University of Wroclaw, Cybulskiego 36, 50-205 Wroclaw, Poland

Received 19 December 1979

Zeitschrift für Physik C Particles and Fields

© by Springer-Verlag 1980

Z. Physik C, Particles and Fields 5, 201–204 (1980)

Abstract. The connection between the statistical bootstrap model with an arbitrary symmetry group and the thermodynamical description of hadronic matter is considered. A relationship is given between an internal symmetry and the appearence of a multiphase structure.

Acknowledgement. One of the authors (L.T.) is very indebted to Professor R. Hagedorn for discussions and helpful comments.

References

1. R. Hagedorn: Nuovo Cimento Suppl. 3, 147 (1965)

First question; is there a fireball of matter?
Two extreme views on stopping in RHI collisions

Fly-through | full stopping

AL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

al collisions between heavy nuclei at extremely high energies: The fragmentation region

R. Anishetty*
Physics Department, University of Washington, Seattle, Washington 98195

P. Koehler and L. McLerran†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 11 August 1980)

We discuss central collisions between heavy nuclei of equal baryon number at extremely high energies. We make a crude estimation of the energy deposited in the fragmentation regions of the nuclei. We argue that the fragmentation-region fragments thermalize, and two hot fireballs are formed. These fireballs would have rapidities close to the rapidities of the original nuclei. We discuss the possible formation of hot, dense quark plasmas in the fireballs.

collisions of very-high-energy nuclei are to be the subject of intense experimental tigation in the next few years.

shall discuss the theory of such collisions in aper. We shall concentrate on describing al collisions between nuclei of equal baryon er.

The fragmentation regions of the nuclei represent an area of phase space where new phenomena might occur. "Fragmentation region" refers to the region of phase space of particles where the particles have longitudinal momentum close to that of the original nucleus projectile or target. In the fragmentation region, the nucleus fragments and inelastically produced particles might form a hot, dense fireball. We shall soon see that this forma-

Volume 97B, number 1 PHYSICS LETTERS 17 November

HOT HADRONIC MATTER AND NUCLEAR COLLISIONS ☆

R. HAGEDORN
CERN, Geneva, Switzerland

and

J. RAFELSKI [1]
CERN, Geneva, Switzerland
and Institut für Theoretische Physik der Uni
D-6000 Frankfurt a/M, Fed. Rep. Germany

Received 22 August 1980

we develop a description of hadronic matter with particular emphasis on hot nuclear matter as c in relativistic heavy ion collisions. We apply our theory to calculate temperatures and of hadronic

Transparency ⇐Two opposite views⇒ SPS-RHIC large stopping
LHC a nice fireball in all cases

Citations favor wrong paper: 272 vs 239 today

(Small System) Strangeness Enhancement and Canonical Hadronization Phase Space

For many details I recommend reading the 20 year old text

Hadrons and Quark–Gluon Plasma

Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (No. 18)

Jean Letessier
Université de Paris VII (Denis Diderot)

Johann Rafelski
University of Arizona

Hardback (ISBN-13: 9780521385367 | ISBN-10: 0521385369) Also available in Paperback | Adobe eBook

At CERN: Strangeness a popular QGP signature

I argued 1980-81 that anti-strangeness in QGP can be more abundant than anti-light quarks. Many experiments followed.

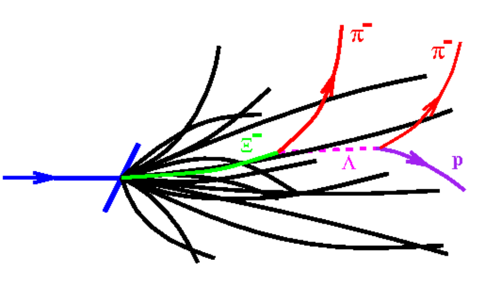
A: There are many strange particles allowing to study different physics questions $(q = u, d)$:

$$K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad K^*(890),\quad \Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),\quad \Lambda(1520)$$

$$\phi(s\bar{s}),\quad \Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\quad \Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

B: Production rates hence statistical significance is high.

C: Strange hadrons are subject to a self analyzing decay



Fulbright Flex researcher Johann Rafelski at Wigner Centre for Physics

Johann Rafelski from *The University of Arizona* in Tucson, USA, was awarded a Senior Flex Fulbright Fellowship to visit in Summer 2019 and 2020 the Wigner Research Centre for Physics in Budapest. Eugene Paul Wigner was a Hungarian-American theoretical physicist, engineer and mathematician who won Noble prize in 1963. The Wigner Institute is the largest Hungarian fundamental science research center where the research legacy of Prof. Wigner continues. Rafelski will be given the title "Distingusihed Wigner Professor" by this institute.

Rafelski's primary host is Prof. Tamás Biró, vice-director of the Institute for Particle and Nuclear Physics, incorporating half of the Wigner Centre. Prof. Rafelski is well known to the Hungarian Physics community, and this relation has roots that go back nearly 40 years, when the young Dr. Rafelski proposed "Strangeness Signature" of the primordial phase of matter, the quark-gluon plasma. At that time a bit younger graduate student Tamas Biro was charged by his supervisor Prof. Dr. Joseph Zimanyi to review Rafelski's ideas and to improve the mathematical-theoretical description. The effort of Biro and Zimanyi helped Rafelski to refine his proposal further which became one of the corner stones of the research field where, since then, a few thousand scientists perform experiments at largest particle colliders simulating the Big-Bang conditions in the laboratory.

A low level connection of Rafelski with Budapest continued for the following decades. For example after Rafelski started the new conference series "Strangeness in Quark Matter", within a few years in late '90s the meeting took place in Budapest. However, a direct collaborative research effort of Rafelski and Biro did not occur even though both work in parallel to this day in several research fields. This possibility has been opened now by the Fulbright Flex Program.

(C) Hungarian-American Fulbright Commission

Both researchers seen in the picture came to visit the Fulbright office in Budapest during a preparatory visit June 19, 2018 (Rafelski on right). They are looking forward to a fruitful and rewarding joint effort addressing the most intriguing current questions in the area of fundamental theoretical physics.

Instant success of strangeness signature proposal

First strangeness signature 1980: ratio of $\bar{s}/\bar{q}$ in $\overline{\Lambda}/\bar{p}$ triggers Marek's strange interest!

CPOD, WROCLAW, June 2, 2016

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

$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T} \qquad (23)$$

The function $x^2K^2(x)$ 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, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

FROM HADRON GAS TO QUARK MATTER II

J. Rafelski

Institut für Theoretische Physik der Universität Frankfurt

and

R. Hagedorn

CERN--Geneva

Ref.TH.2969-CERN

13 October 1980

80-12-212

高工研図書室

ABSTRACT

We describe a quark-gluon plasma in terms of an many questions remain open. A signature of the quark-gluon phase surviving hadronization is suggested.

In *Statistical mechanics of quarks and hadrons* proceedings Bielefeld, August 24-31, 1980

picked up by Marek in Dubna . . .

REFERENCES

1. G.Chapline et al. Phys.Rev., 1975, D8, p. 4302; R.Hagedorn. Preprint CERN, TH. 3207, Geneva, 1981.
2. J.Rafelski. Preprint UFTP, 1982, 80/82 and 86/82; M.I.Grenstein, G.M.Zinovjev. Preprint ITP-82-109E, Moscow 1982.
3. J.W.Harris et al. Phys.Rev.Lett., 1981, 47, p. 229.
4. M.Anikina et al. JINR, P1-82-333, Dubna, 1982.
5. N.Akhababian et al. JINR, D1-82-445, Dubna, 1982.
6. M.Anikina et al. International Conference on Nucleus-Nucleus Collisions, Michigan, 1982, (abstract); E.Okonov. JINR, D2-82-568, Dubna, 1982.
7. A.Abdurakhimov et al. Nucl.Phys., 1981, A362, p. 367.
8. M.Anikina et al. Z.Phys., 1981, C9, p. 105.

Received by Publishing Department on July, 20, 1983.

4

Anikina M. et al. E1-83-521

A Study of Λ-Production in Central Nucleus-Nucleus Interactions at a Momentum of 4.5 GeV/c Per Incident Nucleon

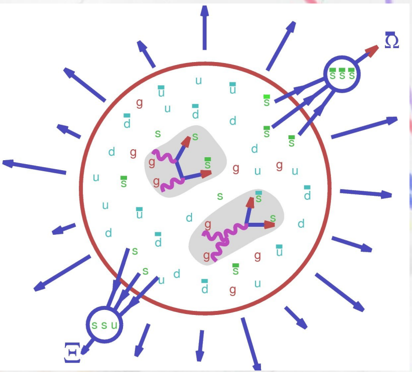
Transverse momenta and rapidities of Λ's produc leus-nucleus collisions at 4.5 GeV/c per nucleon /CC , CZr , CPb , OPb/ have been studied and compared with t He-Li interactions at the same incident momentum. Pola hyperons was found to be consistent /within the errors/ (αP_{Λ} = -0.06 ±0.11) for 224 Λ's from central collis of $\bar{\Lambda}/\Lambda$ production ratio was estimated to be less than confidence level.

The analyzed experimental data were obtained usin 2 m streamer spectrometer SKM-200.

The investigation has been performed at the Labora Energies, JINR.

Communication of the Joint Institute for Nuclear Resear

Strange hadrons from QGP: two-step formation mechanism

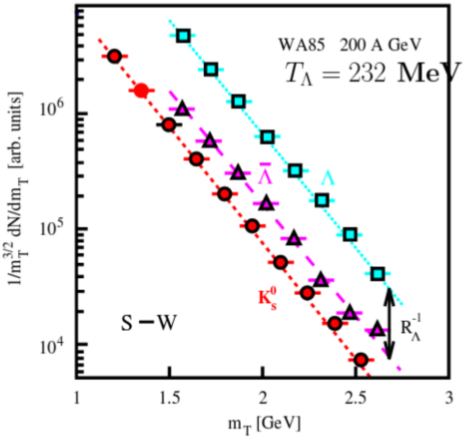


1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed
   $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

Evaporation-recombination formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP is signature of quark mobility thus of deconfinement. Enhancement of flavored (strange, charm,. . .) antibaryons progressing with 'exotic' flavor content. J. Rafelski, *Formation and Observables of the Quark-Gluon Plasma* Phys.Rept. **88** (1982) p331; P. Koch, B. Muller, and J. Rafelski; *Strangeness in Relativistic Heavy Ion Collisions*, Phys.Rept. **142** (1986) p167

Anticipated: Sudden hadronization of QGP
Proposed evidence: matter-antimatter symmetry

High $m_\perp$ slope universality



SUDDEN hadronization without rescattering.

Discovered in S-Pb collisions by WA85, very pronounced in Pb-Pb Interactions.

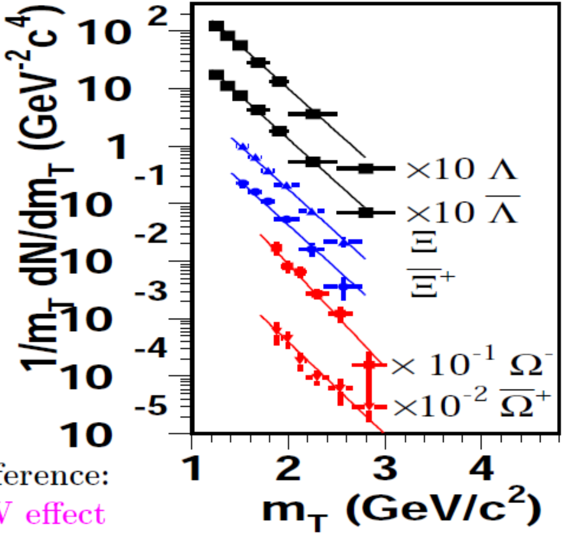
Emanuele Quercigh

Why is the slope of baryons and antibaryons the same?

Pb-Pb SPS collisions also show matter-antimatter symmetry

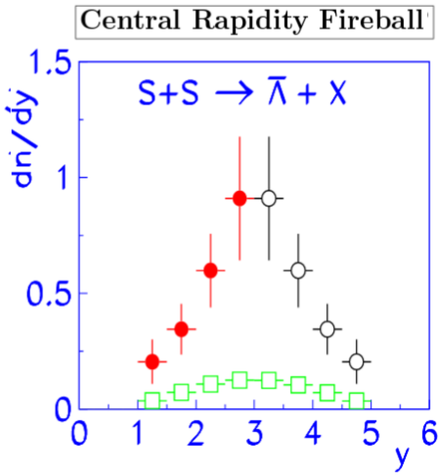
WA97	$T_{\perp}^{\mathrm{Pb}}$ [MeV]
T^{K^0}	230 ± 2
T^{Λ}	289 ± 3
$T^{\overline{\Lambda}}$	287 ± 4
T^{Ξ}	286 ± 9
$T^{\overline{\Xi}}$	284 ± 17
$T^{\Omega+\overline{\Omega}}$	251 ± 19

Λ within 1% of $\overline{\Lambda}$



Kaon – hyperon difference:
EXPLOSIVE FLOW effect

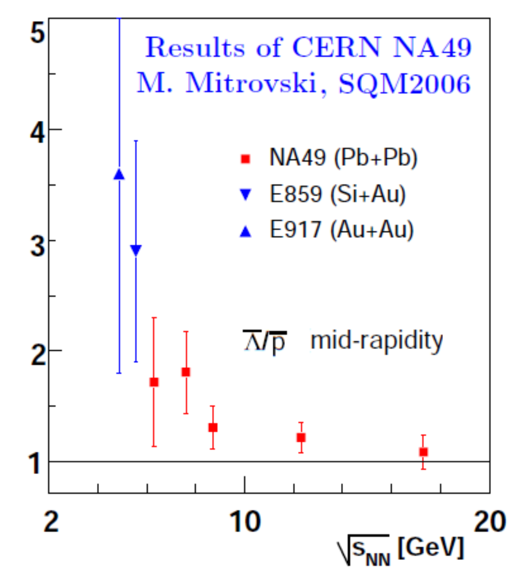
Anticipated: Central QGP fireball
Proposed evidence: (Strange)Antimatter

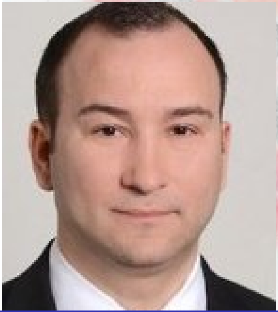


First antibaryon enhancement result, 1990-94, SPS-NA35II EXCESS $\bar{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions. From Yiota Foka, PhD Thesis, Geneva University 1994.

Conclusion: by early 1990's we have convincing evidence of QGP formation at SPS energy heavy ion collisions in-

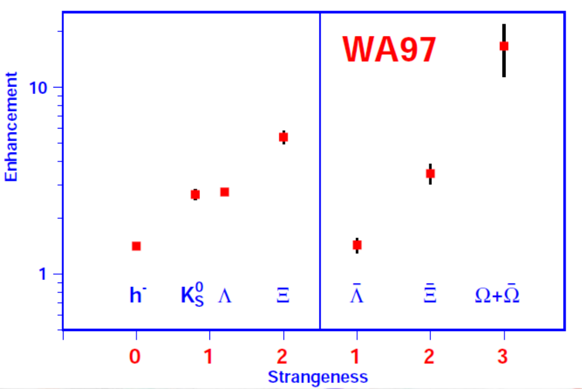
NA49 Pb-Pb SPS confirmation $\overline{\Lambda}/\bar{p} > 1$ (1980 prediction)





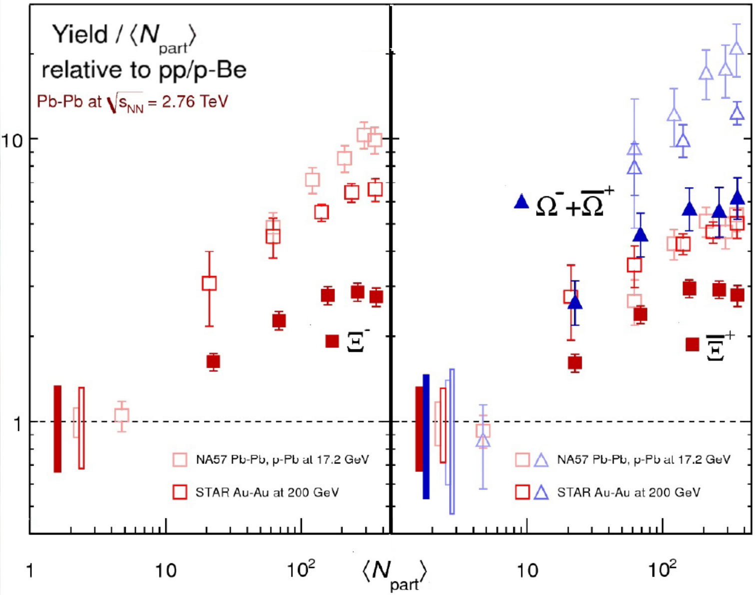
Predicted: Strange antibaryons enhanced

WA97 SPS Antihyperons: The largest observed QGP medium effect



Enhancement GROWS with a) strangeness b) antiquark content as we predicted. Enhancement with respect to yield in p–Be collisions, scaled up with the number of ‘wounded’ nucleons. Result → CERN QGP discovery announcement in 2000. All other CERN strangeness experimental results agree.

Today: Effect remains largest medium effect in RHI collisions

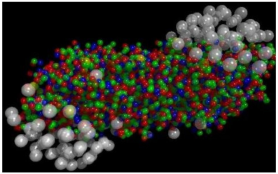


Reminder: When and how did we discover QGP?

CERN press office

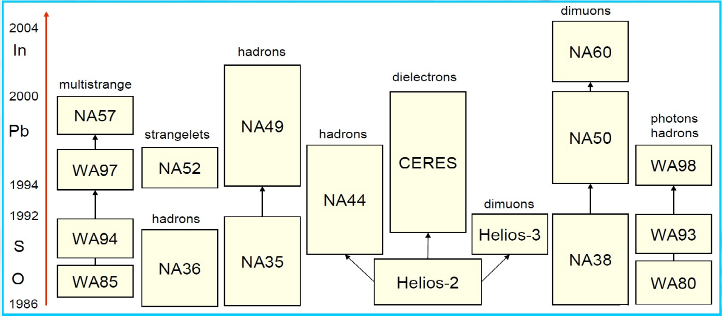
New State of Matter created at CERN

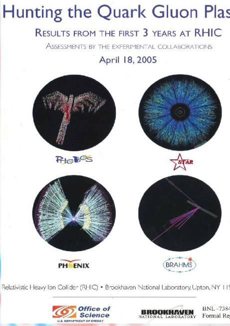
10 Feb 2000



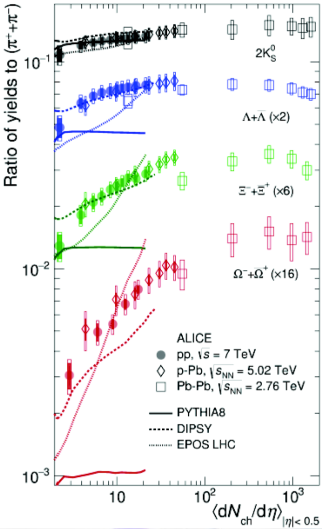
At the April 2005 meeting of the American Physical Society, held in Tampa, Florida a press conference took place on Monday, April 18, 9:00 local time. The public announcement of this event was made April 4, 2005:

EVIDENCE FOR A NEW TYPE OF NUCLEAR MATTER At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL), two beams of gold atoms are smashed together, the goal being to recreate the conditions thought to have prevailed in the universe only a few microseconds after the big bang, so that novel forms of nuclear matter can be studied. At this press conference, RHIC scientists will sum up all they have learned from several years of observing the worlds most energetic collisions of atomic nuclei. The four experimental groups operating at RHIC will present a consolidated, surprising, exciting new interpretation of their data. Speakers will include: Dennis Kovar, Associate Director, Office of Nuclear Physics, U.S. Department of Energy's Office of Science; Sam Aronson, Associate Laboratory Director for High Energy and Nuclear Physics, Brookhaven National Laboratory. Also on hand to discuss RHIC results and implications will be: Praveen Chaudhari, Director, Brookhaven National Laboratory; representatives of the four experimental collaborations at the Relativistic Heavy Ion Collider; and several theoretical physicists.





Current interest in small systems: Strange antibaryon enhancement smoothly rising with entropy of fireball



Nature Physics 2017; doi:10.1038/nphys4111 ALICE

Significant enhancement of strangeness with multiplicity in high multiplicity pp events

pp behavior resamble p-Pb : both in term of value of the ratio and shape

No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy

At high mult. pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

Models fail to riproduce data. Only DIPSY gives a qualitative description.

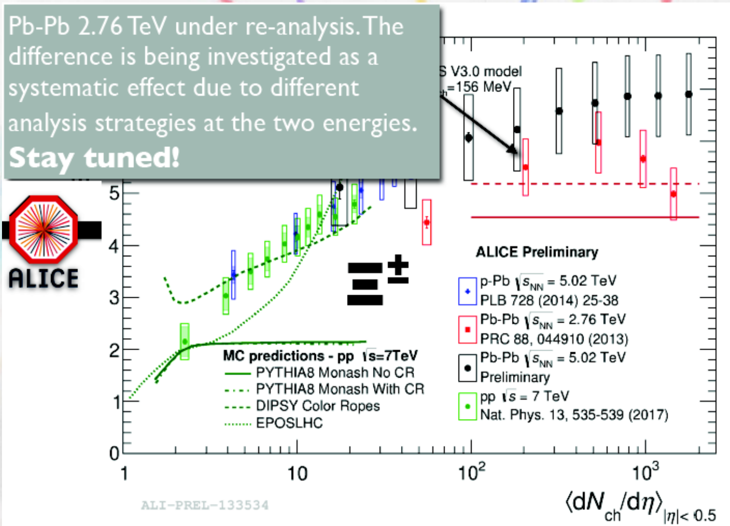
ALI-PUB-106878

Alessandro Grelli **10/7/2017**

Small systems: $\Xi(ssq)$ Alice 2014 needs minor attention

Pb-Pb 2.76 TeV under re-analysis. The difference is being investigated as a systematic effect due to different analysis strategies at the two energies.

Stay tuned!



Ratio of p_T-integrated yield to pions show compatibility

No evident energy dependence. Smooth trend among systems

Small system: particle yield constrained by conservation law: Canonical phase space required

Volume 97B, number 2 PHYSICS LETTERS 1 December 1980

THE IMPORTANCE OF THE REACTION VOLUME IN HADRONIC COLLISIONS

Johann RAFELSKI [1,2]
Institut für Theoretische Physik der Universität, D-6000 Frankfurt/Main, West Germany

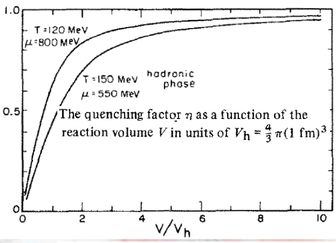
and

Michael DANOS
National Bureau of Standards, Washington, DC 20234

We consider particle production in the frame of the thermodynamic description [1] and explore the physical consequences arising from the conservation of quantum numbers which are conserved exactly

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.



The quenching factor η as a function of the reaction volume V in units of $V_h = \frac{4}{3}\pi(1\ \text{fm})^3$

PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

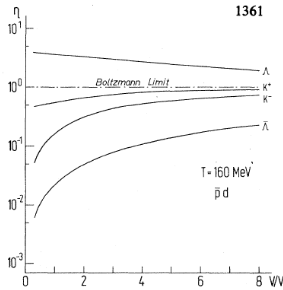
Strangeness abundances in $\bar{p}$-nucleus annihilations

C. Derreth and W. Greiner
Institut für Theoretische Physik der Universität Frankfurt, 6000 Frankfurt, Federal Republic of Germany

H.-Th. Elze* and Johann Rafelski
Institute of Theoretical Physics and Astrophysics, University of Cape Town, Rondebosch 7700, Cape Town, South Africa

(Received 27 September 1984)

Strange particle abundances in small volumes of hot hadronic gas are determined in the canonical ensemble with exact strangeness and baryon number conservation. Substantial density and baryon number dependence is found. A $\bar{p}$d experiment is examined and applications to $\bar{p}$-nucleus annihilations are considered.



Small system: An elegant nonabelian group theory approach

Ref.TH.3053-CERN
26 March 1981

Ref.TH.3053-CERN

PHASE TRANSITION IN HADRONIC MATTER WITH INTERNAL SYMMETRY *)

K. Redlich**) and L. Turko**)
CERN -- Geneva

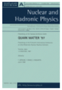
受入
81-5-69

ABSTRACT

A general formalism for the description of a thermodynamical system with internal symmetry is introduced. Results are applied to the statistical bootstrap model describing hadronic clusters with isospin conservation taken into account and equations of state are obtained. It is shown that at the sufficiently high energy density, a phase transition occurs. A new phase is an intermediate one between hadronic matter and a quark-gluon plasma phase.

Nuclear Physics A

Volume 638, Issues 1–2, 10 August 1998, Pages 399c-402c



Canonical strangeness enhancement

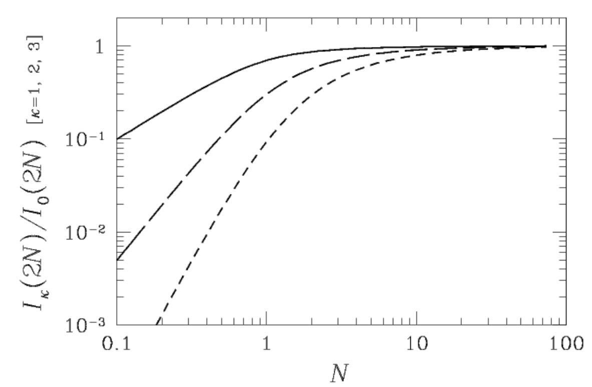
J. Sollfrank [a], F. Becattini [b], K. Redlich [c], H. Satz [d]

https://doi.org/10.1016/S0375-9474(98)00395-9 Get rights and content

REFERENCES

1. F. Becattini, M. Gaździcki and J. Sollfrank, Euro. Phys. J.
2. J. Sollfrank, P. Huovinen and P.V. Ruuskanen, nucl-th/9801023.
3. S. Abatzis et al. (WA94 Collaboration), Phys. Lett. B 354 (1995) 178.
4. S. Abatzis et al. (WA85 Collaboration), Heavy Ion Physics 4 (1996) 79.
5. I. Králik et al. (WA97 Collaboration), this proceedings.
6. F. Becattini and U. Heinz, Z. Phys. C 76 (1997) 269.
7. M. Gaździcki, Heavy Ion Physics 4 (1996) 33.
8. M. Gaździcki and O. Hansen, Nucl. Phys. A 528 (1991) 754.
9. F. Becattini, Z. Phys. C 69 (1996) 485.
10. M. Gaździcki, J. Phys. G 23 (1997) 1881.
11. M. Jamin, in Proceedings of *QCD 97*, Montpellier, July 1997 (hep-ph/9709484).
12. K. Redlich, H. Satz and J. Sollfrank, University Regensburg preprint TPR-98-04.

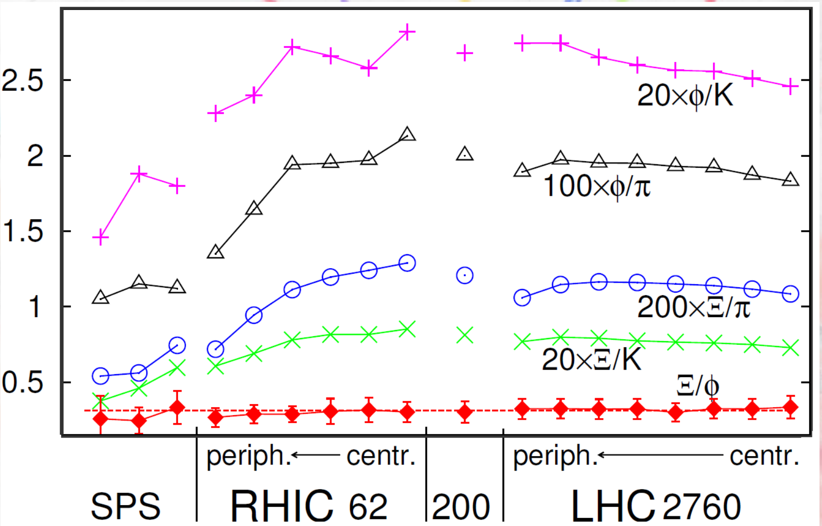
Strangeness conservation alone: in QGP book JL/JR; p225-232:
1-2-3-strange flavored particle suppression factors



$$\langle N_\kappa^{CE}\rangle = N_\kappa^{GC}\,\frac{I_\kappa(2N_{pair}^{GC})}{I_0(2N_{pair}^{GC})}.$$

Canonical yield-suppression factors I_κ/I_0 as function of the grand-canonical pair yield N. Short-dashed line: the suppression of triply-strange-flavored hadrons; long-dashed line: the suppression of doubly-strange-flavored hadrons; and solid line, the suppression of singly-strange-flavored hadrons.

$\Xi(ssq)/\phi(s\bar{s})$ (nearly) constant: same production mechanism



M. Petran, J. Rafelski, *Multistrange Particle Production and the Statistical Hadronization Model* Phys.Rev. C **82** (2010) 011901

The chemical hadronization analysis from (re)invention to generalization

Physics Letters B
Volume 262, Issues 2–3, 20 June 1991, Pages 333-340
open access

Strange anti-baryons from quark-gluon plasma

Johann Rafelski Department of Physics, University of Arizona, Tuczon, AZ 85721

Received 5 April 1991, Available online 17 October 2002.
https://doi.org/10.1016/0370-2693(91)91576-H

Abstract

Experimental results on strange anti-baryon production in nuclear S→W collisions at 200 *A* 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.

Chemical nonequilibrium and deconfinement in 200*A* GeV sulphur induced reactions

Jean Letessier and Johann Rafelski
Phys. Rev. C **59**, 947 – Published 1 February 1999 Received 17 June 1998
DOI: https://doi.org/10.1103/PhysRevC.59.947
PHYSICAL REVIEW C
covering nuclear physics

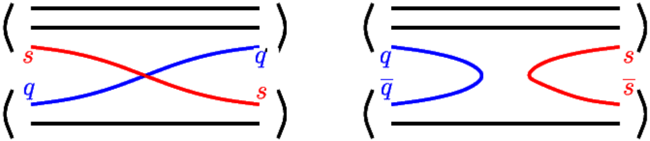
We interpret hadronic particle abundances produced in S-Au/W/Pb $200A$ GeV reactions in terms of the final state hadronic phase space model and determine by a data fit of the chemical hadron freeze-out parameters. Allowing for the flavor abundance nonequilibrium a highly significant fit to experimental particle abundance data emerges, which supports the possibility of strangeness distillation. We find under different strategies stable values for freeze-out temperature $T_f = 143 \pm 3$ MeV, baryochemical potential $\mu_B = 173 \pm 6$ MeV, ratio of strangeness (γ_s) and light quark (γ_q) phase space occupancies $\gamma_s/\gamma_q = 0.60 \pm 0.02$, and $\gamma_q = 1.22 \pm 0.05$ without accounting for collective expansion (radial flow). When introducing flow effects which allow a consistent description of the transverse mass particle spectra, yielding $|v_c| = 0.49 \pm 0.01\ c$, we find $\gamma_s/\gamma_q = 0.69 \pm 0.03$, $\gamma_q = 1.41 \pm 0.08$. The strange quark fugacity is fitted at $\lambda_s = 1.00 \pm 0.02$ suggesting chemical freeze-out directly from the deconfined phase.

Magic coincidence: while we battled our referee for 6 months Krzysztof Redlich enters this field with the 2 page preprint in August 1998: *Unified description of freezeout parameters in relativistic heavy ion collisions*, Phys.Rev.Lett. 81 (1998) 5284-5286

Chemical reactions involving quarks

EXAMPLE: Strangeness in HG:

Relative chemical equilibrium | **Absolute** chemical equilibrium



EXCHANGE REACTION | **PRODUCTION REACTION**

Absolute equilibrium $\gamma \to 1$ **require more rarely occurring truly inelastic collisions with creation of new particles.**

γ_i controls overall abundance of quark 'i' pairs	Absolute chemical equilibrium
λ_i controls difference between strange and non-strange quarks 'i'	Relative chemical equilibrium

WHY STATISTICAL HADRONIZATION MODEL... (SHM) WORKS

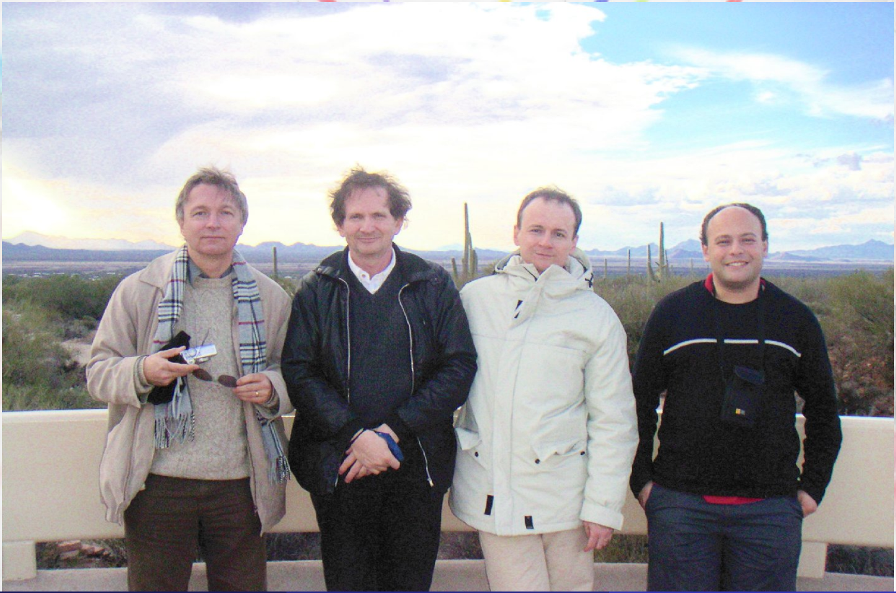
a) Confinement: $\Longrightarrow$ breakup into free quarks not possible;
b) Strong interaction: $\Longrightarrow$ equal hadron production strength irrespective of produced hadron type
$\Longrightarrow$ 'elementary' hadron yields depend only on the available phase space
Historical approaches:

- 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 $E \to T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles:
  $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Our interest: bulk QGP fireball properties of hadron source evaluated independent of complex explosion dynamics $\Longrightarrow$ analyze integrated hadron spectra.

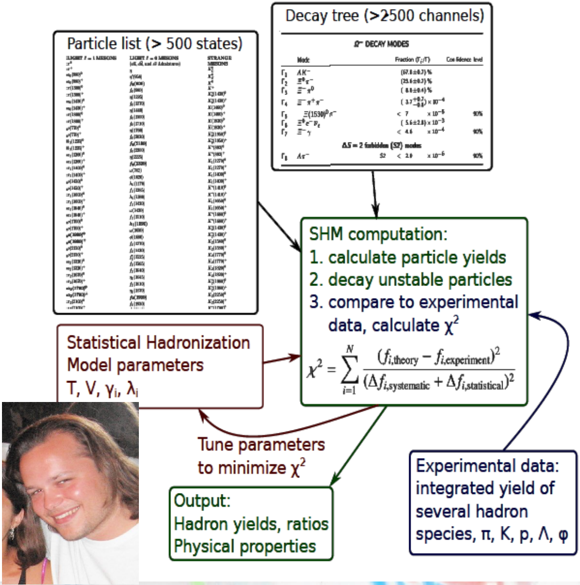
SHARE Idea/Team: US-Polish NATO collaboration 2002/04

Statistical HAadronization with REsonances



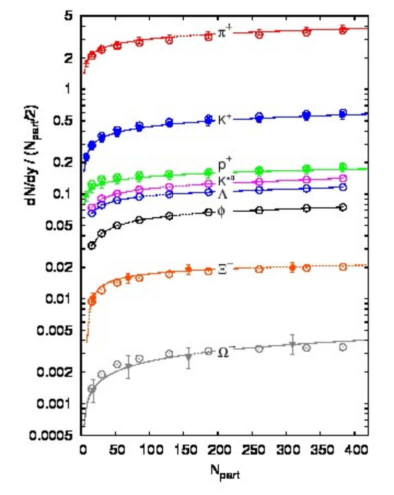
PROCEDURE – FITTING SHM PARAMETERS TO DATA

1. Input: T, V, γ_q, γ_s, λ_q, λ_s.λ_3
2. Compute yields of all hadrons
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties, constraints
6. Tune parameters to match data (minimize χ^2)



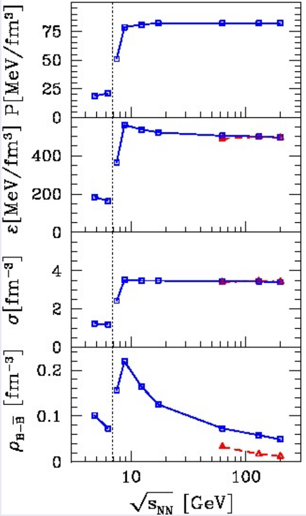
Examples SHM Analysis (Chemical Nonequilibrium)

Particle Yield Example:LHC



M. Petran, J.Letessier, V. Petracek, J. Rafelski Phys.Rev. C **88** (2013) no.3, 034907

Bulk properties from SHM yields



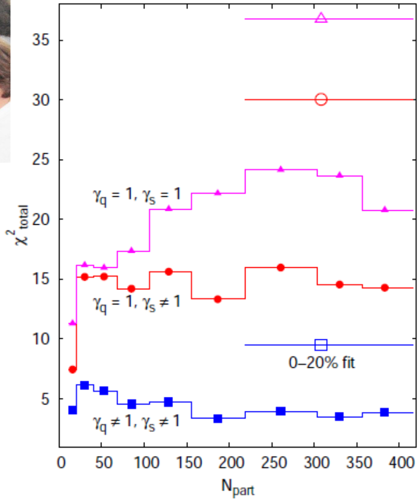
J. Letessier, J. Rafelski, Eur.Phys.J. A **35** (2008) 221-242

SHM fit Quality LHC Pb-Pb 2.76 TeV data

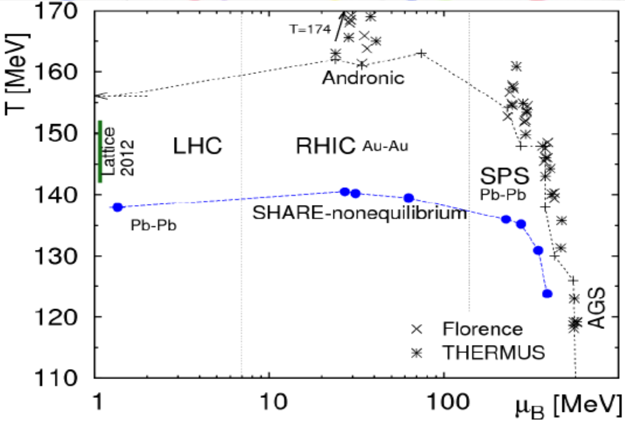
Chemical non-equilibrium SHM works at all centralities

Non-equilibrium

- $\chi^2/\mathrm{ndf} \simeq 4.5/9 = 0.5$,
- constant across centrality
- improvement by factor of 3 resp. 5 comparing to $\gamma_q = 1$
- Only in peripheral collisions $\gamma_q \simeq 1$ maybe possible



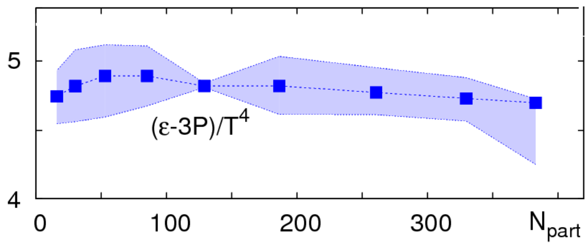
SHARE consistent with lattice QCD
Chemical nonequilibrium + supercooling
= sudden fireball breakup



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.

SPS, RHIC, LHC *AA* SHM Digest

- Strange antibaryon signature of QGP leads to discovery of universal properties of QGP at hadronization; differences in: Volume size, Strangeness saturation.
- Universality of fireball bulk properties across the entire reaction energy domain we express in terms of the invariant measure



- At SPS, RHIC: Baryon number deposition varies strongly as function of collision energy. This is the chemical potential dependence on collision energy. WHY? – To clarify question: why there is no McLerran-Bjorken transparency?

A few first analysis observations and summary

- ALICE small system results shows growth γ_s of strangeness yield with size of the system.
- Hadronization condition T a few MeV higher compared to large systems: conclusion there is less/no supercooling in less explosive expansion.
- Corresponding bulk matter properties are higher. No test of universal hadronization / conformal anomaly was as yet performed.
- Small system net flavor content universally zero (and it seems we are sensitive due to small system): there is no electric charge, etc.
- **There is no doubt that after 38 years of waiting the $pp \rightarrow AA$ ALICE results demonstrate that there are 10-20-30% canonical phase space effects: when strange pairs are few and baryon number is rare, strange antibaryons are slightly suppressed as the correct theory predicts. Dominant effect still from strangness chemical non-equilibrium γ_s . No publication forthcoming as lack of resources prevents appropriate analysis effort.**

Cudo-wny Wrocław

compact
ultra
dense
object

why
not
yet?

June 2019

Max Born Symposium