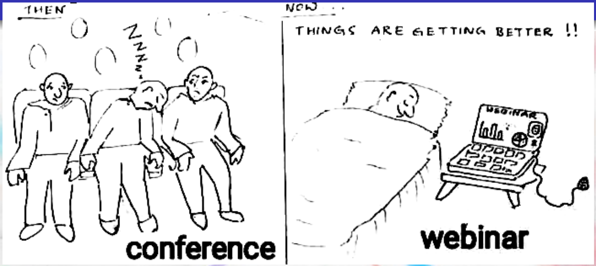
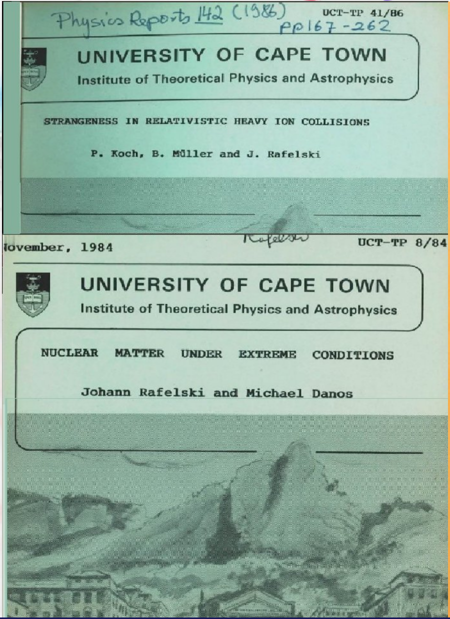
Strange and Productive Strong Interactions: With the Kraków School of Theoretical Physics



The relativistic heavy ion collision research program had been created to discover and study how hadrons melt and later freeze again out of the transient, a new phase of matter, the quark gluon plasma (QGP). We learn in the laboratory about matter creation in the early Universe. Here I will describe the strong relationship across past decades between the Kraków School of Theoretical Physics and research work on strangeness as THE signature of QGP.

1984-87: From Cape Town To Krakow?



Physics Reports 142 (1986) pp167-262

UCT-TP 41/86

UNIVERSITY OF CAPE TOWN

Institute of Theoretical Physics and Astrophysics

STRANGENESS IN RELATIVISTIC HEAVY ION COLLISIONS

P. Koch, B. Müller and J. Rafelski

Rafelski

November, 1984

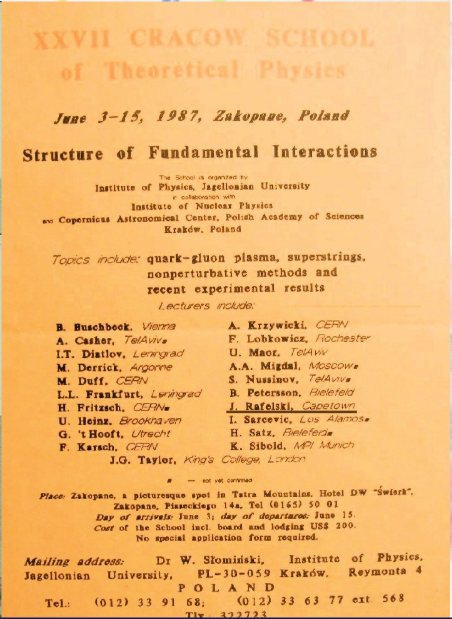
UCT-TP 8/84

UNIVERSITY OF CAPE TOWN

Institute of Theoretical Physics and Astrophysics

NUCLEAR MATTER UNDER EXTREME CONDITIONS

Johann Rafelski and Michael Danos



XXVII CRACOW SCHOOL of Theoretical Physics

June 3-15, 1987, Zakopane, Poland

Structure of Fundamental Interactions

The School is organized by
Institute of Physics, Jagellonian University
in collaboration with
Institute of Nuclear Physics
and Copernicus Astronomical Center, Polish Academy of Sciences
Kraków, Poland

Topics include: quark-gluon plasma, superstrings, nonperturbative methods and recent experimental results

Lecturers include:

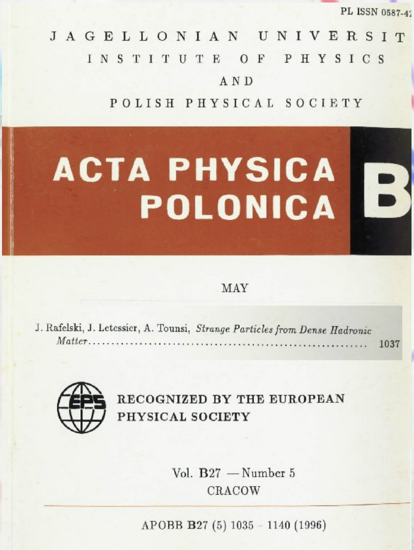
B. Buschbeck, *Vienna*
A. Casher, *TelAviv**
I.T. Diatlov, *Leningrad*
M. Derrick, *Argonne*
M. Duff, *CERN*
L.L. Frankfurt, *Leningrad*
H. Fritzsch, *CERN**
U. Heinz, *Brookhaven*
G. 't Hooft, *Utrecht*
F. Karsch, *CERN*
A. Krzywicki, *CERN*
F. Lobkowicz, *Rochester*
U. Maor, *TelAviv*
A.A. Migdal, *Moscow**
S. Nussinov, *TelAviv**
B. Petersson, *Bielefeld*
J. Rafelski, *Capetown*
I. Sarcevic, *Los Alamos**
H. Satz, *Bielefeld**
K. Sibold, *MPI Munich*
J.G. Taylor, *King's College, London*

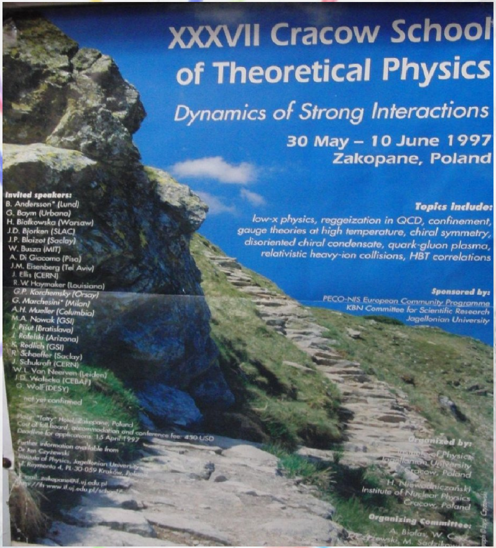
* — not yet confirmed

Place: Zakopane, a picturesque spot in Tatra Mountains, Hotel DW "Świerk", Zakopane, Piaseckiego 14a, Tel (0165) 50 01
Day of arrivals: June 3; *day of departures:* June 15.
Cost of the School incl. board and lodging US$ 200.
No special application form required.

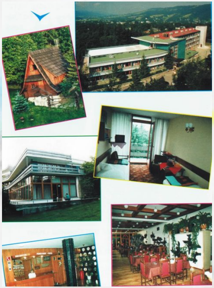
Mailing address: Dr W. Słomiński, Institute of Physics, Jagellonian University, PL-30-059 Kraków, Reymonta 4
POLAND
Tel.: (012) 33 91 68; (012) 33 63 77 ext. 568
Tlx: 322723

1997 I made it to Zakopane





1997: A special occasion



1997: What occasion? Wieslaw Czyż 70th BD, and,

In my opinion QGP had been observed

ACTA PHYSICA POLONICA B Vol. 28 No 12 (1997) 2841

HADRONIC SIGNATURES OF DECONFINEMENT IN RELATIVISTIC NUCLEAR COLLISIONS *

(Received October 6, 1997)

Dedicated to Wieslaw Czyż on the occasion of his 70th birthday

We describe the remarkable accomplishments of the current heavy ion Pb–Pb collision experiments involving strange particle production, carried out at 158A GeV at CERN–SPS. Together with earlier 200A GeV S-induced reactions, these results imply that, at central rapidity, a novel mechanism of strangeness production arises, accompanied by excess entropy formation. We argue that:

- these results are consistent with the formation of a space-time localized, highly excited, dense state of matter;
- the freeze-out properties of strange hadrons are suggestive of the formation of a color-deconfined, thermally and nearly chemically equilibrated phase, which provides at present the only comprehensive framework to describe all experimental data;
- the matter fireball is undergoing a transverse expansion with nearly the velocity of sound of relativistic matter; longitudinal expansion is not in the scaling regime.

We present a first analysis of the recent Pb–Pb results and discuss several alternative reaction scenarios. We evaluate quantitatively strangeness production in the deconfined quark-gluon phase and obtain yields in agreement with the experimental observations made in 200A GeV S–W and 158A GeV Pb–Pb interactions. We also present a qualitative discussion of J/Ψ results consistent with our understanding of strange particle results.

PACS numbers: 25.75.–q, 12.38. Mh, 24.85. +p

* Presented by Jan Rafelski at the XXXVII Cracow School of Theoretical Physics, Zakopane, Poland, May 30–June 10, 1997

4.2. Late emission scenario: HG with or without QGP?

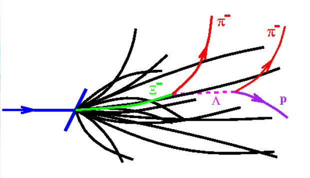
$$\begin{aligned} T_{\rm f} &= 155 \pm 7\,\mathrm{MeV}, & &\to v_\perp \simeq 0.5 \simeq v_{\rm s};\\ \lambda_{\rm q} &= 1.56 \pm 0.09, & &\to \lambda_{\rm s} = 1.14;\\ \chi^2/9 &= 0.84, & &\to \ \mathrm{C.L.} > 60\%\,. \end{aligned} \qquad (4.5)$$

Let us stress again that in our here presented work, we did assume that thermal quark-gluon degrees of freedom are at origin of many of the hadronic particle production phenomena in relativistic hadron reactions. Many simple, but subtle experimental observations point in this natural direction. For example, all so far studied $m_\perp$ spectra in S- and Pb-induced reactions have the same shape for strange baryons and antibaryons of the same kind, and even for different kinds, where comparison can be made in same range of $m_\perp$. This is not an accident, but result of either complete thermal equilibrium, or of their origin in a thermal source composed of their constituents (quarks). Only a thermal quark liquid can deliver this result naturally.

Similarly, we take the presence of near chemical equilibrium of strangeness to be a signal of primordial QGP phase. The phase space occupancy factor expected in the QGP phase is of magnitude 0.6 and is enhanced by the lower strangeness density in the HG phase by a factor 1.5 to reach unity. The chemical parameters that are observed lead to abundance anomalies such as $\bar{\Lambda}/\bar{p} > 1$. There is a priori no reason for a HG state to reach condition amenable to this result, should it not arrive from a QGP state.

All told, we believe that the most simple an consistent reaction picture involves formation of deconfined phase of hadronic matter both in S- and Pb-induced reactions. The difference between both cases is that the former leads to a small enough fireball that can rapidly disintegrate under influence of the longitudinal flow and without forming an intermediate fully equilibrated HG phase. The Pb–Pb reactions, comprising five time the amount of matter, considerably higher energy density and much less longitudinal flow, appear to undergo a more protracted evolution history,

QGP signatures: 1980- Strangeness proposed, several CERN experiments followed: *Anti-strangeness in QGP:* $\bar{s} > \bar{q}$ *in SPS experiments*



FROM HADRON GAS TO QUARK MATTER II

J. Rafelski
Institut für Theoretische Physik
der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

80-12-212

Ref.TH.2969-CERN
13 October 1980

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.

A: Strange hadrons are subject to a self analyzing decay

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

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

$$\Lambda(qqs), \quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}), \quad \Lambda(1520), \ldots$$

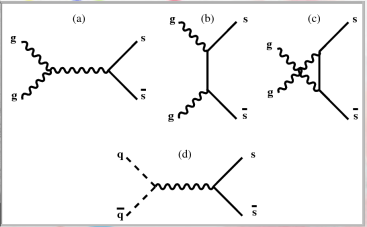
$$\phi(s\bar{s}), \quad \Xi(qss), \quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}), \ldots$$

$$\Omega(sss), \quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

C: Production rates hence statistical significance is high.

THEORETICAL CONSIDERATION within QCD

A: 1982 Berndt Müller & JR PRL48 (1982) 1066 show production of strangeness dominated by gluon fusion $\boxed{GG \to s\bar{s}}$
strangeness⇔gluons in QGP;



Berndt at age 34.

B: coincidence of scales:

$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$
strangeness yield can grow gradually - make models of time/size dep.

Instant success of strangeness signature proposal

Strangeness in quark–gluon plasma

Johann Rafelski

Based on a lecture given at the Bielefeld Workshop on 'Quark Matter Formation and Heavy Ion Collisions', May 10–14, 1982
S. Afr. J. Phys. 6 (1983) 37–43

Institut für Theoretische Physik der Universität, Frankfurt/Main
and Department of Physics, University of Cape Town, Rondebosch

It is argued that observation of the strange-particle abundance may lead to identification of the quark–gluon plasma and measurement of some of its properties. Approach to chemical equilibrium and competitive processes in the hadronic gas phase are discussed.

Tucson, SQM January 1995

picked up by Marek in Dubna . . .

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Received by Publishing Department
on July, 20, 1983.

Anikina M. et al. E1-83-521

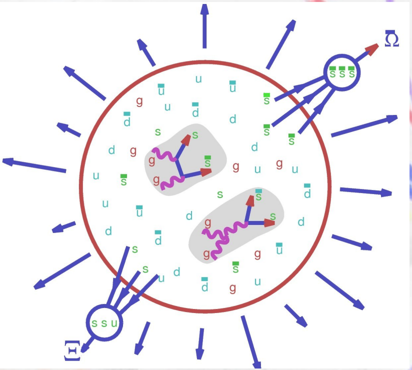
A Study of Λ-Production
in Central Nucleus-Nucleus Interactions
at a Momentum of 4.5 GeV/c Per Incident Nucleon

Transverse momenta and rapidities of Λ's produced in central nucleus-nucleus collisions at 4.5 GeV/c per nucleon /CC, CNe, ONe, CCu, CZr, CPb, OPb/ have been studied and compared with those from inelastic He-Li interactions at the same incident momentum. Polarization of Λ hyperons was found to be consistent /within the errors/ with zero ($\alpha P_\Lambda = -0.06 \pm 0.11$) for 224 Λ's from central collisions. The upper limit of $\bar{\Lambda}/\Lambda$ production ratio was estimated to be less than 10^{-2} at a 90% confidence level.

The analyzed experimental data were obtained using the triggered 2 m streamer spectrometer SKM-200.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1983

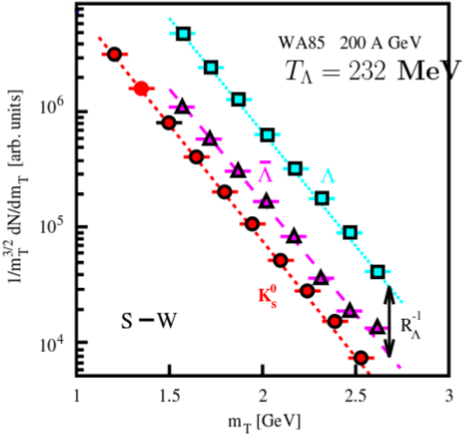


1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed
   s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ quarks

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: Photo of authors above is contemporary.

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.

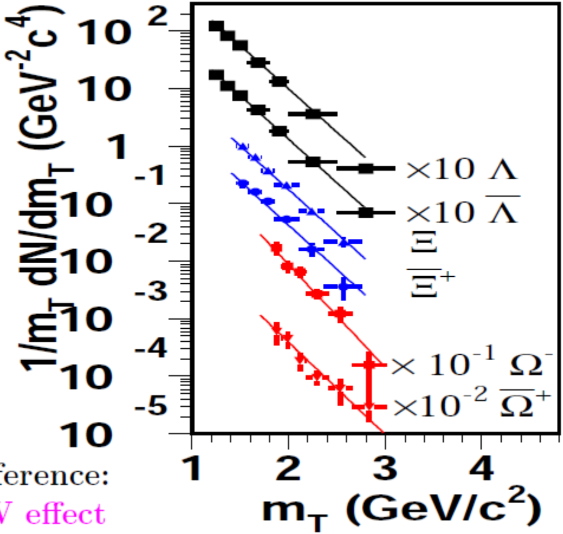
Emanuele Quercigh

Why is the slope of baryons and antibaryons the same?

Pb-Pb SPS collisions also show matter-antimatter symmetry: Sudden hadronization of QGP

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 $\overline{\Lambda}$

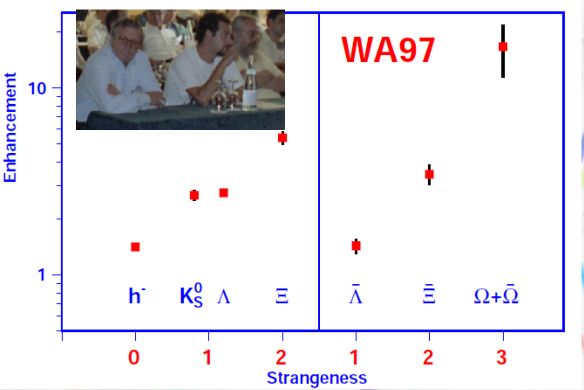


Kaon – hyperon difference:

EXPLOSIVE FLOW effect

Predicted: Strange antibaryons enhanced

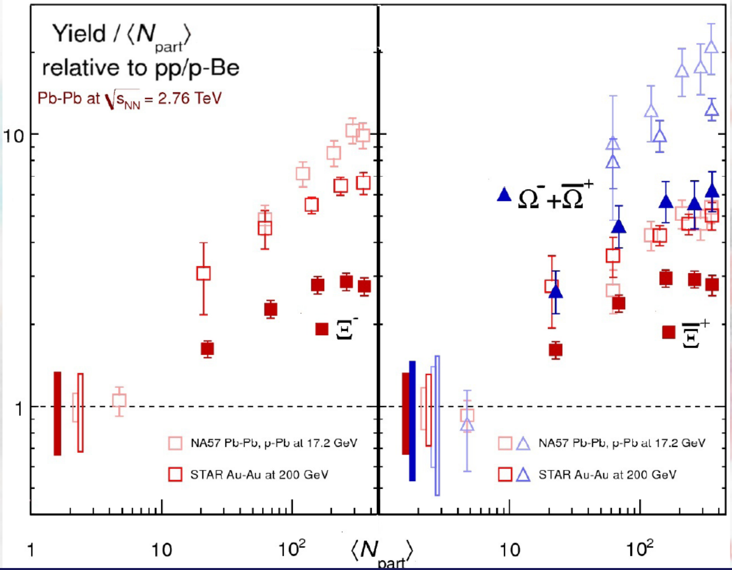
WA97 SPS Antihyperons: The largest observed QGP medium effect



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 $\rightarrow$ CERN QGP discovery announcement in 2000. All other CERN strangeness experimental results agree.

Emanuele Quercigh, Federico Antinori, Karel Safarik in picture: Hagedorn Fest in Divonne, 1994 a couple years before these results were obtained

25 years of experiments: the strange (anti)baryon enhancement predicted 1980-1986 is the largest QGP medium effect observed



The chemical hadronization analysis (SHM, 1991)

ELSEVIER

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

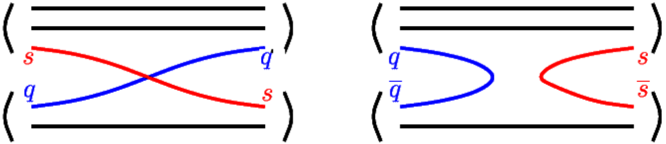
We interpret hadronic particle abundances produced in S-Au/W/Pb $200A$ GeV reactions in terms of the final state hadronic phase space model and determine by a data fit of the chemical hadron freeze-out parameters. Allowing for the flavor abundance nonequilibrium a highly significant fit to experimental 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.

Nonequilibrium parameters describe time evolution of fireball system

Hadronization: Chemical reactions involving quarks

Requires understanding of kinetic theory: picture from Koch-Müller Rafelski 1986 Physics Reports (1000+citations).
Invitation to read before reinventing SHM incorrectly.

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

a) **Confinement** : $\Longrightarrow$ breakup into free quarks not possible;

b) **Strong interaction** : $\Longrightarrow$ equal hadron production strength

$\Longrightarrow$ 'elementary' hadron yields depend only on the available phase space

Different approaches:

- **Micro-canonical phase space** :
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER
  Model should describe an average event
- **Canonical phase space** : sharp number of particles
  R. Hagedorn started here in 1960's
  ensemble average energy $E \to T$ +Tsallis+. . .
  T could be, but needs not to be, a kinetic process temperature
- **Grand-canonical phase space** : average energy and number of particles: $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

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

I coauthored in APPB+Proc 12 SHM relevant works: (out of 22 APPB contributions)

J Rafelski, J Letessier, A Tounsi

Strange Particles from Dense Hadronic Matter

Acta Phys. Pol. B **27**, 1037 (1996)

After a brief survey of the remarkable accomplishments of the current heavy ion collision experiments up to 200A GeV, we address in depth the role of strange particle production in the search for new phases of matter in these collisions. In particular, we show that the observed enhancement pattern of otherwise rarely produced multistrange antibaryons can be consistently explained assuming color deconfinement in a localized, rapidly disintegrating hadronic source. We develop the theoretical description of this source, and in particular study QCD based processes of strangeness production in the deconfined, thermal quark-gluon plasma phase, allowing for approach to chemical equilibrium and dynamical evolution. We also address thermal charm production. Using a rapid hadronization model we obtain final state particle yields, providing detailed theoretical predictions about strange particle spectra and yields as functions of heavy ion energy. Our presentation is comprehensive and self-contained: we introduce the procedures used in data interpretation in considerable detail, discuss the particular importance of selected experimental results, and show how they impact the theoretical developments.

J. Rafelski, J. Letessier

Diagnosis of QGP with Strange Hadrons

Acta Phys. Pol. B **30**, 3559 (1999)

We review the current status of strangeness as signature of the formation and dissociation of the deconfined QGP at the SPS energy scale, and present the status of our considerations for RHIC energies. By analyzing, within the framework of a Fermi statistical model, the hadron abundance and spectra, the properties of a disintegrating, hadron evaporating, deconfined QGP fireball are determined and can be compared with theory for the energy range 160–200A GeV on fixed target. We discuss in more detail our finding that the pion yields occur near to pion condensation condition. Dynamical models of chemical strangeness equilibration are developed and applied to obtain strangeness production in a QGP phase at conditions found at SPS and expected at RHIC. The sudden QGP break up model that works for the SPS data implies at RHIC dominance of both baryon, and antibaryon, abundances by the strange baryon and antibaryon yields.

J. Rafelski, J. Letessier, A. Tounsi

Hadronic Signatures of Deconfinement in Relativistic Nuclear Collisions

Acta Phys. Pol. B **28**, 2841 (1997)

We describe the remarkable accomplishments of the current heavy ion Pb–Pb collision experiments involving strange particle production, carried out at 158A GeV at CERN–SPS. Together with earlier 200A GeV S-induced reactions, these results imply that, at central rapidity, a novel mechanism of strangeness production arises, accompanied by excess entropy formation. We argue that: (i) these results are consistent with the formation of a space-time localized, highly excited, dense state of matter; (ii) the freeze-out properties of strange hadrons are suggestive of the formation of a color-deconfined, thermally and nearly chemically equilibrated phase, which provides at present the only comprehensive framework to describe all experimental data; (iii) the matter fireball is undergoing a transverse expansion with nearly the velocity of sound of relativistic matter; longitudinal expansion is not in the scaling regime. We present a first analysis of the recent Pb–Pb results and discuss several alternative reaction scenarios. We evaluate quantitatively strangeness production in the deconfined quark–gluon phase and obtain yields in agreement with the experimental observations made in 200A GeV S–W and 158A GeV Pb–Pb interactions. We also present a qualitative discussion of J/Ψ results consistent with our understanding of strange particle results.

J. Letessier, J. Rafelski

Quark–Gluon Plasma in Pb–Pb 158 A GeV Collisions: Evidence from Strange Particle Abundances and the Coulomb Effect

Acta Phys. Pol. B **30**, 153 (1999)

The hadronic particle production data from relativistic nuclear Pb–Pb 158 A GeV collisions are successfully described within the chemical non-equilibrium model, provided that the analysis treats Ω and $\overline{\Omega}$ abundances with care. We further show that there is a subtle influence of the Coulomb potential on strange quarks in quark matter which is also seen in our data analysis, and this Coulomb effect confirms the finding made by chemical analysis in the S–Au/W/Pb 200 A GeV collisions that the hadron particle source is deconfined with respect to strange quark propagation. Physical freeze-out conditions (pressure, specific energy, entropy, and strangeness) are evaluated and considerable universality of hadron freeze-out between the two different collision systems is established.

Above is 177 pages

more... !

J. Rafelski, J. Letessier
Strangeness and Statistical Hadronization: How to Study Quark–Gluon Plasma

Acta Phys. Pol. B **34**, 5791 (2003)

Statistical hadronization is presented as mechanism for (strange) particle production from a deconfined quark–gluon plasma (QGP) fireball. We first consider hadronic resonance production at RHIC as a test of the model. We present in detail how the hadrochemistry determines particle multiplicities and in case of sudden hadronization allows investigation of QGP properties. A comparative study of strange hadron production at SPS and RHIC is presented. The energy dependence of physical observables shows regularities and a potential discontinuity in the low RHIC range, when comparing these different energy domains. Considering the energy scan program at CERN-SPS we show that the K^+/π^+ discontinuity is a baryon density effect.

G. Torrieri, J. Letessier, J. Rafelski, S. Steinke
Statistical Hadronization with Resonances

Acta Phys. Pol. B **35**, 2911 (2004)

We introduce the equilibrium and non-equilibrium statistical hadronization picture of particle production in ultra-relativistic heavy ion collisions. We describe the related physical reaction scenarios, and show how these can lead to quark pair yield non-equilibrium. Using the SHARE1.2 program suite we quantitatively model particle yields and ratios for RHIC-130 run. We study how experimental particle ratios can differentiate between model scenarios, and discuss in depth the importance of hadronic resonances in understanding of hadron production processes.

J. Rafelski, J. Letessier
Status of Strangeness-Flavor Signature of QGP

Acta Phys. Pol. B **37**, 3315 (2006)

Is the new state of matter formed in relativistic heavy ion collisions the deconfined quark–gluon plasma? We survey the status of several strange hadron observables and discuss how these measurements help understand the dense hadronic matter.

M. Petráň, J Letessier, V. Petráček, J. Rafelski
Statistical Hadronization of Multistrange Particles

Acta Phys. Pol. B **41**, 2785 (2010)

We study multistrange hadrons produced in NA49 and STAR experiments at center of mass energies varying from $\sqrt{s_{NN}} = 7.61$ GeV to 200 GeV. We show that the yields of Ξ, $\overline{\Xi}$ and ϕ can help to constrain the physical conditions present in the hot dense fireball source of these multistrange hadrons created in heavy ion collision. We address the question of chemical equilibrium of individual quark flavors before and after hadronization and offer a few predictions for LHC.

M. Petráň, J. Letessier, V. Petráček, J. Rafelski
Strangeness Production in Au–Au Collisions at $\sqrt{s_{NN}} = 62.4$ GeV

Acta Phys. Pol. B Proc. Suppl. 5, 255 (2012)

We obtain strangeness production as function of centrality in a statistical hadronization model analysis of all experimental hadron production data in Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Our analysis describes successfully the yield of strange and multi-strange hadrons recently published. We explore condition of hadronization as a function of centrality and find universality for the case of chemical non-equilibrium in the hadron phase space corresponding to quark-gluon plasma (QGP) in chemical equilibrium.

J. Rafelski
Strangeness and Quark-Gluon Plasma

Acta Phys. Pol. B **43**, 829 (2012)

I review the foundational motivations which led us to the ultra relativistic heavy ion collision research at SPS, RHIC and now LHC: the quantum vacuum structure; the deconfined nature of the quark-gluon plasma (QGP) phase filling the Universe for the first 30 μs after the Big Bang; the origin of mass of stable matter; and the origin of flavor. The special roles of strangeness enhancement and strange antibaryon signature are highlighted. It is shown how hadron production can be used to determine the properties of QGP and how the threshold energy for QGP formation is determined.

Above is 110 pages

end!

J. Rafelski, M. Petran
Strangeness in QGP: Hadronization Pressure

Acta Phys. Pol. B Proc. Suppl. 7, 35 (2014)

We review strangeness as signature of quark–gluon plasma (QGP) and the hadronization process of a QGP fireball formed in relativistic heavy-ion collisions in the entire range of today accessible reaction energies. We discuss energy dependence of the statistical hadronization parameters within the context of fast QGP hadronization. We find that QGP breakup occurs for all energies at the universal hadronization pressure $P = 80 \pm 3$ MeV/fm^3.

J. Rafelski
The Mar(e)k of QGP: Strangeness

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Strangeness signature of quark–gluon plasma (QGP) is central to the exploration of baryon-dense matter: the search for the critical point and onset of deconfinement. I report on the discovery of QGP by means of strangeness: the key historical figures and their roles in this quest are introduced and the experimental results obtained are discussed. The important role of antihyperons is emphasized. The statistical hadronization model and sudden hadronization are described. Results of present day data analysis — strangeness and entropy content of a large fireball, and the universal hadronization condition describing key features of all explored collision systems — are presented.

Above is 40 pages

Total of 12 articles (out of 22 in APPB) is 327 pages across 20 years.

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

Sstatistical HAadronization with REsonances

2000-06 Golden age of scientific collaboration Kraków-Arizona

ELSEVIER Computer Physics Communications 167 (2005) 229–251

SHARE: Statistical hadronization with resonances

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Abstract

SHARE is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. With the physical input of intensive statistical parameters, it generates the ratios of particle abundances. The program includes cascade decays of all confirmed resonances from the Particle Data Tables. The complete treatment of these resonances has been known to be a crucial factor behind the success of the statistical approach. An optional feature implemented is the Breit–Wigner distribution for strong resonances. An interface for fitting the parameters of the model to the experimental data is provided.

ELSEVIER Physics Letters B 633 (2006) 488–491

Balance of baryon number in the quark coalescence model

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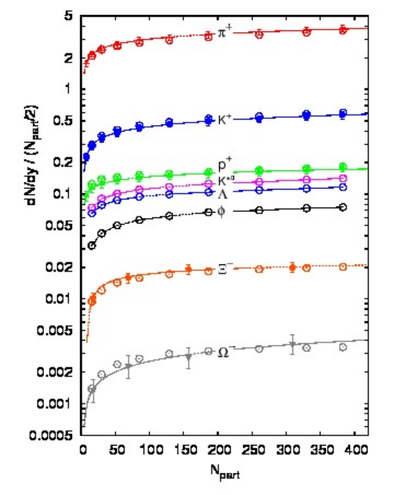
The charge and baryon balance functions are studied in the coalescence hadronization mechanism of quark–gluon plasma. Assuming that in the plasma phase the $q\bar{q}$ pairs form uncorrelated clusters whose decay is also uncorrelated, one can understand the observed small width of the charge balance function in the Gaussian approximation. The coalescence model predicts even smaller width of the baryon–antibaryon balance function: $\sigma_{B\bar{B}}/\sigma_{+-} = \sqrt{2/3}$

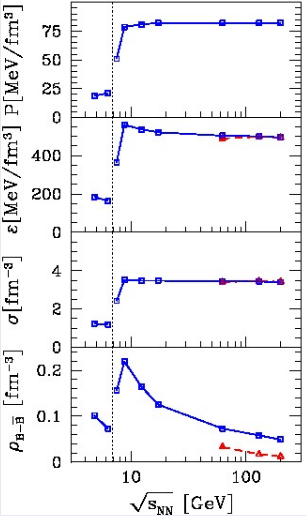
Examples SHM Analysis (Chemical Nonequilibrium)

Particle Yield Example:LHC



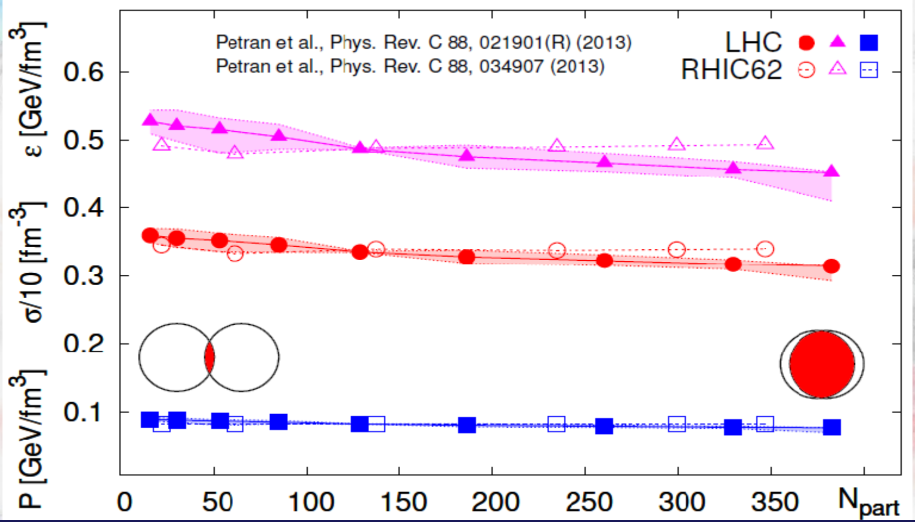
M. Petran, J.Letessier, V. Petracek, J. Rafelski Phys.Rev. C **88** (2013) no.3, 034907

Bulk properties from SHM yields



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

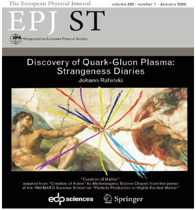
Bulk properties smooth as function of centrality – smaller systems hadronize a bit earlier: ε=energy density, σ=entropy density, P=pressure balance between bulk source and hadron gas

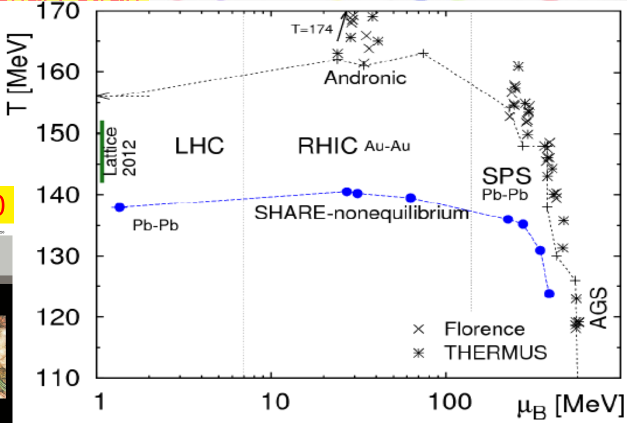


Consistency with lattice QCD REQUIRES: Chemical nonequilibrium + supercooling = sudden fireball breakup

Work with Michal Petran

Review: 2020

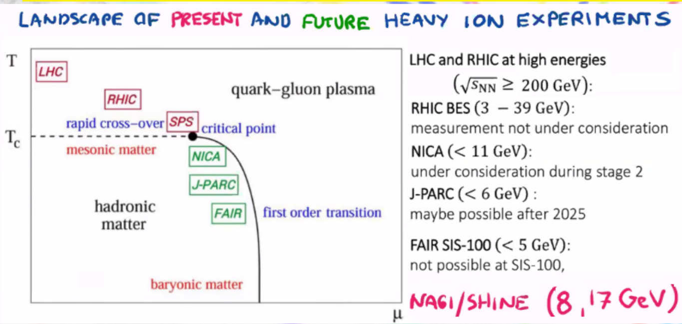




Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

Conclusion 1: This meeting demonstrated that The future is assured for RHI collisions

Many future opportunities; old projects find new purpose: says Marek

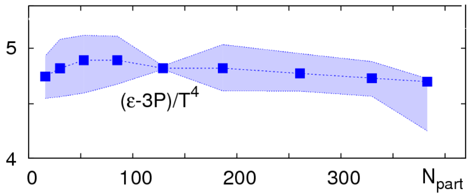


Conclusion 2: Rapid progress addressing foundations of RHI col.

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

Conclusion 3: Strangeness+SHM+non-eq-HG works

- Strange antibaryon signature of QGP leads to discovery of universal properties of QGP at hadronization; differences in:
  Fireball volume size, baryon content, and in strangeness saturation
  distinguishes SPS, RHIC, LHC, small vs large bulk systems
- We found across the entire SPS,RHIC,LHC reaction energy domain
  Universality of fireball bulk properties



  shown above in terms of the invariant measure
- Volume at hadronization grows with available energy. Strangness in QGP reaches saturation. Baryon number deposition varies:
  Puzzle: why are baryons stopped at SPS and even at RHIC?

Conclusion 4: We are in ZOOM since Kraków cherishes Traditions!!

10 Years ago: 50 years, today 60 years, … in 2060 … someone in this ZOOM-room is looking forward to the 100 year celebrations!

Long Live The Kraków School of Theoretical Physics! Sto Lat, Sto Lat niech żyj

Our plan: recapture in person the many different spirits

Time has come to thank for this wonderful hospitality

A dedication

Jean Letessier - whose name appeared in this talk multiple times, has passed away in Paris in midst of the Covid this Spring – he needed a ‘minor’ follow-up hospital treatment which did not work out. We see him below in company he did sail with (not quite) around the world. Harbor is near in this 2003 picture.

Hans Gutbrod | Jean Letessier | JR

Jean was a great friend, his advise was cherished by his colleagues at the LPTHE lab at Paris-University where he worked for 50 years.