For many details I recommend reading the 20 year old text

Hadrons and Quark–Gluon Plasma

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Jan Rafelski, CERN-TH-ALICE, June 15, 2018
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 ($q = u, d$):

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

\[ \phi(s\bar{s}), \quad \Xi(qss), \quad \bar{\Xi}(\bar{q}\bar{s}s), \quad \Omega(sss), \quad \bar{\Omega}(s\bar{s}s) \]

B: Production rates hence statistical significance is high.

C: Strange hadrons are subject to a self analyzing decay
First strangeness signature 1980: \[ \frac{s}{\bar{q}} \text{ in } \frac{\Lambda}{\bar{p}} \text{ triggers Marek's strange interest!} \]

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

\[ \frac{s}{\bar{q}} = \frac{1}{2} \left( \frac{m_s}{m} \right)^2 K_2 \left( \frac{m_s}{m} \right) e^{\mu/3T} \tag{28} \]

The function \( x^2 R^2(x) \) is, for example, tabulated in Ref. 15). For \( x = m_s/m \) 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, \( \frac{s}{\bar{q}} \approx 5 \). As \( \mu \to 0 \) there are about as many \( \bar{u} \) and \( \bar{d} \) quarks as there are \( \bar{s} \) quarks.

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

picked up by Marek in Dubna . . .
Strange hadrons from QGP: two-step formation

1. $GG \rightarrow s\bar{s}$ (thermal gluons collide)
2. $GG \rightarrow c\bar{c}$ (initial parton collision)

Gluon dominated reactions

Hadronization of pre-formed $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

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

High $m_\perp$ slope universality

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

Sudden hadronization without rescattering.

Why is the slope of baryons and antibaryons the same?
Anticipated: Central QGP fireball
Proposed evidence: (Strange)Antimatter


Conclusion: by early 1990’s we have convincing evidence of QGP formation at SPS energy heavy ion collisions including S-S.
Predicted: Strange antibaryons enhanced
Today: largest medium effect in RHI collisions

Yield / \langle N_{\text{part}} \rangle
relative to pp/p-Be

Pb-Pb at \sqrt{s_{NN}} = 2.76 \text{ TeV}

\begin{figure}
\begin{center}
\includegraphics[width=\textwidth]{chart.png}
\end{center}
\end{figure}

- \Omega^- + \Omega^+
- \Xi^-
- \Xi^+
- NA57 Pb-Pb, \mu-Pb at 17.2 \text{ GeV}
- STAR Au-Au at 200 \text{ GeV}
\( \Xi(ssq)/\phi(s\bar{s}) \) (nearly) constant:
same production mechanism

a) Confinement: \[ \implies \] breakup into free quarks not possible;
b) Strong interaction: \[ \implies \] equal hadron production strength irrespective of produced hadron type
\[ \implies \] ‘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 \( E \rightarrow T \) temperature
  \( T \) could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles:
  \( N \rightarrow \mu \iff \Upsilon = e^{(\mu/T)} \)

Our interest: bulk QGP fireball properties of hadron source evaluated independent of complex explosion dynamics \[ \implies \] analyze integrated hadron spectra.
SHARE Idea/Team: US-Polish NATO collaboration 2000

Statistical Hadronization with Resonances
Examples SHM Analysis (Chemical Nonequilibrium)

Particle Yield Example: LHC


Bulk properties from SHM yields

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.
Strange antibaryon signature of QGP: at all energies where data exist there is clear evidence for the same new state of matter. Differences: Volume, Strangeness saturation.

SHARE based determination of hadronization condition reveals near perfect Universality of fireball bulk properties across the entire reaction energy domain, and L-QCD consistency

Where we can evaluate: Baryon number deposition varies strongly as function of collision energy. This is the chemical potential dependence on collision energy. WHY? – To clarify question: why no McLerran-Bjorken transparency?
Current interest in small systems:
Strange antibaryon enhancement smoothly rising with entropy of fireball

Significant enhancement of strangeness with multiplicity in high multiplicity pp events

pp behavior resemble 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.
Small particle yield constrained by conservation law:
Canonical phase space required
PHASE TRANSITION IN HADRONTIC MATTER WITH INTERNAL SYMMETRY *)

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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.
Strangeness conservation alone
p225-232: 1-2-3-strange flavored particle suppression factors

\[ \langle N_{\kappa}^{CE} \rangle = N_{\kappa}^{GC} \frac{I_{\kappa}(2N_{\text{pair}}^{GC})}{I_0(2N_{\text{pair}}^{GC})}. \]

Canonical yield-suppression factors \( I_{\kappa}/I_0 \) 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.
A few first analysis observations and summary

- We performed a few hobby (lack of resources) analysis of the ALICE small system results and there is evidence that in addition to the growth $\gamma_s$ of strangeness yield with size of the system there is canonical phase space required as was expected. Effects are not overwhelming but noticeable.

- Hadronization conditions seems a few MeV higher compared to large systems: conclusion there is no supercooling, less explosive expansion.

- Corresponding bulk matter properties are higher. No test of universal hadronization / conformal anomaly was performed.

- Small system flavor content universally zero (and it seems we are sensitive due to small system): there is no electric charge, etc. So a few (more than one) canonical constraints need to be implemented. Maybe Bjorken model (scaling solution) works for ALICE $pp$ results.

No systematic effort to prove any of this was undertaken (lack of resources).
The Universe Composition in Single View

Different dominance eras: Temperature grows to right