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Faces of quark matter

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Abstract. Based on an analysis in the framework of a coalescence hadronization model (ALCOR) we conclude that in heavy ion collisions at CERN SPS and RHIC energies a new type of matter, the massive quark-antiquark matter is produced.

Keywords: quark-gluon plasma, hadronization
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1. Introduction

The heavy ion community is on the search of quark-gluon plasma already for more than 30 years. For this purpose large amount of money was spent. Thus it is timely to ask the question: what have we delivered in exchange for this support? Could we produce a piece of quark-gluon plasma? Have we determined the properties of this matter? Could we arrive to results which will be worthwhile to mention after a few years has passed?

In this lecture we try to shed some light to a few of these questions.

2. Time evolution of heavy ion collision

The different reaction models offer even qualitatively very dissimilar pictures for the flow chart of a heavy ion collision (see Fig.1). Some of the models assume that the first collision of the incoming nucleons produce directly most of the hadrons appearing in the final state. In contrast other models are based on the production of a collective intermediate state which expands and hadronize in a later stage only. Some of them use even the concept of thermal equilibrized intermediate state. The main goal of heavy ion research is to find out whether this collective state is formed in the heavy ion collision, and if it is formed then what are its properties.

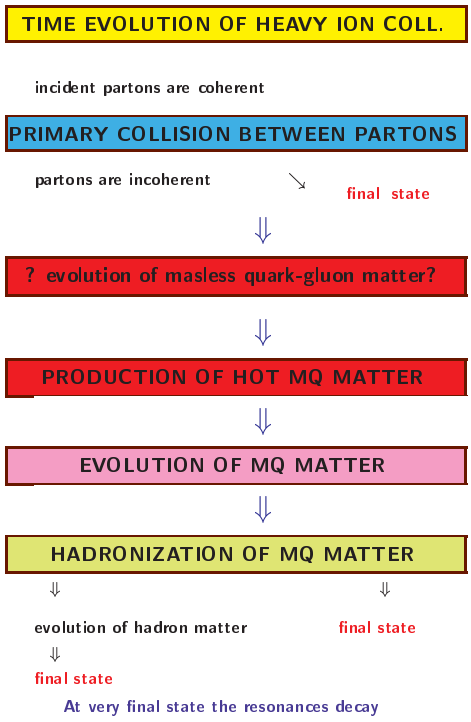

Fig. 1. The flowchart of the heavy ion collision. Notation: MQ = massive quark

3. Qualitative considerations

When we try to draw a picture of the heavy ion collisions, it is enlightening to recall two earlier ideas (perhaps in a somewhat subjective way).

V.N. Gribov pointed out that in the nucleon-nucleus reaction at the first collision the incident nucleon looses its low momentum components, since their cross section are the largest (Ref. [1]). The remaining "wounded nucleon" (A. Bialas in Ref. [2]) will interact with the next nucleon in a modified way.

According to the above considerations we can distinguish the following type of collisions:

a) soft collisions: the dress of both incoming nucleons is intact;

b) semi-hard collisions: one of the incoming nucleons is "wounded", while the other incoming nucleon has an intact dressing;

c) both incoming nucleons are wounded.

One more fact: in a recent calculation it was shown that the transverse momentum distribution of partons produced in the collision of bombarding and target partons has an exponential shape [3]. Fig. 2 displays the m_t distributions of the produced massive quarks obtained in a perturbative QCD calculation, The spectral shape, which is exponential in a wide m_t range is a result of the structure of the reaction matrix element. Thus the observation of an exponential spectrum is by no means an indication of any thermalization.

With these considerations in mind we may phrase the following problems:
• Is it true, that the strange quark-antiquark pairs ($s\overline{s}$ are produced thermally in the fireball?
• Or are they produced in the primary collisions?
• In the latter case the $s\overline{s}$ pairs are not a signature for quark-antiquark plasma.

Nevertheless the free recombination of massive quarks and antiquarks is a signature for the formation of deconfined quark-antiquark matter.

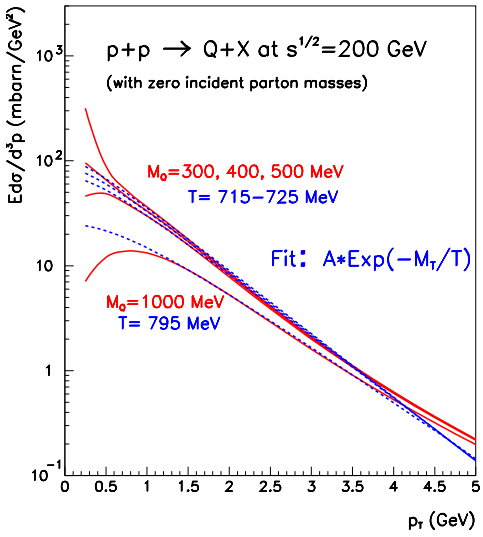

Fig. 2. Invariant transverse momentum spectra of massive quarks produced in $p+p$ reaction at $\sqrt{s}=200$ GeV. The incident parton masses are zero, the produced quarks are heavy with effective masses $M_Q = 300, 400, 500, 1000$ MeV. Figure is redrawn from Ref. [3].

4. The early concept of the quark matter

At the beginning for the description of hadron matter — quark-gluon plasma phase transition we used the following ideas:
• at the beginning of heavy ion collision a quark-gluon plasma with massless quarks, antiquark and gluons is produced;
• a first order phase transition occurs, quasistatically satisfying the Gibbs criteria;
• homogeneous distributions and a few averaged particle properties (e.g. μ_q, μ_s, T) describe everything
ALL THESE IDEAS ARE KILLED BY THE NEW OBSERVATIONS obtained at CERN SPS for the rapidity dependence of the multiplicity ratios (see Fig. 3).

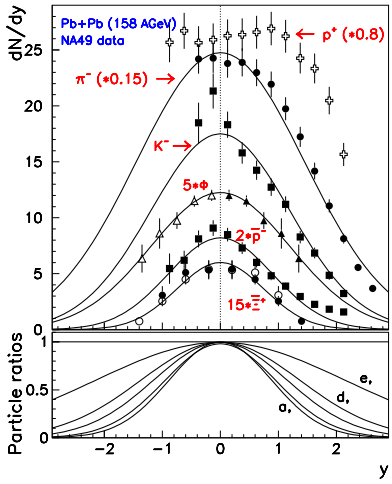

Fig. 3. Top panel: Normalized rapidity spectra of hadrons produced in Pb+Pb collision at $E_{LAB} = 158$ AGeV. Data are from Refs.[4, 5]. Bottom panel: particle ratios normalized to unity at the mid-rapidity. The lines indicate: a, $\overline{\Xi}^+/K^-$; b, $\overline{\Xi}^+/\Phi$; c, $\overline{p}^-/\pi^-$; d, $\overline{p}^-/K^-$; e, Φ/π^-.

The BRAHMS experiment at RHIC confirms the strong rapidity dependence, the proton to antiproton ratio was measured at different rapidities as: $\overline{p}/p = 0.64 \pm 0.03$ at $y = 0$ and $\overline{p}/p = 0.41 \pm 0.03$ at $y = 2$ [6].

It was observed also, that the expansion of the hot region is very fast, excluding the possibility of a slow quasistatic phase transition.

What is the way out from this contradictory situation?

One has to introduce a new concept instead of assuming an ideal massless quark-gluon plasma. Such an attempt is done in the ALCOR model introducing the massive quark-antiquark matter.

5. The ALCOR (ALgebraic COalescence Rehadronization) model

In the ALCOR model [7,8] we assume, that just before the hadronization the dense matter can be described as a mixture of dressed up, massive quarks and antiquarks. The effective mass of the gluons at this point is much larger than that of the quarks [9], consequently the gluon fission into quark-antiquark pairs is enhanced and massive gluons disappear from the mixture. During the hadronization the quark numbers, as well as the antiquark numbers, remain constant.

At this point it is proper to insert a short explanation. At very high temperature, say at $T > 3 * T_c$ we may assume a non interacting quark-antiquark-gluon plasma with zero mass (current mass) constituents. However, as we approach the critical temperature, the interaction between the constituents will become stronger and stronger. This intensive interaction is expressed by the large effective mass of the constituents, which automatically reduce the pressure, faster then the energy density.

5.1. Basic equations of the ALCOR hadronization model

According to the coalescence assumption the hadron numbers are proportional to the number of quarks from which they consist. For baryons and antibaryons we assume

$$\begin{array}{rclll} p & = & C_{\rm p}\, b_{\rm q}\, b_{\rm q}\, b_{\rm q}\, q\, q\, q & \overline{p} = C_{\overline{p}}\, b_{\overline{\rm q}}\, b_{\overline{\rm q}}\, b_{\overline{\rm q}}\, \overline{q}\, \overline{q}\, \overline{q} & \pi = C_{\pi}\, b_{\rm q}\, b_{\overline{\rm q}}\, q\, \overline{q} \\ \Lambda & = & C_{\Lambda}\, b_{\rm q}\, b_{\rm q}\, b_{\rm s}\, q\, q\, s & \overline{\Lambda} = C_{\overline{\Lambda}}\, b_{\overline{\rm q}}\, b_{\overline{\rm q}}\, b_{\overline{\rm s}}\, \overline{q}\, \overline{q}\, \overline{s} & K = C_{K}\, b_{\rm q}\, b_{\overline{\rm s}}\, q\, \overline{s} \\ \Xi & = & C_{\Xi}\, b_{\rm q}\, b_{\rm s}\, b_{\rm s}\, q\, s\, s & \overline{\Xi} = C_{\overline{\Xi}}\, b_{\overline{\rm q}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, \overline{q}\, \overline{s}\, \overline{s} & \overline{K} = C_{\overline{K}}\, b_{\overline{\rm q}}\, b_{\rm s}\, \overline{q}\, s \\ \Omega & = & C_{\Omega}\, b_{\rm s}\, b_{\rm s}\, b_{\rm s}\, s\, s\, s & \overline{\Omega} = C_{\overline{\Omega}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, \overline{s}\, \overline{s}\, \overline{s} & \eta = C_{\eta}\, b_{\overline{\rm s}}\, b_{\rm s}\, \overline{s}\, s \end{array} \qquad (1)$$

Here the normalization coefficients, $b_{\rm i}$, are determined uniquely by the requirement, that the number of the massive quarks do not change during the hadronization. Due to this principle we have 4 (6 , if u and d are treated separately) conserved quantities in contrast to the 2 parameters $\mu_{baryon}, \mu_{strange}$ of the thermal models

This is the basic assumption for all quark counting methods The equations showing that the number of a given type of quarks in the final hadron population must be equal to the number of this type of quarks in the hadronizing quark matter are as follows:

$$\begin{array}{rcl} s & = & 3\,\Omega + 2\,\Xi + \Lambda + \overline{K} + \eta \\ \overline{s} & = & 3\,\overline{\Omega} + 2\,\overline{\Xi} + \overline{\Lambda} + K + \eta \\ q & = & 3\,p + \Xi + 2\,\Lambda + K + \pi \\ \overline{q} & = & 3\,\overline{p} + \overline{\Xi} + 2\,\overline{\Lambda} + \overline{K} + \pi\ . \end{array} \qquad (2)$$

5.2. The consequences of the simplified equations

Applying the trivial assumption that the coalescence coefficient for a given type of particle and antiparticle is the same : $C_x = C_{\overline{x}}$, we obtain the following antibaryon to baryon ratios:

$$\begin{aligned}
\frac{\overline{p}}{p} &= \frac{b_{\overline{\mathrm{q}}}\, b_{\overline{\mathrm{q}}}\, b_{\overline{\mathrm{q}}}\, \overline{q}\,\overline{q}\,\overline{q}}{b_{\mathrm{q}}\, b_{\mathrm{q}}\, b_{\mathrm{q}}\, q\, q\, q} \\
\frac{\overline{\Lambda}}{\Lambda} &= \frac{b_{\overline{\mathrm{q}}}\, b_{\overline{\mathrm{q}}}\, b_{\overline{\mathrm{s}}}\, \overline{q}\,\overline{q}\,\overline{s}}{b_{\mathrm{q}}\, b_{\mathrm{q}}\, b_{\mathrm{s}}\, q\, q\, s} = \frac{b_{\mathrm{q}}\, b_{\overline{\mathrm{s}}}\, q\,\overline{s}}{b_{\overline{\mathrm{q}}}\, b_{\mathrm{s}}\, \overline{q}\, s} \cdot \frac{\overline{p}}{p} \\
\frac{\overline{\Xi}}{\Xi} &= \frac{b_{\overline{\mathrm{q}}}\, b_{\overline{\mathrm{s}}}\, b_{\overline{\mathrm{s}}}\, \overline{q}\,\overline{s}\,\overline{s}}{b_{\mathrm{q}}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, q\, s\, s} = \frac{b_{\mathrm{q}}\, b_{\overline{\mathrm{s}}}\, q\,\overline{s}}{b_{\overline{\mathrm{q}}}\, b_{\mathrm{s}}\, \overline{q}\, s} \cdot \frac{\overline{\Lambda}}{\Lambda} \\
\frac{\overline{\Omega}}{\Omega} &= \frac{b_{\overline{\mathrm{s}}}\, b_{\overline{\mathrm{s}}}\, b_{\overline{\mathrm{s}}}\, \overline{s}\,\overline{s}\,\overline{s}}{b_{\mathrm{s}}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, s\, s\, s} = \frac{b_{\mathrm{q}}\, b_{\overline{\mathrm{s}}}\, q\,\overline{s}}{b_{\overline{\mathrm{q}}}\, b_{\mathrm{s}}\, \overline{q}\, s} \cdot \frac{\overline{\Xi}}{\Xi}
\end{aligned} \tag{3}$$

Here we introduce the notation

$$D = \frac{b_{\mathrm{q}}\, b_{\overline{\mathrm{s}}}\, q\,\overline{s}}{b_{\overline{\mathrm{q}}}\, b_{\mathrm{s}}\, \overline{q}\, s} = \frac{K}{\overline{K}} \tag{4}$$

and thus with this we can can write eq. (3) in the simple form

$$\frac{\overline{\Lambda}}{\Lambda} = D \cdot \frac{\overline{p}}{p} \qquad \frac{\overline{\Xi}}{\Xi} = D \cdot \frac{\overline{\Lambda}}{\Lambda} \qquad \frac{\overline{\Omega}}{\Omega} = D \cdot \frac{\overline{\Xi}}{\Xi} \tag{5}$$

Such simple relations as shown in eqs. (3)-(5) were first obtained for the linear coalescence model ($b_i \equiv 1$ for all b_i) in Ref. [10].

5.3. Coalescence equations without isospin symmetry

The effect of isospin asymmetry also can be taken into account in ALCOR by the proper quark combinatorics in the rehadronization. After relaxing the isospin symmetry assumption we treat the u and d quarks separately.

The coalescence equations for baryonic and mesonic flavor clusters now read:

$$\begin{aligned}
p^+ &= C_{\mathrm{p}}\, b_{\mathrm{u}}\, b_{\mathrm{u}}\, b_{\mathrm{d}}\, u\, u\, d & \pi^+ &= C_{\pi^+}\, b_{\mathrm{u}}\, b_{\overline{\mathrm{d}}}\, u\,\overline{d} \\
n^0 &= C_{\mathrm{n}}\, b_{\mathrm{u}}\, b_{\mathrm{d}}\, b_{\mathrm{d}}\, u\, d\, d & \pi^0 &= C_{\pi^0}\, (b_{\mathrm{u}}\, b_{\overline{\mathrm{u}}}\, u\,\overline{u} + b_{\mathrm{d}}\, b_{\overline{\mathrm{d}}}\, d\,\overline{d})/2 \\
\Lambda^0 + \Sigma^0 &= C_{\Lambda}\, b_{\mathrm{u}}\, b_{\mathrm{d}}\, b_{\mathrm{s}}\, u\, d\, s & \pi^- &= C_{\pi^-}\, b_{\mathrm{d}}\, b_{\overline{\mathrm{u}}}\, d\,\overline{u} \\
\Sigma^+ &= C_{\Sigma^+}\, b_{\mathrm{u}}\, b_{\mathrm{u}}\, b_{\mathrm{s}}\, u\, u\, s & K^+ &= C_{K^+}\, b_{\mathrm{u}}\, b_{\overline{\mathrm{s}}}\, u\,\overline{s} \\
\Sigma^- &= C_{\Sigma^-}\, b_{\mathrm{d}}\, b_{\mathrm{d}}\, b_{\mathrm{s}}\, d\, d\, s & K^- &= C_{K^-}\, b_{\overline{\mathrm{u}}}\, b_{\mathrm{s}}\, \overline{u}\, s \\
\Xi^0 &= C_{\Xi^0}\, b_{\mathrm{u}}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, u\, s\, s & K^0 &= C_{K^0}\, b_{\mathrm{d}}\, b_{\overline{\mathrm{s}}}\, d\,\overline{s} \\
\Xi^- &= C_{\Xi^-}\, b_{\mathrm{d}}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, d\, s\, s & \overline{K}^0 &= C_{\overline{K}^0}\, b_{\overline{\mathrm{d}}}\, b_{\mathrm{s}}\, \overline{\mathrm{d}}\; s \\
\Omega^- &= C_{\Omega}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, b_{\mathrm{s}}\, s\, s\, s & \eta &= C_{\eta}\, b_{\overline{\mathrm{s}}}\, b_{\mathrm{s}}\, \overline{s}\, s \\
& & \eta' &= C_{\eta'}\, (b_{\mathrm{u}}\, b_{\overline{\mathrm{u}}}\, u\,\overline{u} + b_{\mathrm{d}}\, b_{\overline{\mathrm{d}}}\, d\,\overline{d})/2
\end{aligned} \tag{6}$$

Here again the normalization coefficients, $b_{\rm i}$, are determined uniquely by the quark number conservation demand:

$$\begin{aligned}
u &= 2\,p^+ + n^0 + \Lambda^0 + \Sigma^0 + 2\,\Sigma^+ + \Xi^0 + \pi^+ + (\pi^0+\eta')/2 + K^+ \\
\overline{u} &= 2\,\overline{p}^- + \overline{n}^0 + \overline{\Lambda}^0 + \overline{\Sigma}^0 + 2\,\overline{\Sigma}^- + \overline{\Xi}^0 + \pi^- + (\pi^0+\eta')/2 + K^- \\
d &= 2\,n^0 + p^+ + \Lambda^0 + \Sigma^0 + 2\,\Sigma^- + \Xi^- + \pi^- + (\pi^0+\eta')/2 + K^0 \\
\overline{d} &= 2\,\overline{n}^0 + \overline{p}^- + \overline{\Lambda}^0 + \overline{\Sigma}^0 + 2\,\overline{\Sigma}^+ + \overline{\Xi}^+ + \pi^+ + (\pi^0+\eta')/2 + \overline{K}^0 \\
s &= 3\,\Omega^- + 2\,\Xi^- + 2\,\Xi^0 + \Lambda^0 + \Sigma^0 + \Sigma^+ + \Sigma^- + \overline{K}^0 + K^- + \eta \\
\overline{s} &= 3\,\overline{\Omega}^+ + 2\,\overline{\Xi}^+ + 2\,\overline{\Xi}^0 + \overline{\Lambda}^0 + \overline{\Sigma}^0 + \overline{\Sigma}^- + \overline{\Sigma}^+ + K^0 + K^+ + \eta
\end{aligned} \qquad (7)$$

In eq. (10) π is the number of directly produced pions. (Note that most of the observed pions are created in the decay of resonances.)

5.4. Consequences of the isospin asymmetric equations

The isospin asymmetric ALCOR gives the following baryon ratios:

$$\begin{aligned}
\frac{\overline{p}}{p} &= \frac{b_{\overline{\rm u}}\, b_{\overline{\rm u}}\, b_{\overline{\rm d}}\, \overline{u}\,\overline{u}\,\overline{d}}{b_{\rm u}\, b_{\rm u}\, b_{\rm d}\, u\, u\, d} \\
\frac{\overline{\Lambda}}{\Lambda} &= \frac{b_{\overline{\rm u}}\, b_{\overline{\rm d}}\, b_{\overline{\rm s}}\, \overline{u}\,\overline{d}\,\overline{s}}{b_{\rm u}\, b_{\rm d}\, b_{\rm s}\, u\, d\, s} = \frac{b_{\rm u}\, b_{\overline{\rm s}}\, u\,\overline{s}}{b_{\overline{\rm u}}\, b_{\rm s}\, \overline{u}\, s} \cdot \frac{\overline{p}}{p} \\
\frac{\overline{\Xi}^0}{\Xi^0} &= \frac{b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, \overline{u}\,\overline{s}\,\overline{s}}{b_{\rm u}\, b_{\rm s}\, b_{\rm s}\, u\, s\, s} = \frac{b_{\rm d}\, b_{\overline{\rm s}}\, d\,\overline{s}}{b_{\overline{\rm d}}\, b_{\rm s}\, \overline{d}\, s} \cdot \frac{\overline{\Lambda}}{\Lambda} \\
\frac{\overline{\Xi}^+}{\Xi^-} &= \frac{b_{\overline{\rm d}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, \overline{d}\,\overline{s}\,\overline{s}}{b_{\rm d}\, b_{\rm s}\, b_{\rm s}\, d\, s\, s} = \frac{b_{\rm u}\, b_{\overline{\rm s}}\, u\,\overline{s}}{b_{\overline{\rm u}}\, b_{\rm s}\, \overline{u}\, s} \cdot \frac{\overline{\Lambda}}{\Lambda} \\
\frac{\overline{\Omega}}{\Omega} &= \frac{b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, b_{\overline{\rm s}}\, \overline{s}\,\overline{s}\,\overline{s}}{b_{\rm s}\, b_{\rm s}\, b_{\rm s}\, s\, s\, s} = \frac{b_{\rm d}\, b_{\overline{\rm s}}\, d\,\overline{s}}{b_{\overline{\rm d}}\, b_{\rm s}\, \overline{d}\, s} \cdot \frac{\overline{\Xi}^+}{\Xi^-}
\end{aligned} \qquad (8)$$

Let us introduce the notations:

$$B = \frac{b_{\rm d}\, b_{\overline{\rm s}}\, d\,\overline{s}}{b_{\overline{\rm d}}\, b_{\rm s}\, \overline{d}\, s} = \frac{K^0}{\overline{K}^0}\,, \qquad D = \frac{b_{\rm u}\, b_{\overline{\rm s}}\, u\,\overline{s}}{b_{\overline{\rm u}}\, b_{\rm s}\, \overline{u}\, s} = \frac{K^+}{K^-}\,, \qquad C = \frac{B}{D} = \frac{K^0/\overline{K}^0}{K^+/K^-} \qquad (9)$$

Using these factors B, C and D, antibaryon to baryon ratios can be written as

$$\begin{aligned}
\frac{\overline{\Lambda}^0}{\Lambda^0} &= D \cdot \frac{\overline{p}^-}{p^+} \qquad & \frac{\overline{\Xi}^0}{\Xi^0} &= C \cdot D \cdot \frac{\overline{\Lambda}^0}{\Lambda^0} \\
\frac{\overline{\Xi}^+}{\Xi^-} &= D \cdot \frac{\overline{\Lambda}^0}{\Lambda^0} \qquad & \frac{\overline{\Omega}^+}{\Omega^-} &= C \cdot D \cdot \frac{\overline{\Xi}^+}{\Xi^-}
\end{aligned} \qquad (10)$$

The correction factor C shows the effect of isospin. For a system with equal number of neutrons and protons $C = 1$. For other cases it can be obtained by inserting the experimental values into the defining equation, eq. (10), or calculating it from a model. In the ALCOR $C = 1.0$ due to isospin symmetry.

Addendum: in the complete ALCOR calculation the resonances belonging to the two lowest baryon multiplets and to the lowest two meson multiplets are also included.

6. Hadron ratios at midrapidity at RHIC

If we are interested of particle multiplicities in a restricted rapidity interval, we have to use in the equations described above the quark numbers belonging to this interval and then the hadron numbers obtained from the coalescence equations are also those belonging to this interval.

7. Comparison with experimental data

7.1. Parameter free predictions of ALCOR

The set of relations eq. (3) and eq. (10) are parameter free predictions. They agree surprisingly well with the experimental results at SPS and RHIC energies on the ratios $\overline{p}/p$, $\overline{\Lambda}/\Lambda$, $\overline{\Xi}/\Xi$, $\overline{\Omega}/\Omega$ and K^-/K^+, as it was shown in Ref. [11].

7.2. The full ALCOR calculation

For the full calculation we have to define the three input parameters of ALCOR [7,8]:
• number of new $u\overline{u}$ and $d\overline{d}$ pairs is obtained from the number of π^- (or h^-);
• number of new strange $s\overline{s}$ pairs is obtained from the number of K^- (or K^-/π^-);
• the stopping factor (i.e. the percentage of incident quarks stopped into the investigated rapidity interval) is obtained from the ratio K^+/K^-.

Now one can use the ALCOR model for Au+Au collision at $\sqrt{s} = 130$ AGeV. We choose 211 newly produced $u\overline{u}$ and $d\overline{d}$ pairs, and 105.5 $s\overline{s}$ pairs (which means $f_s = 2N_{s\overline{s}}/(N_{u\overline{u}} + N_{d\overline{d}}) = 0.5$) and assume that 5.8 % of the total nucleon numbers stopped into the central unit of rapidity (which means 9 protons and 14 neutrons) in the Au+Au collision. We can calculate the rapidity densities and hadronic ratios in the central rapidity region, where experimental data exist. Table 1 displays published experimental data and the appropriate calculated ALCOR results. The ALCOR parameters were fixed from the first 3 measured data.

	ALCOR model	Experimental data	STAR reference
h^-	280	280 ± 20	[12]
K^-/π^-	0.14	0.15 ± 0.01	[13]
K^+/K^-	1.14	1.14 ± 0.06	[13]
$\overline{p}^-/p^+$	0.63	0.60 ± 0.03	[13]
$\overline{\Lambda}/\Lambda$	0.73	0.73 ± 0.03	[13]
$\overline{\Xi}^+/\Xi^-$	0.83	0.82 ± 0.08	[13]
Ξ^-/π^-	0.015	0.013 ± 0.01	[14]
Φ/K^{*0}	0.38	0.49 ± 0.13	[15]
$\overline{p}^-/h-$	0.087	0.070 ± 0.002	[16]

Table 1. Hadron production in Au+Au collision at $\sqrt{s} = 130$ AGeV from the ALCOR model and the experimental data from STAR [12–16]. The first 3 rows are the inputs for fit the 3 necessary ALCOR parameters.

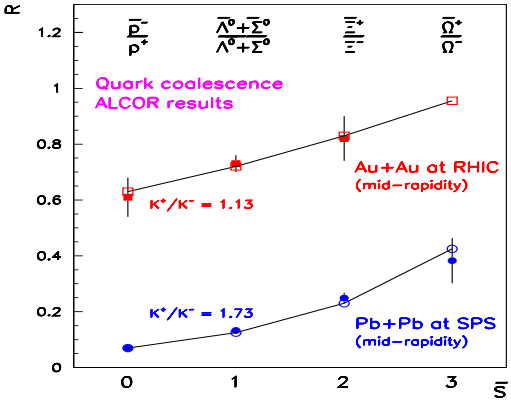

Fig. 4. Calculated (open symbols) and measured (full symbols) hyperon ratios for SPS (WA97) and RHIC (STAR) experiments, see Ref. [17].

8. Energy dependence of physical quantities

Since the rapidity density of charged particles is increasing with increasing energy, we can investigate the energy dependence of the ALCOR parameters. From available AGS, SPS and RHIC data (see Fig. 5), one can determine the 3 necessary parameters and calculate the results from the ALCOR model. Fig. 6. displays the tendency of the stopping into the mid-rapidity region and Fig. 7 shows the energy dependence of the number of newly produced light quark-antiquark pairs ($dN_{u\overline{u}}/dy$) and the strange ones indicated by f_s in a logarithmic energy scale.

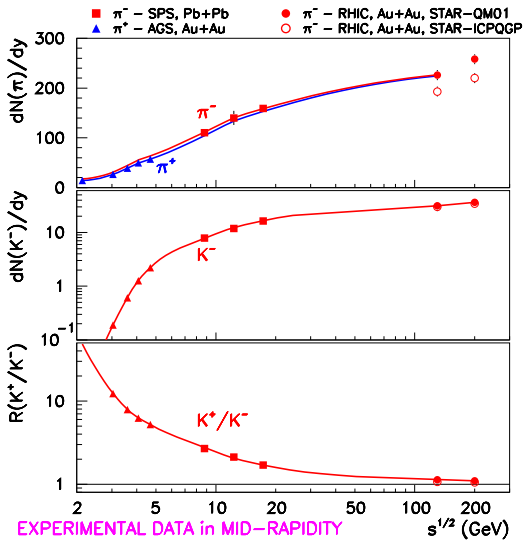

Fig. 5. The three input (measured) data for ALCOR as a function of energy. Data are from the AGS, SPS and RHIC experiments.

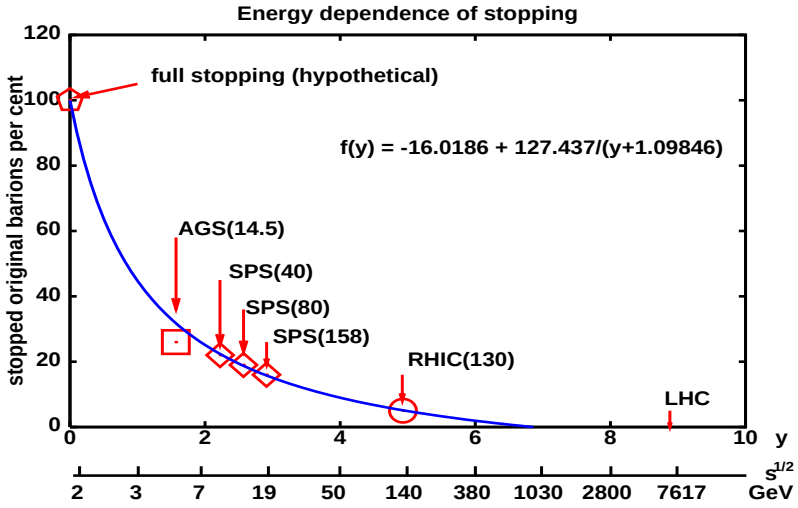

Fig. 6. Energy dependence of the stopping parameter in the mid-rapidity region.

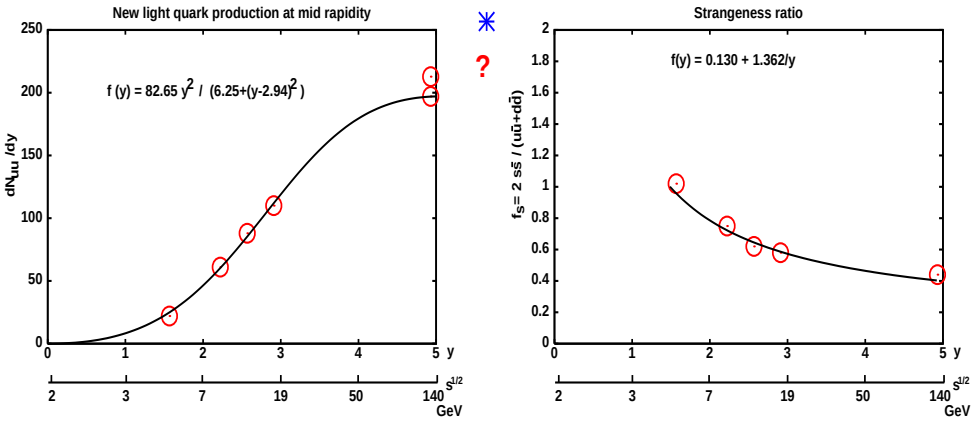

Fig. 7. The energy dependence of the ALCOR parameters: the rapidity density, $dN_{uu}/dy = dN_{dd}/dy$, of newly produced light quark-antiquark pairs (left panel); ratio of the newly produced strange quark-antiquark quarks to non-strange ones, f_s (right panel).

9. Charge fluctuation

In a recent paper [18] interesting observation was made on the problem of charge fluctuation. In earlier papers it was suggested [19], that the ratio

$$D = 4\frac{< \delta Q^2 >}{< N_{ch} >} \tag{11}$$

is $D \approx 3$ for hadron gas in equilibrium, while it is $D \approx 1$ for the quark gluon plasma. Here $< \delta Q^2 >$ is the average of the charge fluctuation and $< N_{ch} >$ is the average value of the charge multiplicity. The measured D value is near to 3 . That would indicate that in heavy ion reactions not a quark-gluon plasma, but a hadron gas was produced. However, in Ref.[18], it was shown, that in the coalescence scenario (ALCOR) one can also expect a $D \approx 3$ value. Thus one can conclude that the measured charged fluctuation is also in agreement with the basic assumption of the ALCOR, i.e. during the hadronization the number of constituent quarks and the number of constituent antiquarks are conserved.

10. Conclusion

In this paper we have shown that the assumptions of the ALCOR model are in agreement with the experimental facts. These assumptions are: a) the matter just before the hadronization consists of a mixture of massive quarks and antiquarks; b) the number both of the quarks and the antiquarks are conserved during the sudden hadronization; c) the hadrons are formed by coalescence process.

We have investigated the energy dependence of particle ratios and thus found that the Wroblinski factor (f_s) has a definite energy dependence. This indicates that the strange quark-antiquark pairs and the light quark-antiquark pairs are produced with different mechanisms having different energy dependence.

We quoted Ref. [18], where it was shown that the charge fluctuations calculated from the massive quark matter is also in agreement with the experimental results.

Finally we may conclude, that we have not seen the signature of an ideal quark-gluon plasma, but **we found that in the heavy ion collisions a new type of matter, the massive quark-antiquark matter is produced**.

Note added in proof: The quark coalescence model was misubderstood many times and it induced surprisingly strong misinterpretations. This situation is well demonstrated in the critic of a very recent publication (see Ref. [20]), where it was stated:

"The emphases in refs. [10,11] are in the multiplicative aspect of the probabilities of having quarks and antiquarks in the same region of the phase space in their formation of hadrons. That results in an undesirable feature of s and $\overline{s}$ imbalance in the linear version [10], which is not satisfactorily resolved in the nonlinear version [11] by the introduction of unknown factors."

In the contrary, in both Refs. [10, 11] particle ratios are calculated in a way, that all unknown factors drop from the results. In the nonlinear version the b_i coefficients are normalization factors ensuring the different particle conservation rules. To interpret these normalization factors as "introduction of unknown factors" is equivalent to such a statement, that the conservation of electric charge is an introduction of an "unknown rule".

In our opinion the appearence of the b_i factors in our calculations is not quite trivial, but nevertheless it is not that difficult to understand.

Acknowledgments

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