HYPERON RATIOS AT RHIC AND THE COALESCEENCE PREDICTIONS AT MID-RAPIDITY

J. ZIMÁNYI, P. LÉVAI, T. CSÖRGŐ, T.S. BIRÓ
MTA KFKI RMKI, H-1525 Budapest 114, POB 49, Hungary
e-mail: jzimanyi@sunserv.kfki.hu

Quark coalescence predictions for various multi-strange baryon to anti-baryon ratios for central Au+Au collisions at RHIC energies are compared to preliminary data of the STAR collaboration. The formation of Quark Matter and the sudden recombination of its constituent quarks into hadrons is found to be in agreement with these preliminary data. It seems that strange hadron and antihadron production in Au+Au collisions at RHIC is similar to that in Pb+Pb collisions at CERN SPS.

In the Quark Matter’99 conference the possibility of an interesting scenario for the RHIC reactions was pointed out. Namely we may meet the situation that in the first stage of the collision a sort of quark gluon plasma fireball is formed. This fireball expands and cools, and just before the hadronization this matter may change into a Quark Matter similar to that state which was present at the SPS Pb+Pb collisions at the beginning of hadronization. The basic degrees of freedom of this state are the dressed valence quarks, the gluonic degrees of freedom are suppressed e.g. due to their large effective mass. The earlier fragmentation of these gluons resulted in new valence quarks, that are the constituents of the final state hadrons. Keeping in mind this possibility, theoretical predictions were made for the RHIC Au+Au collisions based on a coalescence model, which successfully described - among others - the antihyperon to hyperon ratios at SPS.

Recently preliminary experimental data were shown for these ratios by the STAR collaboration. Thus it is timely to compare these new experimental results with the theoretical predictions.

1 The Linear Coalescence Model

In the following we shall demonstrate the deficiency of the linear coalescence model in a very simple case. The idea of coalescence was created many years ago for the understanding of some low energy nuclear physics problems. Among others the production of deuterons in low energy heavy ion reaction was explained by the assumption that a neutron and a proton will coalesce if they are near to each other in space and momentum space. We shall denote by \( k \) the number of particles of type \( k \) within the rapidity interval, in which...
the particle ratios are constant. (In low energy reactions these numbers are the total numbers of particles within the fireball.) The number of produced deuterons, \(d\), is assumed to be proportional to the number of protons, \(p\), and the number of neutrons, \(n\). The factor of proportionality, \(c_d\), can be calculated from the elementary cross sections and the phase-space distribution of protons and neutrons. This leads to the linear coalescence model prediction

\[
d = c_d p n. \tag{1}
\]

This kind of relationship expresses the essence of the linear coalescence model. It is an acceptable approximation as long as a small fraction of protons and neutrons will coalesce into deuterons, \(c_d << 1\). The linear coalescence model, however, has a serious deficiency if a substantial part of the nucleons are forced into deuterons. To demonstrate the problem, let us assume, that \(p = n = A\), and all the nucleons have to be confined into deuterons at the end of the fireball lifetime. This way we model a situation similar to the hadronization of the constituent quark matter. The conservation of baryon number demands that the baryon charge should be preserved during the coalescence process:

\[
p + n = 2d \tag{2}
\]

which leads to the requirement

\[
p + n = 2 c_d p n, \tag{3}
\]

that implies

\[
2A = 2c_d A^2. \tag{4}
\]

Baryon number conservation and linear coalescence thus requires

\[
c_d = 1/A. \tag{5}
\]

However, the coalescence coefficient \(c_d\) can be calculated from the cross section of the \(p + n \rightarrow d\) reaction and the phase-space distribution of protons and neutrons, independently of the total number of these particles, \(2A\). Hence eq. (4) cannot be fulfilled in the general case and the assumption of linear coalescence leads to contradiction.

What is the logical error in the linear coalescence model which leads to the above, obviously unacceptable result? Essentially this is the lack of a feed-back: those nucleons, who are already bound in a deuteron, cannot be used any further for the formation of new deuterons. Out of \(A\) protons and \(A\) neutrons, exactly \(A\) deuterons can be formed, if a bound state formation happens with unit probability. However, linear coalescence calculation would predict \(\propto A^2\) deuterons, which is way too large, if \(A >> 1\).
This sort of error in linear coalescence can be corrected by introducing a suitable renormalization factor, $b$, which takes care of the additional reduction of produced particles due to the lack in the reactivity of the already bound constituents. This leads to reconciliation of the constraints from conservation laws and the proportionality of produced particles with the available number of their constituents.

With this re-normalization factor, the coalescence equation eq. (1) is modified,

$$d = c_d b_p p b_n n,$$

and eq.(3) still ensures the conservation of the baryon charge. In the simple case of $p = n = A$, this determines the normalization factor, $b_p = b_n = b$ and predicts the of deuterons, $d$, as follows:

$$b = \frac{1}{(c_d A)^{1/2}},$$

$$d = A \neq p n = A^2.$$

Note also that the total number of deuterons after the completion of the recombination becomes independent from the exact value of the coalescence coefficient $c_d$, because of the constraint that all protons and neutrons have to be converted to deuterons in this example. This has to be contrasted to the result of linear coalescence calculations, where the formation of a small number of deuterons from a gas of protons and neutrons depends essentially on the coefficient of coalescence, $c_d$.

The method of introduction of normalization coefficients can be generalized for more complex cases that involve the full recombination of different type of constituents into various kind of bound states subjected to conservation laws. In case of hadronization (recombination of valence quarks into hadrons), the resulting non-linear quark coalescence model is the ALCOR model, the name of which stands for ALgebraic COalescence in Rehadronization.

2 ALCOR: Quark Combinatorics in Rehadronization

The nonlinear ALCOR coalescence model was created for situations, where the subprocesses are not independent, they compete with each other. In this model the coalescence equations relating the number of a given type of hadron to the product of the numbers of different quarks from which the hadron consists reads as:
\[ p = C_p b_q b_q b_q q q \]
\[ \Lambda = C_\Lambda b_q b_q b_s q s \]
\[ \Xi = C_\Xi b_q b_s q s s \]
\[ \Omega = C_\Omega b_s b_s s s s \]

(9)

\[ \pi = C_\pi b_q b_q \bar{q} \bar{q} \]
\[ K = C_K b_q b_s q \bar{s} \]
\[ \bar{K} = C_{\bar{K}} b_q b_s \bar{q} s \]
\[ \eta = C_\eta b_s b_s \bar{s} \]

(10)

Here the normalization coefficients, \( b_i \), are determined uniquely by the requirement, that the number of the constituent quarks do not change during the hadronization — which is the basic assumption for all quark counting methods:

\[ s = 3 \Omega + 2 \Xi + \Lambda + \bar{K} + \eta \]
\[ \bar{s} = 3 \bar{\Pi} + 2 \Xi + \Lambda + K + \eta \]
\[ q = 3 p + \Xi + 2 \Lambda + K + \pi \]
\[ \bar{q} = 3 \bar{p} + \Xi + 2 \bar{\Lambda} + \bar{K} + \pi \]

(11)

In eq. (11) \( \pi \) is the number of directly produced pions. (Most of the observed pions are created in the decay of resonances.) Substituting eqs. (9-10) into eq. (11), one obtains equations for the normalization constants. These constants are then given in terms of quark numbers and \( C_i \) factors.

3 ALCOR Predictions Compared to Preliminary RHIC Data

3.1 Parameter independent hyperon ratios for SPS and RHIC

In order to arrive at the detailed predictions of the ALCOR model, one has to solve numerically the set of equations eqs. (9-11). The ALCOR predictions for the particle multiplicities (especially for the antihyperon to hyperon ratios), were shown in Refs. 5, 6 for the SPS energy.

Later on an interesting observation was pointed out in Ref. 8. Namely it was shown, that within the framework of the linear coalescence model in the antiparticle/particle ratios the uncertain \( c_i \) coalescence factors drop out, and
thus one obtains direct relations between particle ratios. Unfortunately the linear coalescence model contradicts to the different conservation laws.

In the later development, however, it was shown in Refs. that even in the charge conserving normalized (non-linear) coalescence model one can obtain parameter independent ratios between particle multiplicities. These relations have the form:

\[
\frac{\Xi}{\Xi} = D \frac{p}{p}, \quad \frac{\Lambda}{\Lambda} = D \frac{\Xi}{\Xi}, \quad \frac{\Omega}{\Omega} = D \frac{\Xi}{\Xi}, \tag{12}
\]

where

\[
D = \frac{K^+}{K^-}. \tag{13}
\]

Thus if the dynamics of hadronization is the coalescence process, then these relations should hold among the measured quantities. The preliminary results of the STAR experiment for Au+Au collision at \( \sqrt{s} = 130 \text{ AGeV} \),

\[
\frac{p}{p} = 0.61 \pm 0.06 \\
\frac{\Lambda}{\Lambda} = 0.73 \pm 0.03 \\
\frac{\Xi}{\Xi} = 0.82 \pm 0.08 \\
K^+/K^- = 1.12 \pm 0.06 \tag{14}
\]

clearly satisfy the relations eqs. (12-13), as required by quark combinatorics.

Similar results support the quark coalescence mechanism observed in Pb+Pb collision at \( E_{\text{beam}} = 158 \text{ AGeV} \) energy at CERN SPS,

\[
\frac{p}{p} = 0.07 \pm 0.01 \\
\frac{\Lambda}{\Lambda} = 0.133 \pm 0.007 \\
\frac{\Xi}{\Xi} = 0.249 \pm 0.019 \\
\frac{\Omega}{\Omega} = 0.383 \pm 0.081 \tag{15}
\]

which also satisfy the relations among the ratios demanded by quark coalescence with

\[
K^+/K^- = 1.8 \pm 0.2. \tag{16}
\]

Hence the multi-strange baryon to anti-baryon ratios in central Au+Au collisions at RHIC and in central Pb+Pb collisions at CERN SPS are consistent with the formation and the sudden rehadronization of Quark Matter, consisting of valence quarks and anti-quarks.
3.2 Detailed ALCOR predictions for RHIC

The first ALCOR predictions for RHIC were given for Au+Au collision at $\sqrt{s} = 200$ GeV in Ref.\(^1\). The first data sets were taken at the bombarding energy of $\sqrt{s} = 130$ A GeV, and the preliminary values for particle ratios were reported by the STAR Collaboration in October 2000 at the XXXth International Symposium on Multiparticle Dynamics\(^2\) as well as at the Quark Matter in January 2001.\(^3\) These data were similar to the ALCOR predictions for particle ratios at $\sqrt{s} = 200$ AGeV. Here we re-evaluate the ALCOR predictions for the lower than expected values of $\sqrt{s}$. We utilize the capability of the ALCOR model to work in a reasonably small rapidity bin ($\Delta y \approx 1$) where all the available quarks and antiquarks are able to interact to form the measured mesons and baryons. The calculation of hadron multiplicities in the ALCOR model is based on the number of quarks and antiquarks in the rapidity interval under study. These quark and antiquark numbers consist of the $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ pairs produced in the collision and the $u$ and $d$ quarks of the colliding nuclei. We utilize the measured (preliminary) value of the central rapidity density of the negatively charged hadrons:

$$dN_{h^{-}}/dy = 264 \pm 18 . \quad (17)$$

If we apply the parameter of the strangeness ($f_s = N_{s\bar{s}}/(N_{u\bar{u}} + N_{d\bar{d}}) = 0.22$) and baryon production ($\alpha_{\text{eff}} = 0.85$) determined at CERN SPS energy, then we are very close to make a full calculation of all hadronic ratios. The only missing information is the number of stopped nucleons in this rapidity region. (In previous calculations at CERN SPS energy we have not used this information, because total hadron numbers were calculated including all stopped nucleons.) Choosing 197 newly produced $u\bar{u}$ and $d\bar{d}$ pairs (this means 86 $s\bar{s}$ pairs) and assuming that 5 % of the total nucleon numbers stopped into the central unit of rapidity (which means 8 proton and 12 neutron), we can calculate the measured rapidity densities and hadronic ratios for the Au+Au collision at $\sqrt{s} = 130$ AGeV in the central rapidity as displayed in Table 1.

Investigating particle production in the central rapidity we repeat our calculation for Pb+Pb collision also at CERN SPS energy. The central rapidity density of the negatively charged hadrons was measured by NA49 Collaboration:\(^4\)

$$dN_{h^{-}}/dy = 195 \pm 15 . \quad (18)$$

In the ALCOR calculation we use 121 newly produced $u\bar{u}$ and $d\bar{d}$ pairs (this means 53 $s\bar{s}$ pairs) and assume 17 % of the total nucleon numbers to be stopped into the central unit of rapidity (which means 28 proton and 42 neutron). For this case ALCOR model yields $dN_{h^{-}}/dy = 195$ in the central
| ALCOR model | Preliminary data | Ref. |
|------------|-----------------|-----|
| $h^-$     | 260             | STAR [4] |
| $\bar{p}^+ / p^+$ | 0.63 | 0.61 ± 0.06 | STAR [4] |
| $\Lambda / \Lambda$ | 0.72 | 0.73 ± 0.03 | STAR [4] |
| $\Xi^+ / \Xi^-$ | 0.83 | 0.82 ± 0.08 | STAR [4] |
| $K^+ / K^-$ | 1.13 | 1.12 ± 0.06 | STAR [4] |
| $K^+ / \pi^+$ | 0.142 | 0.15 ± 0.01 | STAR [13] |
| $K^{++} / h^-$ | 0.077 | 0.065 | STAR [4] |
| $\bar{K}^{--} / h^-$ | 0.067 | 0.060 | STAR [4] |

Table 1. Hadron production in Au+Au collision at $\sqrt{s} = 130$ AGeV from the ALCOR model and the preliminary experimental data [4,13]

rapidity and the following baryon/antibaryon ratios: $\bar{p} / p = 0.07$, $\Lambda / \Lambda = 0.125$, $\Xi / \Xi = 0.230$ and $\Omega / \Omega = 0.425$. The obtained ratio $K^+ / K^- = 1.73$ fulfills also the expectation, see eqs.(15-16).

The calculated and the measured antibaryon/baryon ratios at SPS and RHIC energies are displayed in Figure 1.

4 Summary: Quark Matter at CERN SPS and at RHIC

It seems that the gluonic degrees of freedom are liberated in the initial state in Au+Au collisions at RHIC, as evident from data on jet quenching [14,15] and this initial state seems to be different from that of Pb+Pb collisions at CERN SPS [13]. As the fireball expands and cools the gluon dominated initial state in the $\sqrt{s} = 130$ AGeV Au+Au reactions at RHIC decays to a quark matter kind of state, where constituent quark and antiquark degrees of freedom are dominant. This quark-antiquark matter undergoes a sudden hadronization similarly to that at CERN SPS.

The success of the coalescence model to describe the experimental data at RHIC and SPS strongly supports the validity of the basic assumption behind the ALCOR model: before the hadronization, the basic degrees of freedom of the expanding fireball are massive (constituent) quarks and antiquarks. These elements of the deconfined phase coalesce into final state hadrons in a sudden process.
Figure 1. Particle ratios at mid-rapidity in Pb+Pb collisions at SPS (open circle) and in Au+Au collision at RHIC (open square). Preliminary experimental data (filled circle and square) are from Refs. 3, 4, 10, 11.

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