Quark coalescence in the mid rapidity region at RHIC

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Abstract.
We utilize the ALCOR model for mid-rapidity hadron number predictions at AGS, SPS and RHIC energies. We present simple fits for the energy dependence of stopping and quark production.

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1. Introduction

By comparing the assumptions and predictions of different models for describing relativistic heavy ion collisions, each among others and with experiments, it is time to make this comparison throughout a wide energy range, from AGS via SPS to RHIC and LHC energies. This is crucial both for pinning down the question of transition between qualitatively different behaviors, dominated by hadron – hadron or parton – parton reactions, respectively. Investigating the energy dependence is as well important to find differences in the agreement of different models with the trends revealed by a vast amount of new experimental data.

One of the longest standing debate of the last years is that between followers of the equilibrium concept and pursuer of micro-dynamical approaches. Considering quark coalescence our ALCOR model \cite{1,2,3} belongs to the second party. Even if one would allow for less detailed models by making predictions, the global chemical equilibrium hypothesis \cite{4,5,6} in our opinion is ruled out. It is in particular worth to mention here, that the solely fact, that certain particle ratios are rapidity dependent, contradicts to global chemical equilibrium. In fact a RHIC experiment has found different anti-proton to proton ratios at mid rapidity and moderate rapidity: $\bar{p}/p = 0.64$ at $y = 0$ and $\bar{p}/p = 0.41$ at $y = 2$ \cite{4}.

Taking this experimental fact into account we utilize now the formerly global quark matter hadronization model ALCOR to the mid-rapidity window only. The underlying assumption is that there is no significant exchange of flavor between far lying rapidity intervals (this is a reminder to the Bjorken flow picture and to different versions of string and color rope models). The unit width mid-rapidity window

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is selected for comparison of the predictions of the modified ALCOR model with experimental data at AGS, SPS and RHIC energies. The AGS data are presented rather for estimating the tendency of an assumption of constituent quark matter formation underlying the ALCOR model down to low energies, we actually expect this model to fail at AGS.

In this talk we shall concentrate on the energy dependence of the ALCOR model parameters extracted from fits to a certain few experimental observations (and checking against several others). In order to appreciate these dependencies we briefly discuss the physical picture behind ALCOR and the way how the model parameters are fixed. Finally we sketch some speculations about possible causes for the obtained energy dependence.

2. Out of equilibrium

The name of the ALCOR model stems from the abbreviation of an Algebraic Coalescence Rehadronization model. Hadron formation by coalescence assumes a constituent quark matter before hadronization and a fast process relative to typical interaction times after the hadron formation. In fact ALCOR neglects secondary collisions after hadronization but includes hadronic resonance decays. In the presented version the quark clusters belong to the ground state and to the first excited state hadrons with equal probability (naturally counting spin degeneracies) and all decay to the ground state mesons and baryons before detection.

Due to its basic assumption ALCOR is a statistical model: it considers average events and manipulates with average total numbers in a given section of the phase space (mid-rapidity unit window presently). It is a coalescence model: it describes mesonic prehadrons as $q\bar{q}$ quark – antiquark clusters with varying flavor composition and baryonic ones composed from three quarks ($qqq$), antibaryonic clusters correspondingly from three antiquarks. ALCOR concentrates to the chemical evolution: no chemical potentials are used and no chemical equilibrium is assumed at any instance of the calculation. Finally ALCOR utilizes a picture of thermal but largely massive quark matter without gluons at the beginning of the fast hadronization.

Perhaps it is as interesting to list what ALCOR is not. It is not an equilibrium model, because it relies on branching ratios calculated from in-medium cross-sections. It is not a linear coalescence model, because it uses extra factors, the $b_l$-s, by quark counting in order to take into account concurrence between different hadronization channels. It is also not a transport model, because it assumes a thermalized state to begin with at a given temperature, $T$, the spectra of the finally observed hadrons reflect this thermalized massive constituent quark matter (after an additional free streaming) by assumption. This is one of the major simplifications of the model, this assumption can be tested by comparing to transport models. Finally ALCOR does not assume quark-gluon plasma as a state before hadronization, it actually leaves open the question from what the constituent quark matter is formed from and how has it been thermalized.
3. Quark matter or hadron matter

We would like to stress here again that the concept of “quark matter” we are using in ALCOR is not that of the original free plasma of non-interacting, massless quarks and gluons. In line with the experience gained by studying the interacting QCD plasma with different methods by a great number of people, in particular considering the phenomena of static screening, of massive dispersion relations and the observation hadron-like correlated few-quark-clusters in lattice QCD simulations, we utilize the following picture of “prehadron matter”: it contains very few gluons, quarks and antiquarks occur and interact with large effective masses near to the constituent mass value, and a strong, string-like interaction – also shown in the magnetic area-law in some lattice calculations – bounds these quarks into color neutral clusters with hadronic quantum numbers.

According to this picture the main assumptions of the ALCOR model can be summerized as follows:

- new quark – antiquark pairs are produced before the hadronization process,
- all gluons and gluonic fields fragment into quark - antiquark pairs,
- and therefore the final hadronization is practically a redistribution of quarks and antiquarks among the possible clusters,
- the final hadrons have the same flavor composition as the prehadronic quark clusters.

4. ALCOR predictions and energy dependence

The input parameters of the ALCOR model can be divided to two categories: in the first belong those which are restricted by rational estimates and knowledge about elementary processes. The constituent quark masses we use are designed to describe static hadron properties (we use \(m_u = m_d = 300\) MeV, \(m_s = 500\) MeV). The branching ratios we calculate on the basis of assumed quark matter properties, we use a strong coupling \(\alpha_S = 0.85\), a wave packet size of \(\rho = 0.3\) fm and a medium temperature of \(T = 170\) MeV.

In the second category belong those parameters which are obtained from fitting the results of ALCOR to experimental heavy-ion data. We have three such parameters: the stopping, here defined by the baryon per cent in the mid-rapidity window stemming from the colliding nuclei, is fitted to the experimental \(K^+/K^-\) ratio, and two characteristic parameters of meson production, namely the number of produced light and strange quark pairs, \(N_{\pi\pi}\) and \(f_s = N_{\pi\pi}/(N_{\pi\pi} + N_{\pi\pi})\), are fitted to the \(\pi^-\) and \(K^-\) yield, respectively. These experimental data are displayed in Fig.1 as a function of the bombarding energy.

The results incorporate total and mid-rapidity numbers of elements of the lowest lying meson, baryon and antibaryon multiplets in the SU(3) flavor space, spectra with an assumed flow pattern (in the MICOR version [8]), and predictions to LHC energy using the fitted energy dependence of the parameters.
Let us start with the energy dependence of the stopping power effective to the mid-rapidity window. Here a decreasing tendency of the stopping power effective to the mid-rapidity window is inspected alone from the SPS and RHIC data. Assuming full stopping at low energy, which is a hypothetical point, the best fit reaches zero stopping already at a finite energy, before the LHC regime. The number of stopped baryons in the observed range roughly scale with the energy as the elastic cross section vanishes. The AGS point is somewhat below the fitted curve, but we do not expect ALCOR to be realistic at such a low energy.

Inspecting Fig. 3, it is easy to realize that the energy dependence of the newly produced quark–antiquark pairs seems to saturate around RHIC energy. (This is, however, only one possible fit to the present data, in this respect the LHC result will be crucial.) This behavior agrees with Regge double-pole estimates for the $pp$ cross section at very high energies: $N_{u\bar{u}} \sim \sigma^{tot} \sim A \ln s + B$. Since at high energy the relative rapidity is $y \approx \ln s$, the number of new pairs in the mid-rapidity window, $dN/dy \approx N_{u\bar{u}}/y \approx A + B/(\ln s)$ saturates.
The strangeness ratio, shown in Fig. 4, also falls with increasing bombarding energy. The saturation value at high energy agrees with estimates based on elementary \( pp \) physics, the rise towards lower energies requires explanation. In our opinion it has to do with the fact that the strange constituent mass is bigger than the up and down masses, and therefore strange hadrons show a reduced rapidity dispersion at low bombarding energies. This may occur as an increasing ratio at mid-rapidity.

Finally, as an example, the energy dependence of the \( K^+/\pi^+ \) ratio is shown in Fig. 5. The encircled points are ALCOR results at each respective energy, the line shows a fitted, linear function to these points. Reflecting the decrease of the strangeness ratio in the prehadron matter, this hadronic ratio is also decreasing with increasing bombarding energy.

In conclusion the measured data are in good agreement with ALCOR predictions. We also transformed some of the measured particle numbers into physical quantities with the help of ALCOR, in order to gain a better insight into the energy dependence of the stopping, quark pair creation and strangeness ratio. At RHIC we realize that
New light quark production at mid rapidity

\[ f(x) = \frac{82.65 x^2}{(6.25+(x-2.94)^2)} \]

**Figure 3.** The energy dependence of the newly produced quark pairs as obtained from ALCOR by fitting the $\pi$ yield.

|                | ALCOR model | Preliminary data | Ref. |
|----------------|-------------|------------------|------|
| $h^-/\pi^+$    | 260         | 264 ± 18         | STAR [10] |
| $K^+/\pi^+$    | 0.142       | 0.15 ± 0.01      | STAR [12] |
| $K^+/K^-$      | 1.13        | 1.12 ± 0.06      | STAR [10] |
| $\Xi^-/\pi^-$  | 0.015       | 0.014 ± 0.01     | STAR [11] |
| $\Sigma^-/p^+$ | 0.63        | 0.61 ± 0.06      | STAR [10] |
| $\Lambda/\Lambda$ | 0.72       | 0.73 ± 0.03     | STAR [10] |
| $\Xi^+/$$\Xi^-$ | 0.83        | 0.82 ± 0.08      | STAR [10] |
| $K^{*+}/h^-$   | 0.077       | 0.065            | STAR [10] |
| $K^{*-}/h^-$   | 0.067       | 0.060            | STAR [10] |

**Table 1.** Hadron production in Au+Au collision at $\sqrt{s} = 130$ AGeV from the ALCOR model and the preliminary experimental data [12, 11].
we are near to the complete transparency which will be reached before LHC energy according to ALCOR. At RHIC we are also near to the maximal prehadronization energy density (see number of new midrapidity $q\bar{q}$ pairs in Table 1.).

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