Strange hadron ratios from quark coalescence at RHIC and LHC energies

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Abstract. Quark coalescence models have been applied successfully to reproduce measured hadron production data in relativistic heavy ion collisions at SPS and RHIC energies, which finding strongly supports the formation of deconfined quark matter in these collisions. The investigation of meson and baryon production is an ideal tool to understand dynamical details of hadronization, especially strange hadron numbers and ratios. We display latest results on the production of strange particles in quark coalescence processes in heavy ion collisions at different collider energies.

After many years of investigating hadron-hadron and heavy ion collisions the study of hadron production remained an important research field. The lack of perfect knowledge of the microscopical mechanisms led to the application of many different models, very often from completely opposite directions. Statistical models are based on the introduced statistical weights for produced hadrons [1, 2, 3]. This idea has been developed further and thermal models appeared with the introduction of the temperature parameter and thermal weights for hadrons (see e.g. Ref. [3]). Thermal models became very successful reproducing soft particle production in different high energy particle collisions [4], especially in heavy ion collisions (see e.g. Refs. [5, 6, 7, 8]). On the other hand, these models assume the formation of a sort of thermal and chemical equilibrium in the hadronic phase and determine thermodynamical variables for the produced hadron phase. The deconfined period of the time evolution dominated by quarks and gluons remains hidden: full equilibration generally washes out and destroys large amount of information about the early deconfined phase. The success of statistical models implies the existence of such an information loss during hadronization, at least for certain properties. It is a basic question which properties can survive the hadronization and behave as messengers from the early (quark dominated) stages.

Since our main goal is to create quark matter in heavy ion collisions and determine its properties, we can not be satisfied even with the most perfect hadronic statistical model. We need to survey the messengers of the early phases and investigate hadron production by models based on quark degrees of freedom. Hadronization models with direct quark degrees of freedom have been constructed from the beginning of the heavy ion programme at CERN SPS. In this stream quark coalescence has been proposed many years ago to describe quark matter hadronization [9, 10, 11, 12]. Massive constituent quarks has been considered in the deconfined phase, which quarks and antiquarks are
ready to hadronize through "coalescence", a clustering process driven by an attractive force between the properly coloured quark degrees of freedom. The analysis of lattice QCD data has supported the presence of such massive excitations in the quark-matter phase close to the quark-hadron phase transition \[13\]. The attractive force generated by gluons (which are considered via this interaction and ignored as independent degrees of freedom), and it is modeled by non-relativistic colour potential between the massive quarks and antiquarks. Mesons are produced by quark-antiquark coalescence. Baryons are produced in two steps: at first $3$ diquarks appear through quark-quark coalescence, which is followed by a diquark-quark coalescence into a colourless baryon. Thus we have microscopical steps to describe hadronization and proper physics to fulfill conservation laws.

Particle yields, ratios and spectra measured in heavy ion collisions have been reproduced successfully in the ALCOR \[14, 15\] and MICOR \[16, 17\] coalescence models. However, thermal models were similarly successful in the low-$p_T$ region and more widely used because of their simplicity. At RHIC energy intense data collection has been performed in the intermediate-$p_T$ region ($3 < p_T < 8 \text{ GeV/c}$) and the measured anomalous proton/pion ratio could have been explained by quark coalescence and recombination models \[18, 19, 20\]. Since thermal models could not be applied for these data, the production of relatively rare particles (e.g. intermediate-$p_T$ hadrons, heavy flavours) became the main focus of non-equilibrium models. The interest in coalescence hadronization mechanism has been increased and more applications appeared. One subfield is the strange hadron production: quark chemistry based on strange quark coalescence and annihilation became very successful to describe SPS and RHIC data. Furthermore, quark flow production also moved into the focus of interest. The recognition of valence quark number scaling in asymmetric flow ($v_2$) strongly supports quark matter formation and quark coalescence at RHIC and SPS energies \[21\].

It is natural to ask, if quark coalescence is working properly for heavier flavour and at higher-$p_T$, then what about the soft region, namely bulk hadron numbers, and ratios. During last decade we continously summarized the results of quark coalescence calculations and the successful reproduction of measured data, in parallel giving predictions where it was possible. In this talk we gave a short summary again, analyzing latest SPS and RHIC data and predict the expected particle yields at LHC energy. We would like to emphasize that quark coalescence models are capable to describe large amount of experimental data, in the meantime supporting the formation of deconfined quark matter in heavy ion collisions at SPS and RHIC energies.

Another question is connected to the validity of non-relativistic description in a highly relativistic strongly interacting particle ensemble \[22\]. Although all particles, including quarks in the early stage, are moving with a velocity close to the speed of light, but in a comoving system they can coalesce if only their relative velocity is small. This self-regularization gives the opportunity to describe the effective quark binding steps in a non-relativistic frame with coalescence.
On the other hand, another description exists, which is very similar in many ways: the light-front wave function (LFWF) formalism [23] is based on constituent quarks moving along the light-front and quantum mechanics is recovered in the comoving system. It is interesting to note, that the LFWF formalism and the investigation of quantum-chromodynamics on light-front displays a connection to the AdS/CFT correspondence. Bound states of relativistic massless quarks can be described in this formalism, and an effective Schrödinger equation can be derived, where the effective potential is dictated by conformal symmetry [24]. This correspondence is beyond the scope of our recent study and here we will stay at a phenomenological level including Schrödinger picture and quantum mechanics.

In quark coalescence models [10, 16] a premeson \( h \) consists of quark \( q_1 \) and antiquark \( q_2 \), and production is proportional to densities of constituents, \( n_1 \) and \( n_2 \):

\[
\partial_\mu (n_h u^\mu) = \langle \sigma_{12}^h v_{12} \rangle n_1 n_2 .
\]

In an isotropic plasma state the rate, \( \langle \sigma_{12}^h v_{12} \rangle \), is calculated as a momentum average:

\[
\langle \sigma_{12}^h v_{12} \rangle = \frac{\int d^3\vec{p}_1 d^3\vec{p}_2 f_q(m_1, \vec{p}_1)f_q(m_2, \vec{p}_2)\sigma v_{12}}{\int d^3\vec{p}_1 d^3\vec{p}_2 f_q(m_1, \vec{p}_1)f_q(m_2, \vec{p}_2)} \quad (2)
\]

The quark coalescence cross section is determined from quantum mechanics, assuming a rearrangement ("pick-up") reaction [25]. In the ALCOR model [10] quark plain waves coalesce into a bound two-body system, described by a hydrogen-like wave function. Coalescence process is driven by a Coulomb-potential depending on relative distance, \( r \):

\[
V(r) = \frac{\alpha \langle \lambda_i \lambda_j \rangle}{r} \quad (3)
\]

The colour factor \( \langle \lambda_i \lambda_j \rangle \) is determined by the colour combination of the interacting particles. This factor is \(-4/3\) for quark-antiquark coalescence into a color singlet pre-meson, and \(-2/3\) for quark-quark coalescence into an antitriplet \( (3) \) diquark state.

In a parallel study [22] we have investigated the robustness of the quantum mechanical description, applying different wave-function setups and using Yukawa potential with wide region for the screening mass. We demonstrated that the final results for hadron ratios are very close to each other, although we have very much different intermediate values for coalescence rates and quark ratios obtained from a fitting procedure. Thus we will use here the ALCOR model’s wave function setup, and we display the obtained results. Other wave function setup may yield slightly different hadron ratios, which will be surveyed in the near future and reported elsewhere.

Here in the ALCOR model there are four input parameters. Entropy production is followed by the number of newly produced light quark-antiquark pairs \( (N_u \pi = N_{d\pi}) \). Strangeness production is controlled by the number of newly produced strange quark-antiquark pairs indicated by the ratio \( f_s = N_{s\pi}/(N_u \pi + N_d \pi) \). Baryon to meson ratio is followed by the \( \alpha_s \) effective coupling constant, because meson production is proportional to \( \alpha_s \), but two-steps baryon production depends on \( \alpha_s^2 \). Particle to antiparticle ratios are controlled by the stopping of incoming colliding nucleons into the mid-rapidity region.
In Table 1 the latest results from quark coalescence calculations are summarized at different CERN SPS energies in the mid-rapidity regions of Pb + Pb collisions [26, 27]. The four model parameters are determined from four experimental data, especially from π⁻ and K⁻ numbers indicating entropy and strangeness production, from K⁺/K⁻ ratio indicating particle/antiparticle ratio, and from the absolute number of Ξ⁺ particle connected to the effective coupling constant. (At 20 GeV/n no data were available, in this case Ξ⁻ has been used.) Table 1 displays that entropy production is increasing, but relative strangeness abundance (fₛ) is continuously decreasing with increasing collision energy. One can see, the ratio K⁺/π⁺ is decreasing, as well as the $\bar{\Lambda}^0/\pi^-$ and $\Phi/K^-$ ratios, as we expect from the decreasing of $f_s$. The $K^-/\pi^-$ ratio is slightly increasing, but this is an exception. The energy dependence of $\langle \Omega \rangle/\pi^-$ has a special structure, which should be investigated in details. The stopping is close to be constant, it starts to decrease at highest SPS energy, as well as the effective coupling constant.

We repeat our analysis at RHIC energies. Table 2 displays recent ALCOR results at $\sqrt{s} = 200$ AGeV in Au + Au collisions. We can see that entropy production is increasing further, but strangeness production is saturated at a certain value ($f_s = 0.22$), which number is valid at $\sqrt{s} = 130$ AGeV, also. The coupling constant is also saturated around $\alpha_s = 0.55$, founded at lower RHIC energy. The stopping is decreasing, as it is indicated by close to unity antibaryon to baryon ratios. The quark coalescence model can reproduce bulk particle ratios in most of the cases, except the $\Phi/K^-$. We investigate recently if different wave-function setups could improve this agreement [22], keeping other ratios under good control. Another way to improve the quark coalescence results is to investigate the role of higher baryon and meson resonance production channels.

**Table 1.** ALCOR results at SPS energies, $E_{beam} = 20, 30, 40, 80, 158$ GeV/n.

| Input data | dN/dy at y=0 | 20 GeV/n | 30 GeV/n | 40 GeV/n | 80 GeV/n | 158 GeV/n |
|-----------|-------------|---------|---------|---------|---------|---------|
| π⁻        | 85 ± 5      | 96 ± 5  | 110 ± 5 | 145 ± 5 | 182 ± 5 |
| K⁻        | 5.6 ± 0.2   | 7.8 ± 0.2 | 8 ± 0.5 | 12 ± 0.5 | 17.5 ± 0.5 |
| K⁺/K⁻     | 3.0 ± 0.2   | 2.6±0.2 | 2.55±0.2 | 2.1±0.2 | 1.7±0.2 |
| Ξ⁺        | —           | 0.05 ± 0.02 | 0.07 ± 0.02 | 0.2 ± 0.05 | 0.34 ± 0.04 |

| ALCOR param. | New $u\pi$ | 45 | 50 | 62 | 88 | 123 |
|--------------|------------|----|----|----|----|----|
| $f_s$ strangeness | 0.40 | 0.35 | 0.30 | 0.28 | 0.24 |
| Stopping     | 20 %       | 20 % | 20 % | 20 % | 15 % |
| $\alpha_s$ coupling | 0.80 | 0.80 | 0.80 | 0.80 | 0.72 |
| New # $\bar{Q}Q$ | 252 | 270 | 322 | 450 | 610 |

| ALCOR results | $K⁺/\pi⁺$ | 0.213 | 0.192 | 0.173 | 0.171 | 0.158 |
|---------------|-----------|-------|-------|-------|-------|-------|
| $\bar{\Lambda}^0/\pi^-$ | 1.36 | 1.16 | 1.0 | 0.93 | 0.80 |
| $\Phi/K^-$ | 0.42 | 0.385 | 0.34 | 0.32 | 0.28 |
| $(\Omega^- + \Omega^+)/\pi^-$ | 0.00268 | 0.00217 | 0.00189 | 0.00233 | 0.00244 |
Combining quark coalescence results at SPS and RHIC energies, we can predict different particle yields at LHC energies. We can expect from Table 1 and 2, that strangeness production and effective coupling constant will be very similar at RHIC and LHC energies, on the other hand baryon number stopping into the mid-rapidity region will drop to a minimal value (e.g. 1 %). The only question is connected to the value of entropy production, especially to the new light quark-antiquark pair production. Figure 1. displays the obtained values at SPS and RHIC energies and indicates a linear increase in entropy production with increasing \( \ln \sqrt{s} \). Applying a linear extrapolation we obtain the estimated value \( N_{u\bar{u}}/dy = 500 \) for LHC energies in \( Pb + Pb \) collisions at mid-rapidity. Table 2 displays the ALCOR results for this light quark pair production, keeping the other parameter values, as we discussed above. In order to test the sensitivity of some ratios to the amount of produced entropy, we give, in the last column of Table 2, results of our model assuming a 50 % higher entropy. Many strange particle ratios are insensitive on the higher entropy production, thus other data are necessary to investigate entropy production at LHC energies, e.g. absolute particle numbers.

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Figure 1. The energy dependence of the newly produced quark and antiquarks in the mid-rapidity region. The displayed values are obtained from the ALCOR model fit to the experimental data. The value at LHC energy is obtained from a linear extrapolation.

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