Simple predictions from ALCOR\(_c\) for rehadronization of charmed quark matter

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Abstract. We study the production of charmed hadrons with the help of ALCOR\(_c\), the algebraic coalescence model for rehadronization of charmed quark matter. Mesonic ratios are introduced as factors connecting various anti-baryon to baryon ratios. The resulting simple relations could serve as tests of quark matter formation and coalescence type rehadronization in heavy ion collisions.

Charm hadron production has gained increased attention in relativistic heavy ion collisions at CERN SPS (Super Proton Synchrotron). The measured anomalous suppression of the \(J/\psi\) in \(\text{Pb+Pb}\) collisions [1] is considered as one of the strongest candidates for evidence of quark–gluon plasma (QGP) formation in \(\text{Pb+Pb}\) collisions at 158 GeV/nucleon bombarding energy [2]. So far only \(J/\psi\) and \(\psi'\) production have been measured in heavy ion collisions through dilepton decay channels. However, recent efforts to measure the D-meson [3, 4] support the theoretical investigation of charm production from a different point of view. Namely, it is interesting to search for predictions on the total numbers of charmed hadrons and their ratios. The answer to this question may become very important at the RHIC accelerator, where a large number of charmed quark–anti-quark pairs will be produced and a number of different charmed hadrons may be detected.

In this paper we assume that quark matter is formed in heavy ion collisions and that charmed hadrons will be produced directly from this state via quark coalescence. Quark coalescence has been successfully applied to describe direct hadron production from the deconfined quark matter phase (see the ALCOR [5, 6], the Transchemistry [7] and the MICOR [8] models). In these models the hadronic rescatterings are assumed to be weak and they are neglected. Thus the results of quark coalescence processes have been compared directly to the experimental data—and the agreement have been found to be remarkably good.

Multicharm hadron production has already been investigated in a simplified quark coalescence model and first results were obtained at RHIC and LHC energies, where an appreciable number of charm quark may appear [9]. Here we summarize simple predictions...
from a nonlinear algebraic coalescence model ALCOR, the extension of the ALCOR model of algebraic coalescence of strange quark matter [5,6] for the inclusion of charmed quarks, mesons and baryons.

The description of the charmed baryons has to deal with the fact that two possible \((1/2)^+\) baryon multiplets exist containing \(c\), \(s\) and \(u\) (or \(d\)) quarks, one being flavour symmetric under \(s\) and \(d\) (or \(u\)) exchange and the other being antisymmetric [10]. The heavier (symmetric) states decay into the lighter (antisymmetric) state by emission of a \(\gamma\) or a \(\pi\) meson. However, if quark clusterization is the basic hadronization process, then the effect of these decay processes will be cancelled from charmed anti-baryon to baryon ratios. Neglecting the difference between the light \(u\) and \(d\) quarks and using the notation \(q\) for them, the 10 different types of quark clusters produced can be connected to the 40 lowest lying \(SU(4)\)-flavour baryon species in the following way (see, e.g., [11,12] for precise quark content, hadron names and masses):

\[
\begin{align*}
N(qqq) &= p, n, \Delta^{++}, \Delta^+, \Delta^0, \Delta^- \\
Y(qqs) &= \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Sigma^{++}, \Sigma^{+0}, \Sigma^{-0} \\
\Xi(qss) &= \Xi^0, \Xi^-, \Xi^{+0}, \Xi^{-0} \\
\Omega(sss) &= \Omega^- \\
Y_c(qqc) &= \Lambda_c^+, \Sigma_c^{++}, \Sigma_c^+, \Xi_c^0, \Xi_c^{++}, \Xi_c^{+0}, \Xi_c^{-0}, \Sigma_c^+ \\
\Xi_c(qsc) &= \Xi_c^0, \Xi_c^-, \Xi_c^{+0}, \Xi_c^{-0} \\
\Omega_c(ssc) &= \Omega_c^0, \Omega_c^{+0} \\
\Omega_{ccc}(ccc) &= \Omega_{++}^c.
\end{align*}
\]

Including all of these resonances the entropy will not decrease, rather it will increase by a few per cent during the hadronization of the quarks and anti-quarks [7].

In ALCOR, in the algebraic coalescence model of rehadronization it is assumed that the number of directly produced hadrons is given by the product of the number of quarks (or anti-quarks) from which those hadrons are produced, multiplied by the coalescence coefficients \(C_h\) and by the nonlinear normalization coefficients \(b_i\), that take into account conservation of quark numbers during quark coalescence, as will be explained subsequently. The number of various hadrons and quarks is denoted by the symbol usual for that type of particle, i.e. \(q\), \(s\) and \(c\) denote the number of light, strange and charmed quarks, respectively, \(N\) denotes the number of protons, neutrons and deltas etc.

In this way the baryons and anti-baryons can be described through the following clustering relations:

\[
\begin{align*}
N(qqq) &= C_N \cdot (b_q q)^3 \\
Y(qqs) &= C_Y \cdot (b_q q)^2 \cdot (b_s s) \\
\Xi(qss) &= C_\Xi \cdot (b_q q) \cdot (b_s s)^2 \\
\Omega(sss) &= C_\Omega \cdot (b_q q)^3 \\
Y_c(qqc) &= C_Y^c \cdot (b_q q)^2 \cdot (b_c c) \\
\Xi_c(qsc) &= C_\Xi^c \cdot (b_q q) \cdot (b_s s) \cdot (b_c c) \\
\Omega_c(ssc) &= C_\Omega^c \cdot (b_q q)^2 \cdot (b_c c)
\end{align*}
\]
the following equations, expressing the conservation of the number of quarks: The correct quark counting yields to available quarks and anti-quarks have to end up in the directly produced hadrons. This constraint constituent quarks and anti-quarks do not change during the hadronization, and that all initially available quarks and anti-quarks have to end up in the directly produced hadrons. This constraint is a basic assumption in all models of quark coalescence. Thus the number of directly produced mesons reads as

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As a straightforward extension to the ALCOR model, the nonlinear coalescence factors \( b_q, b_s, b_c \) and the \( b_{\bar{q}}, b_{\bar{s}}, b_{\bar{c}} \) are determined unambiguously from the requirement that the numbers of constituent quarks and anti-quarks do not change during the hadronization, and that all initially available quarks and anti-quarks have to end up in the directly produced hadrons. This constraint is a basic assumption in all models of quark coalescence. The correct quark counting yields to the following equations, expressing the conservation of the number of quarks:

\[
q = 3\Omega(qqq) + 2Y(qqs) + \Xi(qss) + K(qs) + \pi(q\bar{q}) + 2Y_c(qqc) + \Xi_c(qsc) + \Xi_{cc}(qcc) + \overline{D}(q\bar{q}) \tag{5}
\]

\[
\overline{q} = 3\Omega(q\bar{q}q) + 2Y(q\bar{q}s) + \Xi(q\bar{s}s) + \overline{K}(q\bar{s}) + \pi(q\bar{q}) + 2Y_c(q\bar{q}c) + \Xi_c(q\bar{s}c) + \Xi_{cc}(q\bar{q}c) + \overline{D}(q\bar{q}) \tag{6}
\]

\[
s = 3\Omega(sss) + 2\Xi(qss) + \overline{Y}(qqs) + \overline{K}(q\bar{s}) + \phi(s\bar{s}) + 2\Omega_c(ssc) + \Xi_c(qsc) + \Omega_{cc}(ssc) + \overline{D}_s(s\bar{c}) \tag{7}
\]

\[
\overline{s} = 3\overline{\Omega}(sss) + 2\overline{\Xi}(q\bar{s}s) + \overline{Y}(q\bar{q}s) + K(qs) + \phi(s\bar{s}) + 2\overline{\Omega}_c(ssc) + \overline{\Xi}_c(qsc) + \overline{\Omega}_{cc}(ssc) + \overline{D}_s(s\bar{c}) \tag{8}
\]

\[
c = 3\Omega_{ccc}(ccc) + 2\Xi_{cc}(qcc) + \Lambda_c(qqc) + D(q\bar{q}) + J/\psi(\bar{c}\bar{c}) + 2\Xi_{cc}(ssc) + \Lambda_c(qsc) + \Lambda_c(ssc) + \overline{D}_s(s\bar{c}) \tag{9}
\]

\[
\overline{c} = 3\overline{\Omega}_{ccc}(\overline{ccc}) + 2\overline{\Xi}_{cc}(q\bar{q}c) + \overline{\Lambda}_c(q\bar{q}c) + \overline{D}(q\bar{q}) + J/\psi(\bar{c}\bar{c}) + 2\overline{\Xi}_{cc}(ssc) + \overline{\Lambda}_c(q\bar{s}c) + \overline{\Lambda}_c(ssc) + \overline{D}_s(s\bar{c}) \tag{10}
\]
These equations for $q$, $s$, $c$ and $(\bar{q}, \bar{s}, \bar{c})$ determine the six $b_i$ normalization factors—which are not free parameters. These constraints, together with the prescription of the coalescence factors $C_i$, complete the description of hadron production from charmed quark matter by quark coalescence, and define the ALCOR model.

In this paper, we will evaluate only the simplest predictions from ALCOR, by considering ratios of the number of particles to the number of anti-particles and by assuming the symmetry of the coalescence process for charge conjugation, extending the results of [6] to the case of charmed quarks, mesons and baryons.

Assuming that the coalescence coefficients $C$ for hadrons are equal to those for the corresponding anti-particles, for example $C_\Lambda = C_\bar{\Lambda}$, the following relations were obtained for the ratio of light and strange anti-baryons and baryons [6]:

$$\frac{N(qqq)}{N(qq\bar{q})} = \left[ \frac{b_q q}{b_q q} \right]^3 \quad (11)$$

$$\frac{\Xi(qss)}{\Xi(q\bar{q} s)} = \left[ \frac{b_q q}{b_q q} \right]^2 \cdot \left[ \frac{b_s s}{b_s s} \right] \quad (12)$$

$$\frac{\Xi(qss)}{\Xi(q\bar{q} s)} = \left[ \frac{b_q q}{b_q q} \right] \cdot \left[ \frac{b_s s}{b_s s} \right]^2 \quad (13)$$

$$\frac{\Omega(sss)}{\Omega(s\bar{q} s)} = \frac{b_q q}{b_s s} \cdot \left[ \frac{b_s s}{b_s s} \right]^2 \quad (14)$$

Inspecting equations (11)–(14), one can recognize that the kaon to anti-kaon ratio $S_{qs}$ has a special role as it acts as a stepping factor that connects various anti-baryon to baryon ratios,

$$S_{qs} \equiv \frac{K(q\bar{s})}{K(qs)} = \left[ \frac{b_q q}{b_q q} \right] \cdot \left[ \frac{b_s s}{b_s s} \right] \quad (15)$$

This factor $S_{qs}$ substitutes a light quark with a strange quark in the anti-baryon to baryon ratios. Thus it shifts the anti-baryon to baryon ratios and changes their strangeness content by one unit, as the following relations display:

$$S_{qs} S_{qs} \left[ \frac{N}{N} \right] = \frac{Y}{Y} \quad (16)$$

$$S_{qs} S_{qs} \left[ \frac{N}{N} \right] = \Xi \quad (17)$$

$$S_{qs} S_{qs} S_{qs} \left[ \frac{N}{N} \right] = \frac{\Omega}{\Omega} \quad (18)$$

The inverse factor, $S_{sq} = (S_{qs})^{-1}$ decreases the strangeness content and increases the number of light quarks in the anti-baryon to baryon ratios. Note that these relations hold between the ratios of the directly produced anti-baryons to baryons and that the number of observed anti-baryons and baryons have to be corrected to the various chains of resonance decays [6].

Extending the above ALCOR model to the case of charmed baryons and anti-baryons, further relations are obtained:

$$\frac{Y_c(q\bar{q}c)}{Y_c(qqc)} = \left[ \frac{b_q q}{b_c c} \right]^2 \cdot \left[ \frac{b_c c}{b_c c} \right] \quad \frac{\Xi_c(q\bar{q}c)}{\Xi_c(qqc)} = \left[ \frac{b_q q}{b_s s} \right] \cdot \left[ \frac{b_s s}{b_c c} \right] \cdot \left[ \frac{b_c c}{b_c c} \right]$$

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Figure 1. The application of mesonic step factors $S^{qs}$, $S^{sc}$ and $S^{cq}$ on the anti-baryon to baryon ratios. The arrows indicate the three corresponding directions of shifting.

These ratios and the ratios from equations (11)–(14) can be organized into a special structure displayed in figure 1. We can introduce two more factors $S^{sc}$ and $S^{cq}$ constructed as in equation (15) but from the ratios of charmed mesons:

\[
\frac{\Xi_{cc}(qcc)}{\Xi_{cc}(qcc)} = \left[ \frac{b_{c}q}{b_{c}c} \right] \cdot \left[ \frac{b_{c}c}{b_{c}c} \right] \quad \frac{\Omega_{cc}(ssc)}{\Omega_{cc}(ssc)} = \left[ \frac{b_{c}s}{b_{c}s} \right] \cdot \left[ \frac{b_{c}s}{b_{c}s} \right].
\]

These ratios and the ratios from equations (11)–(14) can be organized into a special structure displayed in figure 1. We can introduce two more factors $S^{sc}$ and $S^{cq}$ constructed as in equation (15) but from the ratios of charmed mesons:

\[
S^{sc} \equiv \frac{D_{s}(s\bar{c})}{D_{s}(s\bar{c})} = \left[ \frac{b_{s}s}{b_{c}s} \right] \cdot \left[ \frac{b_{c}c}{b_{c}c} \right].
\]

The factor $S^{sc}$ substitutes a strange quark with a charmed one and the factor $S^{cq}$ changes the charmed quark into a light one. These properties lead to the following identity:

\[
S^{qs} \cdot S^{sc} \cdot S^{cq} \equiv 1.
\]

This identity can be rewritten as an identity between the mesonic ratios:

\[
\frac{D_{s}/D_{s}}{D_{c}/D_{c}} = K/K.
\]

A comparison of this simple relation with experimental data could serve as a test of quark matter formation and coalescence type rehadronization in heavy ion collisions.

The inverse of the step factors is defined as $S^{ji} = (S^{ij})^{-1}$. The structure of the anti-baryon to baryon ratios in ALCOR$_c$ is visualized in a geometric manner in figure 1. This way, more complicated but definitely interesting relations can be obtained. Since the baryons with
one charm quark (or anti-quark) can be measured most easily, one may consider the following relations as candidates for an experimental test:

\[
\frac{\Xi_c(qsc)}{\Xi_c(qsc)} = S^{qs}[\frac{Y_c}{\Xi} = S^{qc}[\frac{\Xi}{\Xi_c}] = S^{sc}[\frac{\Xi_c}{\Xi_c}].
\] (24)

These yield the following simple relations between baryonic and mesonic ratios:

\[
\frac{\bar{Y}/Y}{\bar{Y}_c/Y_c} = D_s/D_s
\] (25)

\[
\frac{\bar{N}/N}{\bar{N}_c/N_c} = D/D
\] (26)

\[
\frac{\bar{N}/N}{\bar{Y}/Y} = K/K.
\] (27)

The validity of equation (27) at CERN SPS energy was already investigated and claimed in [6].

A number of similar expressions can be derived from figure 1, picking up a given ratio and following all the paths to reach the wanted ratio from its neighbours.

In summary, we have made simple predictions from the ALCOR\(_c\) model, extending the ALCOR model of algebraic coalescence and rehadronization of quark matter to the case when charmed quarks and final state hadrons are present in a significant number. We found that the various \(\bar{M}/M\) mesonic ratios relate different \(\bar{B}/B\) ratios. The agreement between the obtained theoretical relations and those in the measured data could serve as proof or disproof of the formation of quark matter in heavy ion collisions followed by a fast hadronization via quark coalescence. The predictions made in this paper are independent of the detailed values of coalescence coefficients, as we have assumed only their symmetry for charge conjugation. The calculations of the absolute numbers of particles produced from ALCOR\(_c\) requires the specification of these coalescence coefficients from calculations of cross sections.

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