Critical Hadronization Pressure

Johann Rafelski† and Jean Letessier‡
† Department of Physics, University of Arizona, Tucson, AZ 85721, USA
‡ LPTHE, Université Paris 7, 2 place Jussieu, F–75251 Cedex 05

Abstract. We discuss the bulk properties of QGP produced at RHIC obtained at time of hadronization. We argue that hadronization of quark–gluon plasma occurs at a critical pressure near to 82 MeV/fm$^3$, obtained for SPS energy range.

1. Introduction

We study the physical properties of the hot and dense fireball, and in particular, the thermal pressure at time of hadronization. In our approach, we consider that at RHIC, as well as at the top SPS energies, a local domain of thermally colliding gluons and quarks has been formed, the quark–gluon plasma (QGP). In the early stages of the collision a high density, and thus pressure buildup occurs which is followed by a fast relativistic collective matter outflow. This system expansion dilutes the density beyond phase equilibrium transformation to hadron gas (HG).

This sub-dense system is unstable and can experience a sudden breakup, converting rapidly from quarks into hadrons, with free streaming particles, only ‘strong’ hadron resonances are subject to possible further interactions. However, this does not alter the final stable particle yields. Thus, fitting the yields of particles using the statistical hadronization model (SHM), we can infer from the measured hadronic particle yields also the yields of other unmeasured hadrons. Summing the contributions of many gas fractions, we obtain the physical conditions of the fireball.

In such a procedure, it is necessary to allow for greatest possible flexibility in characterization of particle phase space, consistent with conservation laws and related physical constraints of QGP breakup. In particular, the QGP yield of strange and light quark pairs has to be nearly preserved while QGP particles are distributed into final state hadrons. This is accomplished using parameters which describe the quark pair yields, i.e., $\gamma_q$ and $\gamma_s$. While these parameters in both phases are not equal, i.e., $\gamma_i^{\text{QGP}} \neq \gamma_i^{\text{HG}}$, $i = q, s$, the yield of pairs are similar, i.e., $N_i^{\text{QGP}} \simeq N_i^{\text{HG}}$, provided that the QGP breakup process is rapid, and that is seen in the HBT data. A value of $\gamma_i \neq 1$ allows to control the density of particles at given temperature, but unlike the chemical potential, $\gamma_i$ acts in the same direction for particles and conjugate (anti) particles. How this works will become clear in next section.

A jump-up in the phase space occupancy parameter $\gamma_q$ replaces an increase in volume associated with a slow re-equilibrating hadronization with mixed phase, a reaction picture incompatible with many reaction observables, including HBT. The rise in occupancy, just like the rise in the volume size needed when chemical equilibrium $\gamma_i^{\text{HG}} = 1$ is assumed, accommodates transformation of a entropy dense QGP phase into entropy dilute HG phase. Similarly, a jump-up in the strangeness phase space
occupancy parameter $\gamma_s$ allows for higher density of strangeness in QGP compared to HG. We have, in general,
\[ \gamma^\text{HG}_{i}(t_f) > \gamma^\text{QGP}_{i}(t_f), \quad i = q, s. \]

The available number of quark pairs in QGP at hadronization decisively influences the possibility to form baryons. In fact, the ratio of baryon to meson yield arising in microscopic dynamics of hadronization is proportional to $\gamma_q$. This establishes the necessity to include the occupancy parameters in order to describe the yields of hadrons, since this is the parameter which allows for a hadronization dependent dynamical relative yield of mesons and baryons. Conversely, a study of particle yields with a fixed light quark equilibrium value $\gamma^\text{HG}_q = 1$ presumes that the relative yield of baryons to mesons is fully chemically equilibrated, and that we know well the spectrum of hadrons. Clearly, neither assumption is safe and the choice $\gamma^\text{HG}_s = 1$ is over-constraining any hadronization model, as of course is the choice $\gamma^\text{HG}_s = 1$.

2. Particle yield SHM data analysis

The analysis of experimental hadron yield results requires a significant book-keeping and fitting effort in order to allow for resonances, particle widths, full decay trees and isospin multiplet sub-states. A program SHARE (Statistical HAdronization with REsonances) suitable to perform this data analysis is available for public use [1, 2]. This program implements the PDG [3] confirmed (4-star) set of particles and resonances, and we use [4] already for two years the modern $\sigma$-meson mass [5] ($m_\sigma = 484$, $\Gamma_\sigma/2 = 255$ MeV).

The important parameters of the SHM, which control the relative yields of particles, are the particle specific fugacity factors $\lambda$ and the space occupancy factors $\gamma$ discussed above. The fugacity is related to chemical potential $\mu = T \ln \lambda$. The occupancy $\gamma$ is, nearly, the ratio of produced particles to the number of particle expected in chemical equilibrium, and thus, meson yield is (nearly) proportional to $\gamma^2$ and baryon yield to $\gamma^3$ (here, we did not distinguish the valance quark content for $u, d, s$ quarks). The actual formula for the momentum distribution is, both for the HG and QGP phase:

\[ \frac{d^6 N}{d^3 p d^3 x} \equiv f(p) = \frac{g}{(2\pi)^3} \frac{1}{\gamma - 1 - 1} e^{E/T} \pm 1 \rightarrow \gamma \lambda e^{-E/T}, \]

where the Boltzmann limit of the Fermi '+' and Bose '-' distributions, applicable, in particular when $m/T > 1$, is indicated. $g$ is the degeneracy factor, $T$ is the temperature and $E = E(p)$ is the single particle energy spectrum, typically $E = \sqrt{m^2 + p^2}$.

The fugacity $\lambda$ is associated with a conserved quantum number, such as net-baryon number, net-strangeness or heavy flavor. Thus, antiparticles have inverse value of $\lambda$, and $\lambda$ evolution during the reaction process is related to the changes in densities due to dynamics, such as expansion. Contrary to $\lambda$, $\gamma$ is the same for particles and antiparticles. Its value changes as a function of time, even if the system does not expand, for it describes buildup in time of the particular particle species. For this reason, $\gamma$ changes rapidly during the reaction, while $\lambda$ is more constant. It is $\gamma$ which carries the information about the time history of the reaction and the precise condition of particle production referred to as chemical freeze-out.
In the quark phase, each particle has its proper chemical yield co-factor, thus for light quarks $q = u, d$, we have yield co-factors $\gamma_q^{\text{QGP}} \lambda_q^{\text{QGP}}$, and for antiquarks $\bar{q}$, we have $\gamma_{q}^{\text{QGP}} \lambda_q^{-1}^{\text{QGP}}$, and similarly for strange quarks $s$ and antiquarks $\bar{s}$. In the HG phase, we need to count valance quark content of each hadron. For example, for the $\Lambda$, the chemical co-factor is $\gamma_s^{\text{HG}} \gamma_q^{\text{HG}} \lambda_q^{\text{HG}} \lambda_s^{\text{HG}}$, while for $\bar{\Lambda}$, it is $\gamma_s^{\text{HG}} \gamma_q^{\text{HG}} \lambda_q^{-1}^{\text{HG}} \lambda_s^{-2}^{\text{HG}}$. We recall that the chemical potentials of baryon number, $\mu_B$, and hyperon number, $\mu_S$, are

$$
\mu_B = 3T \ln \lambda_q, \quad \mu_S = T \ln \lambda_q - T \ln \lambda_s,
$$

where, for historical reasons, hyperon number has opposite quantum number to strangeness. Above and from now on, when the upper index is absent the (chemical) variable considered refers to the final state phase, thus to HG. SHARE allows the conservation of (electrical) charge $Q$, which is done at the cost of introducing the fugacity $\lambda_I^3 \equiv \lambda_u/\lambda_d$ and we note, in this context, that $\lambda_q = \sqrt{\lambda_u/\lambda_d}$.

We evaluate the success of our data fit considering the profile of $\chi^2/\text{dof}$ as function of $\gamma_q$. (see top of figure 1, on left for AGS–SPS energy range, and on right for RHIC. The best fit is clearly not obtained at $\gamma_q = 1$ Note that for a small number of dof, the value of $\chi^2/\text{dof}$ can be very misleading, for this reason the bottom frames in figure 1 show the confidence level $P_C \equiv \text{CL}$.

The meaning of $P_C \equiv \text{CL}$ is explained in “Review of Particle Physics” where
we see, in Figure 32.2, lines of fixed value of $P_C$, for given values $\chi^2$/dof and dof. Note that the value $P_C = 50\%$ is equivalent to $\chi^2$/dof = 1 for the case that very many dof are present. However, for a small number of dof, a very much smaller value of $\chi^2$/dof must be achieved to claim good confidence fit. Only $P_C(\chi^2, \text{dof})$, and not $\chi^2$/dof, expresses confidence in the validity of the model used to fit the data.

Effectively, $P_C(\chi^2, \text{dof})$ also expresses confidence in the data, provided that we believe in the model. This is easily recognized by checking what happens when we intentionally alter an experimental data point, e.g., by 2 s.d. We find that our data fit remains stable in the sense that we find nearly the same model parameters, but $P_C$ becomes much smaller, and the falsified data point contributes dominantly to the error of the fit.

At SPS (left side, bottom frame of figure 1), our fits, carried out with the NA49 2008 data set, converge to a common best value $P_C = 70\%$ [6]. This value has somewhat higher $P_C$ than one should expect on statistical grounds (50%). However, we have treated systematic errors as if these were statistical errors, and have added these linearly to the statistical errors, in effect making many measurement errors too large. On the right hand side, in figure 1 we see RHIC results. It seems that for $\sqrt{s_{\text{NN}}} = 200$ and 130 GeV, the confidence level is here too high, suggesting that the combination of statistical errors with systematic errors was not appropriate (our, here presented, 62 GeV fit comprises some extrapolated and interpolated results and should not be seen as yet to be a ‘real’ data fit).

3. Data used and statistical parameters

The data sets for AGS–SPS study were presented elsewhere [6], the study of total (as opposed to $dN/dy$) hadron yields at RHIC is relying on extrapolations, and the discussion of this matter goes beyond the scope of this presentation. In table 1 we show the in–out data fields for the fits to central rapidity 200, 130 and 62.4 GeV at RHIC, as used here. As seen in table 1 we combine PHENIX data for direct single particle spectra with RHIC data for (strange) particles yields reconstructed from the decay particles using, e.g., the invariant mass method [7], a more complete discussion of our data set goes beyond the scope of this report, see also [4].

Other statistical hadronization (SH) parameters we derive from the data, shown in bottom of table 1 are the source volume $V$ (that is $dV/dy$ for RHIC, the volume associated with the interval of rapidity in which particles are measured), the temperature $T$, at which particles stop changing in yield (chemical freeze-out). Moreover, we obtain chemical potentials $\mu_B = 3\mu_q = 3T \ln \lambda_q$, $\mu_S = T \ln(\lambda_q/\lambda_s)$, related to conserved quantum numbers: baryon number and strangeness, respectively. We also obtain $\lambda_I$ which expresses the asymmetry in the 3-rd component of the isospin. Especially for low energy reactions, where the particle yield is relatively low, this parameter differs significantly from unity. We have become aware by checking the work of other groups pursuing statistical hadronization of QGP and fits to hadron yields that the net charge per net baryon ratio (0.39 for heavy nuclei) is not maintained in this work.

4. Hadronization condition

The SHARE program provides, beyond statistical parameters, also an opportunity to evaluate the physical properties of the bulk matter at hadronization. These show a
Table 1. The constrains, imposed and natural at the top, followed by input particle data and the resulting statistical parameters, and at bottom, the chemical potentials derived from these, for RHIC central rapidity, most central collisions. \( \lambda_q \) values are obtained from the constraint to zero strangeness. The weak feeds allowed were as stated by experimental groups or/and estimated by us, however, in the fit of the \( p, \bar{p} \) yields we accepted complete weak feed from all hyperons.

| \( \sqrt{s_{NN}} \) [GeV] | 62.4 | 130 | 200 |
|--------------------------|------|-----|-----|
| \( P \) [GeV/fm\(^3\)] | 0.082±0.001 | 0.082±0.001 | 0.082±0.001 |
| \( E/b_p \) [GeV] | 0.75±0.075 | 0.75±0.075 | 0.75±0.075 |
| \((s-\bar{s})/(s+\bar{s})\) | 0 | 0 | 0 |
| \( Q/b \) | 0.39±0.01 | 0.4±0.01 | 0.4±0.01 |
| \( \pi^+ \) | 233±26 | 276±36 | 280.4±24.2 |
| \( \pi^- \) | 237±27 | 270±36 | 281.8±22.8 |
| \( K^+ \) | 38±4.3 | 46.7±8 | 48.9±6.3 |
| \( K^- \) | 32.6±4.7 | 40.5±7 | 45.7±5.2 |
| \( \phi/K^- \) | 0.15±0.03 | 0.174±0.03 |
| \( p \) | 34.3±3.8 | 28.7±4 | 28.3±4.8 |
| \( \bar{p} \) | 13.8±1.6 | 20.1±2.8 | 13.5±1.8 |
| \( \Lambda \) | 17.35±0.8 | 16.7±1.3 |
| \( \bar{\Lambda} \) | 12.5±0.8 | 12.7±1.1 |
| \( \Xi^- \) | 1.84±0.2 | 2.17±0.25 |
| \( \Xi^0 \) | 1.16±0.12 | 1.83±0.25 |
| \( \Xi^-/h^- \) | 0.0077±0.0016 |
| \( \Xi^0/\Xi^- \) | 0.853±0.1 |
| \( \Omega \) | 0.229±0.035 |
| \( \Omega^+/\Omega^- \) | 0.176±0.030 |
| \( (\Omega+\bar{\Omega})/h^- \) | 0.0021±0.0008 |
| \( K^0(892)/K^- \) | 0.26±0.08 | 0.23±0.05 |
| \( dV/dy \) [fm\(^3\)] | 1089±74 | 1172±93 | 1156±88 |
| \( T \) [MeV] | 142.9±0.3 | 140.2±0.2 | 140.5±0.5 |
| \( \lambda_q \) | 1.166±0.036 | 1.077±0.020 | 1.066±0.030 |
| \( \lambda_s \) | 1.066* | 1.029* | 1.033* |
| \( \gamma_q \) | 1.53±0.10 | 1.56±0.031 | 1.54±0.14 |
| \( \gamma_s \) | 1.74±0.22 | 2.32±0.31 | 2.30±0.40 |
| \( \lambda_I \) | 0.992±0.003 | 0.997±0.001 | 0.997±0.002 |
| \( \mu_B \) [MeV] | 65.9 | 31.2 | 27.1 |
| \( \mu_S \) [MeV] | 13.5 | 6.4 | 5.6 |

change, from a low density and low pressure system at low \( \sqrt{s} \) (AGS, lowest SPS 20 A GeV data) to a highly compressed phase just above this in energy. In figure 2 we show, in the upper frame, the pressure \( P \) we obtain for the different fits. We find [4, 6], in the study of the high energy SPS data, that hadronization is characterized by a remarkably constant value of \( P \approx 82 \pm 2 \) MeV/fm\(^3\). This result arises in the SPS energy domain (which is involving the total particle yields) without a further constrain. For RHIC, the central rapidity results lack a fixed baryon number and, as shown in previous section, the errors are way too large yielding fit confidence which is too high. We thus decided, at RHIC, to introduce as a additional ‘measurement’ the value \( P \approx 82 \pm 2 \) MeV/fm\(^3\).
In figure 2, we also show in the lower frame the fireball energy per primary hadron, $E/h_p$. This value is also remarkably constant for top SPS and all RHIC reaction energies. The variation we see is, in part, explained by baryon density variation, and at low energy by different properties of the hadronizing system also seen in many other observables. Note that if $\gamma_H = 1$ is forced, the value $E/h_p \simeq 0.75$ rises to 1 GeV [8]. Considering the result achieved at SPS we introduce at RHIC as an additional constraint $E/h_p = 0.75 \pm 10\%$ as is also shown in table 1. With the two constraints, $P$ and $E/h_p$ we find very good data fits with the outcome confirming that the hadronization pressure offers a good characterization of QGP breakup.

Hadron particle pressure emerges, in our study, as a common physical property which defines when and how QGP breaks up into hadrons. Why this is so is explained remembering that, at $P = 1$ atm, water boils in New York and in Beijing at 100°C. The color non-conductivity of the true vacuum acts like a ‘pot cover’ keeping quarks together, the cover recedes when the pressure is high, QGP expands. After QGP breaks, the residual quark pressure turns into hadron pressure. In this picture the quark particle pressure has just the magnitude required to balance the vacuum pressure. Thus, the critical pressure of hadronization must be the vacuum pressure confining color.

The pressure $P$ is compared to several other physical bulk properties of QGP in figure 3. At low energy considering for example, entropy $\sigma$, we note that the AGS and lowest SPS results agree and produce a low value, suggesting a source which is half as dense compared to other results. This would be just what one expects if QGP is not formed at low reaction energies, or/and when there has been a considerable re-equilibration of hadronization products. Consideration of other, more penetrating observables, such as strangeness per entropy $s/S$ and the continuity of
total strangeness production as function of energy support the second hypothesis, a well equilibrating QGP fireball after hadronization.

At high energy, we see that SPS and RHIC bulk properties are consistent. Moreover, the behavior as function of energy of, for example, the net baryon density (bottom frame) is consistent with the expectation that it should be decreasing — since baryon transparency increasing with energy of reaction is an intuitive requirement. Fits which force $\gamma_i = 1$ can fail to produce this natural result.

The values of energy density, $E/V \to 500 \text{ MeV fm}^{-3} = (250 \text{ MeV})^4$, and entropy density, $S/V \to 3.4 \text{ fm}^{-3}$, obtained for the high energy reactions are worth noting. These complement $P \to 82 \pm 2 \text{ MeV fm}^{-3} = (158 \text{ MeV})^4$.

5. Particle yield predictions

In figure 4 we show growth of strangeness pair yield with energy, squares (blue) for the total hadron most central reaction trigger, and RHIC central rapidity most central...
trigger as triangles (red). In table 1 we show the particle yields we obtain, comparison with table 1 shows that our fit is very successful.

Table 2. Output hadron multiplicity data for the RHIC energy range. See text for the meaning of predictions of $N_{4\pi}$ yields at 62.4 and 130 GeV and of $dN/dy$ at 62.4 GeV. The input statistical parameters are seen in table 1. $b = B - \overline{B} \equiv N_W$ for $4\pi$ results and $b = d(B - \overline{B})/dN$ for results at central rapidity. Additional significant digits are presented for purposes of tests and verification. All yields are without the weak decay contributions.

| $\sqrt{s_{NN}}$ [GeV] | 62.4 | 130 | 200 |
|------------------------|------|-----|-----|
| $E_{eq}$ [GeV]         | 2075 | 9008| 21321|
| $\Delta y$            | ±4.2 | ±4.93| ±5.36|
| $dN/dy|_{y=0}$ 5%       | b    | $\pi^+$| $\pi^-$|
|                        | 35.90| 232.5| 235.9|
|                        | 245.9| 247.4| 241.9|
|                        | 51.9 | 50.8 |
|                        | 48.1 | 47.6 |
|                        | 48.2 | 47.5 |
|                        | 7.54 | 7.45 |
|                        | 15.65| 14.99|
|                        | 10.11| 10.27|
|                        | 11.6 | 11.2 |
|                        | 8.18 | 8.26 |
|                        | 2.34 | 2.27 |
|                        | 1.80 | 1.80 |
|                        | 0.46 | 0.45 |
|                        | 0.39 | 0.39 |
|                        | 10.7 | 12.5 | 12.2 |
6. Comments and Conclusions

We believe that the assumption of $\gamma_q = 1$, we often see in literature in the context of the analysis of hadron particle yield data, tests the hypothesis that QGP was not, or only extremely briefly present in relativistic heavy ion collisions. The tacit assumption made is that instead of a QGP, a long-lasting cascade of hadronic reactions allows the HG particles to chemically equilibrate. However, if this were to be true, an even stronger evidence for HG dominance of HI reactions would be that the value $\gamma_q \to 1$ emerges in the analysis, rather than being assumed. However, we find allowing $\gamma_i \neq 1$, $i = q, s$ that, nearly always, the chemical non-equilibrium prevails, with a much higher confidence level. Furthermore, this additional freedom produces QGP like properties of the bulk from which particles emerge.

To summarize, we differ from other groups in the following aspects in our data analysis:

(i) We use $\gamma_q \neq 1$, and thus allow the ratio of baryon to meson yields to be fixed independently of the hadronization temperature;

(ii) We enforce, in the fit, the conserved ratio of charge to baryon number $Q/b = 0.395 \pm 0.01$, and are able to fit the associated $\lambda_{I3}$ fugacity;

(iii) We do not enforce exact strangeness conservation, $\langle s \rangle - \langle \bar{s} \rangle = 0$, but instead, we allow $\delta s = (s - \bar{s})/(s + \bar{s}) = 0 \pm 0.05$ to behave like a measurement, the reasoning is as follows:

a) Summing all measured and unmeasured hadrons in strangeness ‘conservation’ condition, $\Delta s = \sum_i h_i^s - \sum_j h_j^\bar{s} = 0$, combines independent measurement errors and thus, even if the experimental data had all strangeness carrying hadrons, there would be a residual statistical error present in $\delta s$;

b) Some strangeness could escape detection in unknown ‘particles’, for example being bound in (nearly) uds-quark-symmetric semi-stable strangelett (a small drop of quark matter), this leads to $\delta s < 0$ — which is what we find as a preferred result in low energy fits;

c) The experiments did measure many, but not all relevant particles carrying strangeness, e.g., $\Sigma^\pm$ has not been measured, this yield is uncertain and thus $\delta s = 0$ cannot be ever imposed on experimental grounds alone;

d) Introducing an error in $\delta s$, we perform a test of the hypothesis that weak decays remains weak in QGP phase, and thus, the net strangeness remains conserved — another way to understand this is to note that we cannot confirm that weak decays in QGP remain weak to better than the progressing error of individual contributing measurements.

(iv) In the study of RHIC data, we consider a mix of STAR and PHENIX particle yield results, following the principle that the PHENIX integrated single particle spectra are more reliable than those of STAR, and STAR, in turn, given its high acceptance is more reliable in evaluation of yields of hadrons observed in their two or more particle decay channels.

The reader should note that we have, in our fits compared to many other efforts, three more parameters: $\gamma_q$ as explicitly stated above, $\lambda_s$ since we do not fix but fit strangeness conservation and $\lambda_{I3}$ since, as the only group, we enforce a fit to $Q/b$. Thus, we have, in general, one less degrees of freedom (three more parameters and two more ‘data’ points, $\delta s = 0 \pm 0.05$ and $Q/b = 0.395 \pm 0.01$). However, the real issue is that all told we have a 7-dimensional space of parameters, $T, V, \lambda_q, \lambda_s, \gamma_q, \gamma_s$.
and $\lambda_{13}$, which contains many false minima, and the art of finding the domain of the best fit minimum is not easily acquired, and cannot be dispensed with the comment ‘fit is unstable’. Naturally, it takes much more effort to find a true minimum in a 7-d parameter world, compared to a 2-d parameter world which corresponds to the simplest and least physical “equilibrium” model with $T, \mu_B$ as parameters, i.e., setting also $\gamma_s = 1$, fixing $\mu_S$ by strangeness conservation and using only particle ratios in the fit. Whoever practices this today has learned nothing from the work of past 20 years.

The most intriguing result of this analysis is the smoothness, and even near constancy, of physical properties of the fireball at chemical freeze-out condition seen for the top three SPS energies 40, 80 and 158 AGeV, which result agrees well with RHIC fits where we impose the pressure $P$ and hadronization particle energy $E/h_p$. Of particular physical interest is the value of hadronization pressure, $P \simeq 82$ MeV/fm$^3$, obtained at SPS, and found in this work to be consistent with RHIC data — one may imagine that in a phase transformation from quarks to hadrons, the pressure of quarks is transferred into the pressure of color-neutral hadrons, which can escape from the deconfined fireball. Since the flow pressure of quarks transfers smoothly into that of hadrons, we conclude that the thermal pressure of produced hadrons, $P \simeq 82$ MeV/fm$^3$, provides a first estimate of the pressure of the vacuum which keeps color charged quarks inside the fireball up to the point of sudden fireball break-up.

In summary, we presented a high confidence fit of high centrality data from AGS, SPS and RHIC, and have found common ground of results at SPS and RHIC regarding the bulk properties of hadronizing matter. This suggests that a deconfined phase is with great probability already formed at or near 30 A GeV.

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