Sequential hadronization and the opportunities it presents

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Abstract. Continuum extrapolated lattice QCD calculations of quantum number specific susceptibilities and the most recent RHIC and LHC data on produced particle yields, as well as their higher moment fluctuations, can be interpreted using a scenario of sequential flavor dependent hadronization during the QCD crossover transition. I will present the latest data from lattice QCD and experiment and confront the question whether the separation of strangeness and light quark chemical freeze-out could have consequences beyond a simple strangeness enhancement, firstly in the production of exotic strange states and secondly in the flavor dependent evolution of dynamic quantities such as in-medium energy loss and anisotropic flow, which are generated predominantly during the collective partonic phase.

1. Indications of sequential hadronization from the lattice

Lattice QCD data have started to reveal fine differences between conserved quantum numbers when continuum extrapolated data of susceptibilities became available a few years ago. As an example I show in Fig.1a the difference between light and strange quark second order susceptibilities in the QCD crossover region [1]. The inflection point of the $\chi^2_{s,s}$ is clearly shifted to higher temperatures, which on the lattice can be attributed to a simple quark mass effect. In fact recent calculations have shown that the effect is even more prominent for the charm quark susceptibilities [2]. Although the simple $\chi^2$ behavior does not allow us to determine a pseudo-critical temperature, the ratio of $\chi_4/\chi_2$ was proposed as a powerful tool to determine the chemical freeze-out temperature in the thermalized system from first principles [3], rather than relying on statistical fits to the particle yields or ratios [4]. In this context our original paper on flavor hierarchy [1] showed that the continuum extrapolated susceptibility ratio reveals indeed maxima at different temperatures for light and strange quarks. The final proof of a sequential hadronization scenario has to come from the comparison to experimental fluctuation data, though, which can be mapped to the susceptibility ratios on the lattice. It is by no means proven that the maxima obtained in the lattice ratios indeed correspond to the chemical freeze-out data although comparisons to Hadron Resonance Gas (HRG) model calculations, which describe the hadronic phase quite reliably, show that the maxima coincide with the deviations of the HRG curves from the lattice data, see Fig.1b.

Furthermore comparisons of lattice calculations [5, 6] to fluctuation data from STAR on net-protons and net-charge [7, 8], see Fig.2a, seem to indicate lower freeze-out temperatures than the ones obtained from statistical hadronization fits to the yields of all produced particles [4], see Fig2b. Two important points should be noted:
1.) for the comparison to be valid one needs to be able to equate the efficiency corrected net-proton measurements in a finite acceptance bin to the total net-baryon number calculations on the lattice. Many independent studies have been performed to ensure this equivalence [9, 10, 11, 12, 13, 14] and one is now reasonably confident that the comparison can indeed be made to the level accuracy shown in Fig.2. Furthermore HRG results based on a parallel analysis of both net-number measurements show excellent agreement with the lattice results and push them out to even larger chemical potential, as shown in Fig.2b [15].

2.) the reason that the freeze-out temperatures deduced from the fluctuations of net-protons and net-charges are lower than the ones from the fits to all particle yields can again be attributed to the potential flavor hierarchy. Both, net-proton and net-charge multiplicities are dominated by light particles, protons in the one case, pions in the other. If light quarks indeed prefer to freeze-out at a lower temperature then this would explain the measured differences between total yield and specific fluctuation fits. The final proof will lie in a comparison between lattice data and a net-strangeness measurement, which will be discussed in the following sections.
2. Indications of sequential hadronization from experimental data

The first indication of slight deviations in measured particle yields from a fit based on a common chemical freeze-out temperature came from the high precision multiplicity measurements of identified particles in the ALICE experiment, in particular the protons. In contrast to the RHIC data, the excellent position resolution of the Inner Tracking System (ITS) in ALICE enabled the collaboration to perform an in-depth feed-down correction for the protons from the weak decays of strange baryons. After subtracting this contribution the preliminary data shown at SQM in 2014 revealed a difference between the protons and strange and multistrange baryons chemical freeze-out temperature of almost 20 MeV (148 MeV for protons vs. 164 MeV for multi-strange baryons) [16]. A fit with a common freeze-out temperature of 156 MeV was presented at QM 2014 [17], but the fit still shows a deviation of almost 4σ between the protons and the multi-strange baryons as shown in Fig.3a. Several alternative explanations for the low proton yield were proposed following the release of the data [18, 19, 20, 21], some also proposing two freeze-out temperatures, but for different reasons [22]. The suggestion of enhanced hadronic re-interaction in the dense hadronic medium shortly after the chemical freeze-out [21, 23] garnered the most interest since it also tries to address the potential shortcoming of any HRG calculation, which assumes a non-interacting hadron gas as the hadronic phase. Although the idea of enhanced baryon annihilation in the dense cooling system seems appealing, the near perfect agreement between the freeze-out temperature from net-charge fluctuations, which are independent of annihilation, and net-proton fluctuations [6] seems to indicate that the effect of hadronic re-interactions is small. Nevertheless a detailed study of the hadronic interactions using a realistic transport approach is underway and has shown intriguing effects on bringing the chemical freeze-out temperature closer to the QCD crossover temperature deduced from the lattice, in particular at larger chemical potential, i.e. smaller collision energies (RHIC beam energy scan)[23].

The final missing experimental input into the question of flavor separation during the crossover will be a high precision measurement of net-strangeness fluctuations. Unfortunately, in order to fully determine net-strangeness the experiment needs to measure the fluctuations of net-yields of K, Λ, Ξ, and Ω (incl. Σ’s). Since the measurement of multi-strange baryons is significantly statistics limited, even at the highest collision energies and data acquisition rates at the LHC, the question arose whether a subset of strange particles might be sufficient to determine the strange chemical freeze-out. Our recent study showed that just the kaons alone follow the trend of the strange freeze-out, but an in-depth study will likely require the Λ and Ξ as well.

Progress has been achieved experimentally by the STAR collaboration, which has shown preliminary net-kaon moments at QM 2015 [24] and by Ji Xu at this conference, see Fig.3b. Data from ALICE on net-charge, net-proton, and net-kaon are forthcoming, and one can look forward to an interesting interpretation of these results, since the lattice QCD data at \( \mu_B=0 \) are the most reliable.

3. The latest results of comparisons between data and models

The analysis of the STAR kaon fluctuation data shown in Fig.3b using the lattice QCD and HRG methods employed in [6] and [15], respectively, is hampered by the large systematic error on the lower moment ratio, in particular at the relevant highest RHIC energies. Still, the fit procedure in the framework of the HRG formalism [15] leads to a rather clear trend towards a higher freeze-out temperature for the Kaons as shown in Fig.4a. Although the result is still in agreement with the combined fit to the net-proton and net-charge results, a reduction of the systematic to 10% will lead to a significant result as shown by the yellow points in Fig.4a.

Even more importantly the lattice approach, which is independent of the HRG result, has been recently refined to allow a direct comparison between lattice data and a particular particle species, in this case the kaons [25]. Until now lattice QCD only addressed the conserved quantum
Figure 3. (a) Statistical Hadronization model fits to all measured particle yields in ALICE [17]. Although all three models converge on a common temperature, the main deviations seem to be flavor dependent. (b) First preliminary measurements of higher moment fluctuations of the net-kaon distribution in STAR [24] as function of collision energy.

number as a whole, not its individual particle species contributions. The new method is based on showing the equivalence between the lattice and a Boltzmann approximation to the partial pressure, which then allows to break out individual baryonic and mesonic contributions to the pressure on the lattice on the basis of this equivalence. Based on these calculations the data can now be confronted with lattice QCD calculations, which is shown in Fig.4b [25]. Again, the presently large experimental systematic error only allows to set a lower limit for the strange freeze-out temperature, which is still in line with the freeze-out temperatures deduced for the non-strange particles. The figure shows nicely, though, how any improvement on the kaon fluctuation uncertainty will further constrain the temperature.

4. Opportunities for the formation of new states
The concept of a sequential freeze-out of quark flavors poses significant questions for the hadronization process. How does a multi-flavored hadron freeze-out and when does it freeze-out? There seem to be indications from the lattice and from the measurement of strange baryon multiplicities that the light quarks dominate the hadronization process inasmuch as any light quark dominated hadron seems to freeze-out rather late at a lower temperature. This has been shown on the lattice by the HotQCD group studying the D-mesons [26] in contrast to the studies of pure charm states by a subset of the same authors [27]. It also can be seen by an in-depth study of the freeze-out temperatures of strange baryons in ALICE, the Λ seems to prefer a lower freeze-out temperature than the multi-strange baryons. Therefore in the strangeness sector the ideal case to study will be an in-depth comparison of the proton to the Ω baryon. Unfortunately the Ω measurements are still statistics limited, although the upgraded ALICE detector promises
Figure 4. (a) A HRG fit to the preliminary STAR net-kaon $\chi_3/\chi_1$ ratio for central events at a collision energy of 200 GeV shown in Fig.3. The fit, shown in green follows the same procedure than the combined fit to net-charge and net-proton \cite{15} shown in red here. The blue and yellow curve show the uncertainty on the net-Kaon fit assuming statistical errors only or an additional systematic error of 10%, respectively. (b) A direct comparison between the same experimental net-kaon ratio and a continuum extrapolated lattice QCD calculation that breaks out the kaon fluctuations based on partial pressure contributions \cite{25}.

an improvement of at least one order of magnitude.

The easiest way to remedy the apparent strangeness enhancement is to assume that the number of measured strange hadronic states is incomplete and thus requires us to postulate higher mass resonant states that will absorb the abundant strange quarks \cite{28}. This concept is not unrealistic since the Particle Data Group has included many more experimentally confirmed heavy strange resonances in its booklet between 2008 and 2014 \cite{29,30}. The ultimate population of hadronic states can be estimated via the Quark Model \cite{31}. If these states are included in the hadronic calculations, they seemingly can absorb the extra strangeness released by the sequential freeze-out. A new program to find more of these postulated states has been initiated by JLab.

On the other hand the apparent discrepancy of strange hadronic states and a partonic medium still dominated by quasi-free light quarks should lead to strangeness clustering and thus to the possibility of formation of multi-quark strange states, along the lines of the recently discovered charm tetraquark and pentaquark \cite{32,33}. ALICE has investigated the production of H-Dibaryons and the originally claimed strange pentaquark \cite{34}. Unfortunately both of these searches turned out negative \cite{35,36} with limits well within the range of production estimated by thermal models. The reason could again be the dominance of light quarks in these states, and I suggest to search for multi-strange multi-quark states such as the $\Xi\Xi$-dibaryon \cite{38}.

5. Opportunities for a new interpretation of dynamic quantities in the partonic phase

Finally I am trying to address whether dynamic quantities governed by the evolution of the collective partonic phase could be affected by a sequential freeze-out scenario. The two main parameters in question are the shear viscosity as obtained by anisotropic flow $v_\pi$ and the partonic energy loss as obtained by the nuclear modification factor $R_{AA}$. In both cases the modeling of the dynamic evolution of the partonic system very much impacts the final results and the correlation between these two effects. In other words, is it possible that a differing hadronization temperature for different particle species could lead to more or less energy loss and/pr more less anisotropic flow. This question arises mostly on the basis of particle species dependent $R_{AA}$ at RHIC and the LHC. Fig.5(a) shows the published data on $R_{AA}$ from PHENIX \cite{39}. Special emphasis should be given to the apparent difference between the light mesons ($\pi$ and $\eta$) and the
strange mesons (K and \(\phi\)). Below 8 GeV, i.e. in the region where collectivity plays a role and the particles are likely thermal, the strange mesons clearly exhibit less of an energy loss than the light mesons. Fig.5(b) shows preliminary data from ALICE for the energy loss measurements of D-meson vs. \(D_s\)-mesons [40]. Although the error bars are still large one sees a similar trend of the strange D-meson being less suppressed than the light D-meson.

![Figure 5.](image)

Figure 5. (a) The complete set of nuclear suppression factors measured by PHENIX. Special emphasis should be given to the \(\pi\) and \(\eta\) points compared to the K and \(\phi\) points [39]. (b) The nuclear supression factors measured by ALICE for D- and \(D_s\)-mesons [40].

Both effects can potentially be attributed to canonical suppression, i.e. the suppression of strangeness formation in the small proton-proton reference system. But in our picture a canonical suppression is not necessary since all of the strangeness enhancement stems from the increased freeze-out temperature of the thermal deconfined strange quark system. These thermal quarks could potentially lead to an increased recombination cross section with charm quarks in the partonic phase [41] or alternately the strange charmed mesons lose less energy in the partonic system. The only requirement here is that the energy loss is predominantly generated very close to hadronization, i.e. if the system hadronizes at a higher temperature the partonic energy loss ceases earlier and thus generates less of an \(R_{AA}\) for the strange final states. This concept of late energy loss has been proposed and tested by Greco et al. [37] and they found that a temperature dependent energy loss close to freeze-out paired with a temperature-dependent coupling constant indeed leads to an excellent correlation between the experimental \(R_{AA}\) and \(v_n\) results. This agreement eludes most of the other models on the market. One should note, though, that this flavor effect on \(R_{AA}\) should also impact \(v_n\) in the same \(p_T\) range. Hydrodynamical calculations with differing switching temperature from the partonic to the hadronic phase point in that direction [42]. The preliminary ALICE data [43] show much less of an effect for the flow harmonics. One should also recognize that the effect seen, in particular by PHENIX (Fig.4(a)) cannot be explained by recombination or hydrodynamics since all particles that are compared are mesons and have very similar mass. I propose an in-depth study of energy loss in the \(p_T\)-range where thermalization is likely for multi-strange baryons in comparison to protons, in particular using the high statistics soon available from ALICE Run-II. Besides the aforementioned dynamic coefficients it might also be interesting to study bulk viscosity in a more flavor and particle species dependent way [44].
6. Conclusions
I have shown that experimental data on particle yields and fluctuations and lattice QCD
calculations of conserved quantum number susceptibilities can be reconciled if one assumes a
flavor dependent approach to chemical freeze-out. This concept will enable a more detailed
experimental investigation of the process of hadronization and will thus lead to a deeper
understanding of the non-perturbative part of QCD.

In addition to the ongoing fluctuation measurements of net-charges (baryon number, electric
charge and strangeness) I propose several new measurements that would be possible as a
consequence of sequential hadronization. In the particle production sector we suggest to search
for higher mass hadronic resonances, in particular in the strange sector, and for evidence
of strangeness clustering, either through angle-dependent yield and fluctuation measurements
and/or through the discovery of strangeness dominated multi-quark states.

Finally, I propose that sequential hadronization might impact dynamic state variables of the
collective partonic system, such as $R_{AA}$ and $v_n$ if it can be shown that these quantities develop
predominantly close to the QCD crossover temperature.

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