IS THERE LIFE AFTER HADRONIZATION? AN EXPERIMENTAL OVERVIEW*

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Recent experimental findings on the properties of the chemical and kinetic freeze-out are reviewed, including data from low energies (SPS) over RHIC, up to recent results from the LHC. We discuss whether chemical freeze-out coincides with hadronization or if there is evidence for a "life after hadronization" which might significantly change particle abundances.

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1. Introduction

The conventional and simplified scenario of the evolution of a high energy heavy ion reaction is the following: Starting from a Quark-Gluon Plasma (QGP) phase particles hadronize at the critical temperature T_{C} and the system then turns into a hadron gas which further evolves as it expands and cools down. It will reach the chemical freeze-out temperature T_{ch} at which all inelastic reactions cease and the relative particle abundances are frozen out. Afterwards, elastic scattering processes may still continue and possibly modify the momentum distributions of the hadrons until the kinetic freeze-out temperature T_{kin} is reached. After this final freeze-out only free streaming particles propagate towards the detector. The question to be addressed in the following is whether there is any experimental indication for these different phases after hadronization and, if yes, if there is any way of determining the lifetimes of the different phases by measurements.

It is by no means clear that the above described scenario is realized in nature. In fact, there are several other concepts that do not require any extended period between hadronization and chemical or kinetic freeze-out.

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Single freeze-out models, for instance, where chemical and kinetic freeze-out coincide, have been quite successful in describing particle spectra and yields as measured at RHIC [1]. The suggestion that chemical equilibration is generally driven by the vicinity of a phase boundary implies that there is no need for an extended hadron gas phase between hadronization and chemical freeze-out [2]. The same applies to sudden freeze-out models as discussed in [3].

One way to model an extended hadronic phase after hadronization in theory is to couple a hadronic transport model as an afterburner to a hydrodynamic calculation [4]. Alternatively, a hydrodynamical evolution has been combined with an extended freeze-out description [5] to investigate the effect of a continuous decoupling. These approaches allow us to study whether particle abundances and spectra are modified by subsequent hadronic interactions as, *e.g.*, the absorption of anti-baryons. As a consequence, one might observe deviations from the chemical equilibrium value for certain particle species. It has also been pointed out quite early that particles with low hadronic cross sections (*e.g.* Ω^-, ϕ) should freeze-out earlier than other hadrons if there was a long lived hadronic phase [6].

2. Kinetic freeze-out

The left panel of Fig. 1 shows a recent compilation of chemical $T_{\rm ch}$ and kinetic $T_{\rm kin}$ freeze-out temperatures as a function of $\sqrt{s_{NN}}$ [7]. $T_{\rm ch}$ has been extracted from fits with statistical models (*e.g.* [8, 9, 10]) to particle yields measured in central nucleus–nucleus collisions at different energies, while $T_{\rm kin}$ was determined by fits to transverse momentum spectra of pions, kaons, and protons with a blast wave model [11]. The latter model provides a simple parametrization of $p_{\rm t}$ spectra which includes the effect of transverse expansion, thus allowing a simultaneous fit to the spectra of hadrons with different mass with usually reasonable results. The right panel of Fig. 1 shows the resulting average transverse expansion velocity $\langle\beta\rangle$. There is a clear difference between $T_{\rm ch}$ and $T_{\rm kin}$ seen in these fit results with $T_{\rm kin} < T_{\rm ch}$. While $T_{\rm ch}$ reaches a plateau value from about $\sqrt{s_{NN}} = 10$ GeV onwards, $T_{\rm kin}$ rather decreases with increasing $\sqrt{s_{NN}}$. This finding is corroborated by resent results from ALICE which indicate an even lower $T_{\rm kin}$ than observed at top RHIC energies [12]. The natural explanation is an extended hadronic phase between chemical and kinetic freeze-out whose lifetime is increasing as the center-of-mass energy and thus the initial energy density of the system is increasing. This finding agrees with the observation that the freeze-out volume extracted from HBT radii is larger by a factor of two at LHC compared to RHIC [13]. From the LHC data freeze-out times of $\tau_{\rm f} = 10$–11 fm$/c$ have been extracted, which are 40% larger than what is seen at RHIC.

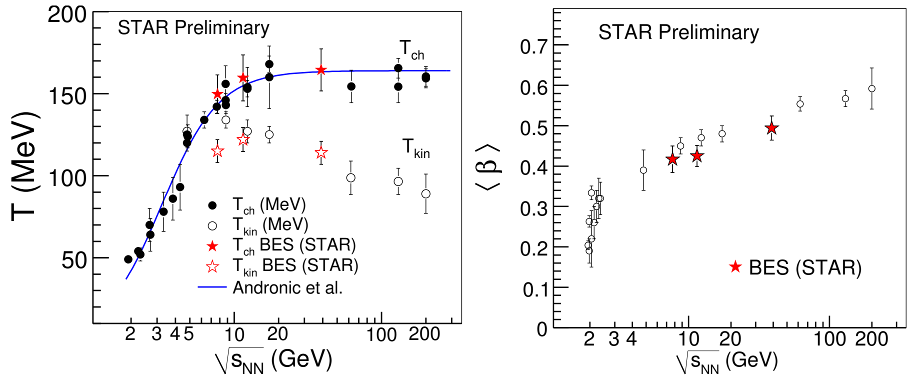


Fig. 1. Left: The chemical $T_{\rm ch}$ (filled symbols) and kinetic $T_{\rm kin}$ (open symbols) freeze-out temperatures as a function of $\sqrt{s_{NN}}$ [7]. The solid line shows a parametrization of $T_{\rm ch}$ [8]. Right: The mean transverse expansion velocity $\langle\beta\rangle$ as a function of $\sqrt{s_{NN}}$ [7].

To address the question whether freeze-out happens due to a dynamic decoupling from interactions in a hadronic stage, the study of the system size dependence of freeze-out parameters plays a decisive role. Due to the interplay between the mean free path of the hadronic scatterings and the changing size of the system, one expects a clear change of freeze-out temperatures if the system size varies [14]. In fact, this is being observed for the kinetic freeze-out temperature (see Fig. 2 (b)).

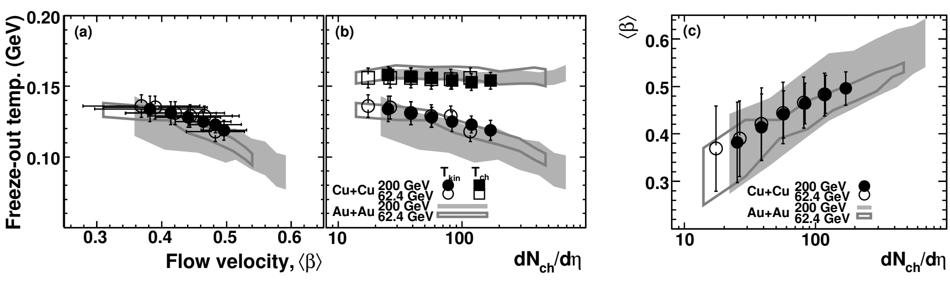


Fig. 2. The centrality dependence of chemical and kinetic freeze-out parameters for Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV [15]. Shown is $T_{\rm kin}$ *versus* $\langle\beta\rangle$ (a), as well as $T_{\rm kin}$ and $T_{\rm ch}$ (b), and $\langle\beta\rangle$ (c) all three as a function of $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta$.

Figure 3 shows a comparison of the kinetic freeze-out conditions of light hadrons (π, K, p, Λ) and the rare Ξ^- and Ω^- as measured at RHIC. As the left panel illustrates, there are clear indications from the blast wave fits that Ξ^- freeze-out at a higher temperature $T_{\rm kin}$. Similarly, the average transverse momenta $\langle p_t \rangle$ of Ξ^- and Ω^- do not follow the roughly linear increase with particle mass as observed for lighter hadrons. The same has been concluded from data taken at the SPS (for a recent review see [17]). This would support the picture that rare particles with low hadronic cross section do decouple earlier from an interacting hadronic phase and are thus less affected by its transverse expansion [18].

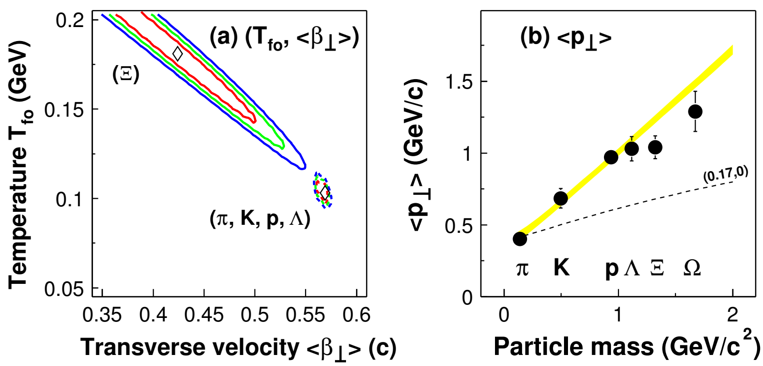


Fig. 3. Left: The kinetic freeze-out temperature $T_{\rm kin}$ and average transverse expansion velocity $\langle \beta \rangle$ extracted from blast wave fits to light hadrons (π, K, p, Λ) and the Ξ^- for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [16]. Right: The average transverse momentum $\langle p_t \rangle$ for different hadrons measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [16].

On the other side, single freeze-out models ($T_{\rm ch} = T_{\rm kin}$) provide a very good description of not only the light hadron p_t spectra measured at RHIC [19], but also of the multi-strange hyperons (Ξ^- and Ω^-) [20]. In contrast to the previous conclusions, this would indicate that there is no need for an extended hadronic phase between chemical and kinetic freeze-out to explain the differences between the different hadron species. In these models the origin of the difference is that the spectra of light particles are rather strongly affected by resonance decays, which is not the case for particles such as Ω^- or ϕ.

More informations on the lifetime of a phase between chemical and kinetic freeze-out can possibly be derived from the measurement of resonance yields. Since strange resonances such as the $K^*(892)$ and $\Lambda(1520)$ have a lifetime that is comparable to the lifetime of the fireball, they will decay to a certain fraction inside of it. As a consequence, the momenta of their decay products could be modified by elastic scattering processes and thus make the experimental reconstruction of the resonance itself via an invariant mass analysis impossible. One would, therefore, measure less resonances than expected from statistical model predictions. In fact, experimental observations are in accordance with this scenario. The ratio of resonance to non-resonance particles (*e.g.* $K^*(892)/K^-$) shows a decrease with increasing system size (see Fig. 4), as expected due to the increasing rescattering time before kinetic freeze-out. However, a quantitative analysis will require also more accurate data. Right now it seems that the effect is even stronger at SPS than at RHIC which would be in contradiction to the larger freeze-out times extracted at higher energies. Upcoming data from the LHC will shed more light on this issue.

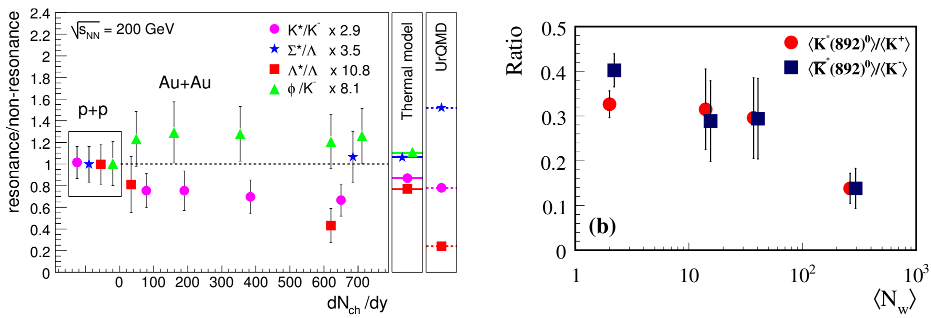
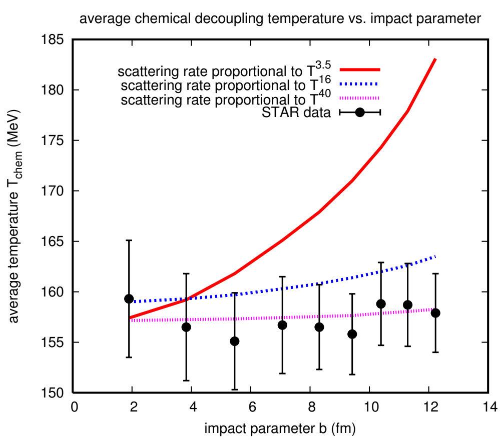


Fig. 4. Left: Resonance to stable particle ratios for $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [21]. The ratios are normalized to unity in $p+p$. Right: The total yield of $K^*(892)$ ($\bar{K}^*(892)$) divided by the total yields of K^+ (K^-) in $p+p$ and nucleus–nucleus collisions at 158 *A*GeV as a function of the average number of wounded nucleon $\langle N_{\mathrm{W}} \rangle$ [22].

3. Chemical freeze-out

The question whether there is any evidence for an extended hadronic phase after hadronization and before chemical freeze-out is much more difficult to answer. One indicator might, again, be the production of particles with low hadronic cross sections like multi-strange baryons. However, there is no observation yet that any of these particles shows a significant deviation from its statistical equilibrium value as expected in the case of an early hadronic decoupling [17]. However, the error bars on these data, especially at lower energies, are still relatively large so that for a more definite statement also improved data sets would be needed. On the other side, it has also been argued that multi-strange particles might not be too sensitive to a hadronic phase, if they already enter this phase with abundances close to equilibrium [4]. Antibaryons are expected to be much stronger affected due to absorption effects which would cause a reduction of the measured yields relative to the chemical equilibrium value. A caveat here is that antibaryon production can be enhanced in a hadron gas by multi-meson fusion processes [25], which usually are not included in hadronic transport models. A recent study of statistical model fits to data sets including and excluding antibaryons, indicates that there might be a significant effect [26]. Also, antiprotons exhibit a decrease of their measured yields with increasing system size [15, 27], as expected if they were subject to increasing absorption in hadronic matter. However, this needs to be disentangled from the system size evolution of the effects of baryon number transfer to mid-rapidity that could result in a similar observation. A striking observation that was made recently, when results on particle yields for Pb+Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV were compared to statistical model predictions, was that the measured proton and antiproton yields are significantly lower than the expectations [12]. However, whether this might be an indication for hadronic rescattering in long lived hadron gas phase will still need further investigations.

One remarkable observation made at RHIC is that the system size dependence of $T_{\rm ch}$ and $T_{\rm kin}$ are clearly different (see Fig. 2 (b)). While $T_{\rm kin}$ shows a significant dependence on system size, $T_{\rm ch}$ does not. As pointed out in [14], this is very difficult to be reconciled with a freeze-out from a normal hadron gas. To describe this behavior scattering rates that depend on temperature as T^n with $n > 20$ are required (see left panel of Fig. 5). It has been pointed out in [28] that exponents of the order of 60 can be



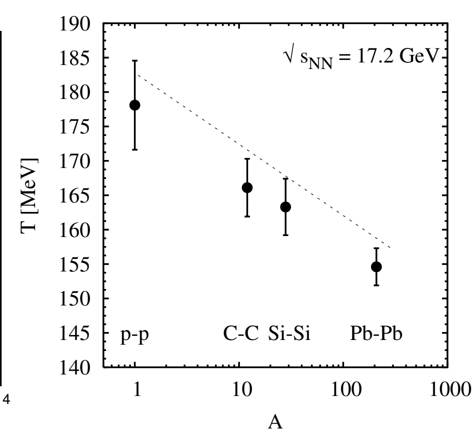


Fig. 5. Left: The impact parameter dependence of the average chemical decoupling temperature $T_{\rm ch}$ computed from hydrodynamics with different temperature dependences of the scattering rates [14], compared with STAR data for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [23]. Right: The fitted temperature at chemical freeze-out $T_{\rm ch}$ as a function of the mass number A in central heavy ion collisions at $\sqrt{s_{NN}} =$ 17.3 GeV (from left to right: p+p, C+C, Si+Si, and Pb+Pb). The dashed line shows a parametrization [24].

realized if chemical freeze-out happens directly at the phase boundary. At high energies and small μ_B the vicinity of deconfinement phase transition would thus provide an explanation for the observed feature. Since at lower energies and consequently higher μ_B the systems freeze-out far away from this phase boundary, it is important to do a systematic investigation of the system size dependence of chemical freeze-out parameters also here. One example is shown in the right panel of Fig. 5. Here a clear A dependence of $T_{\rm ch}$ is found [24], which is in stark contrast to the observations at RHIC and could be interpreted as an effect of hadronic re-interaction. However, one has to take into account that simple geometric effects, as expected in the core-corona scenario [29, 30, 31], can play a dominant role [32]. At SPS energies $T_{\rm ch}$ is found to be quite different between $p+p$ and $A+A$, which is not the case at the top RHIC energy [24]. Therefore, a core-corona superposition will lead in the first case to a system size dependence of $T_{\rm ch}$, in the second case not. Recently, new data from the beam energy scan program of STAR were shown [33]. Also here a system size dependence of $T_{\rm ch}$ was reported for heavy ion collisions at lower energies ($\sqrt{s_{NN}}$ = 7.7, 11.5, and 39.0 GeV). However, in contrast to what is shown in Fig. 5 and what one would expect if smaller systems freeze-out earlier and thus at higher temperatures, a decrease of $T_{\rm ch}$ towards small systems is observed.

4. Conclusions

The answer to the initial question "Is there life after hadronization?" turns out to be not straightforward. Seen from a phenomenological standpoint all observations ($T_{\rm kin}$ from blast-wave fits, $T_{\rm kin}$ depends in system size, low cross section particles seem to freeze-out earlier, resonances get suppressed) are in accordance with the existence of a long lived hadronic phase between chemical and kinetic freeze-out. However, there is also the remarkable success of single freeze-out models which invalids many of the usual arguments. For the existence of a hadronic phase before chemical freeze-out no clear evidence can be derived from the current experimental data. However, there are several not fully understood features (antiprotons at LHC, system size dependence of $T_{\rm ch}$ at low energies) which might provide some clue for future investigations.

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