Are we close to the QGP? – Hadrochemical vs. microscopic analysis of particle production in ultrarelativistic heavy ion collisions. *

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Abstract

Ratios of hadronic abundances are analyzed for pp and nucleus-nucleus collisions at $\sqrt{s} \approx 20$ GeV using the microscopic transport model UrQMD. Secondary interactions significantly change the primordial hadronic cocktail of the system. A comparison to data shows a strong dependence on rapidity. Without assuming thermal and chemical equilibrium, predicted hadron yields and ratios agree with many of the data (π/p, d/p, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\bar{\Lambda}$ etc.). Large discrepancies to the data (> 50 %) are found for the K^0_S/Λ and Ω/Ξ ratios.

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Hadron abundances and ratios have been suggested as possible signatures for exotic states and phase transitions in dense nuclear matter. In addition they have been applied to study the degree of chemical equilibration in a relativistic heavy-ion reaction. Bulk properties like temperatures, entropies and chemical potentials of highly excited hadronic matter have been extracted assuming thermal and chemical equilibrium [1–7].

The present work confronts the conclusions of a series of publications which have attempted to fit the available AGS [8] and SPS [9] data on hadron yields and ratios. The latter have been done either in the framework of a hadronizing QGP droplet [7,11] or of a hadron gas in thermal and chemical equilibrium [6]. (including elementary proton-proton interactions [10]). It has been shown that the thermodynamic parameters T and μ_B imply that these systems have been either very close to or even above the critical T, μ_B line for QGP formation [6,7].

Here, in contrast, the non-equilibrium microscopic Ultra-relativistic Quantum Molecular Dynamics transport model (UrQMD) [12] is used to calculate hadron ratios without thermalization assumptions. We tackle the following questions:

1. Is this microscopic model able to predict elementary hadron production (including yields and ratios)?

2. How do hadron ratios in elementary nucleon-nucleon interactions compare to those stemming from the final state of a nucleus-nucleus reaction?

3. Do isospin and secondary interactions (rescattering) play a major role or is the hadronic makeup of the system fixed after the first primordial highly energetic nucleon-nucleon collisions?

4. To what extent do the hadron ratios depend on rapidity and transverse momentum? How strong is their sensitivity to experimental acceptance cuts?

The UrQMD model [12] is based on analogous principles as (Relativistic) Quantum Molecular Dynamics [13–17]. Hadrons are represented by Gaussians in phase space. The nucleons are initialized in spheres of radius $R = 1.12 A^{1/3}$ fm. Momenta are chosen according to a non-interacting Fermi-gas ansatz. Each nucleon occupies a volume of h^3, thus phase space is uniformly filled (in a statistical sense). Hadrons are then propagated according to Hamilton's equation of motion. The microscopic evolution of the hadrochemistry in heavy-ion reactions requires the solution of a set of hundreds of coupled (Boltzmann-type) integro-differential equations. This means that all (known) hadrons need to be included into the model as realistically as possible. The collision term of the UrQMD model treats 55 different isospin (T) degenerate baryon (B) species (including nucleon-, delta- and hyperon- resonances with masses up to 2 GeV) and 32 different T-degenerate meson (M) species, including (strange) meson resonances as well as the corresponding anti-particles, i.e. full baryon/antibaryon symmetry is included. Isospin is explicitely treated (although the SU(2) multipletts are assumed to be degenerate in mass). For excitations with masses > 2 GeV (B) and 1.5 GeV (M) a string model is used. All (anti-)particle states can be produced – in accord with the conservation laws – both, in the string decays as well as in s-channel collisions or in resonance decays.

Tabulated or parameterized experimental cross sections are used when available. Resonance absorption and scattering is handled via the principle of detailed balance. If no experimental information is available, the cross section is either calculated via an OBE model or via a modified additive quark model, which takes basic phase space properties into account. The baryon-antibaryon annihilation cross section is parameterized as the proton-antiproton annihilation cross section and then rescaled to equivalent relative momenta in the incoming channel. Changes in the order of 50% are observed if the same $\sqrt{s}$ dependence is chosen for all baryon-antibaryon reactions. For a detailed overview of the elementary cross sections and string excitation scheme included in the UrQMD model, see ref. [12].

The UrQMD model allows for systematic studies of heavy-ion collisions over a wide range of energies in a unique way: the basic concepts and the physics input used in the calculation are the same for all energies. A relativistic cascade is applicable over the entire range of energies from 100 MeV/nucleon up to 200 GeV/nucleon (a molecular dynamics scheme using a hard Skyrme interaction is used between 100 MeV/nucleon and 4 GeV/nucleon). All calculations presented here have been performed with UrQMD version 1.0 [12].

Coming to the first question: Is a microscopic model able to predict elementary hadron production (including yields and ratios)? Let us start with a comparison of a compilation of experimental measurements [10] of hadron production in elementary proton-proton collisions with yields as predicted by the UrQMD model in figure 1a). Note the overall good agreement (compatible to thermal model fits [10] yielding a temperature of 170 MeV) which spans three orders of magnitude. ϕ-production is underestimated by a factor of 2. $\Lambda + \Sigma^0$ (as well as the $\bar{\Lambda} + \bar{\Sigma}^0$) production is overestimated. Problems in the strangeness sector are common to most string models and indicate that strangeness production is not yet fully understood on the elementary level [18]. These deviations in the elementary channel have to be considered when comparing with heavy-ion experiments.

Unlike fireball models, UrQMD describes also the momentum distributions (e.g. the $\mathrm{d}N/\mathrm{d}y$, $\mathrm{d}N/\mathrm{d}x_F$ and $\mathrm{d}N/\mathrm{d}p_t$ distributions) for all hadron species under consideration. A detailed description and a comparison to available hadron-hadron data can be found in refs. [12].

Second: How do hadron ratios in elementary nucleon-nucleon interactions compare to those stemming from the final state of a nucleus-nucleus reaction? Do isospin and secondary interactions play a major role or is the hadronic makeup of the system fixed after the first primordial highly energetic nucleon-nucleon collisions? Since even the particle abundances in elementary proton-proton reactions may be described in a thermal model [10] one could speculate that the hadronic final state of a nucleus-nucleus collision should not differ considerably from the primordial "thermal" composition. The upper frame of figure 2 shows hadron ratios calculated by the UrQMD model for the S+Au system at CERN/SPS energies around midrapidity $y_{lab} = 3 \pm 0.5$ (full circles). The ratios are compared to those stemming from a proton-proton calculation (open squares) and from a nucleon-nucleon calculation, i.e. with the correct isospin weighting (open triangles) for the primordial S+Au system, which is obtained by weighting a cocktail of pp, pn and nn events in the following way: $NN(S + Au) = 0.188 \cdot pp + 0.55 \cdot pn + 0.27 \cdot nn$.

The correct isospin treatment is of utmost importance, as it has a large influence on the primordial hadron ratios: Due to isospin conservation the $\bar{p}/p$ and $\Lambda/(p - \bar{p})$ ratios are enhanced by $\sim 30\%$ and $\sim 40\%$, respectively; it is easier to produce neutral or negatively charged particles in a nn or pn collision than in a pp interaction.

Rescattering effects, which are visible when comparing the nucleon-nucleon calculation (open triangles) with the full S+Au calculation (full circles), have even a larger influence on the hadron ratios than isospin: Changes in the ratios due to rescattering are easily on the order of 20%-50%. Ratios involving antibaryons even change by factors of $3 - 5$, due to their high hadronic annihilation cross section. Most prominent examples are the ratios of $\bar{\Xi}/\Xi$ (factor 5 suppression), $\bar{p}/p$ (factor 3 suppression), $\bar{\Lambda}/\Lambda$ (factor 2 suppression), Ξ^-/Λ (factor 2 enhancement) and $K^0_S/\bar{\Lambda}$ (factor 3 enhancement).

The lower frame of figure 2 compares the UrQMD hadron ratios with experimental measurements [9]. We use a data compilation which has been published in ref. [6]. The open circles represent the measurements whereas the full circles show the respective UrQMD calculation for S+Au at 200 GeV/nucleon and impact parameters between 0 and 1.5 fm. For each ratio, the respective acceptance cuts, as listed in [6], have been applied. The size of the statistical errorbars of the UrQMD model does not exceed the size of the plot-symbols. The crosses denote a fit with a dynamical hadronization scheme, where thermodynamic equilibrium between a quark blob and the hadron layer is imposed [7]. A good overall agreement between the data and the UrQMD model is observed, of similar quality as that of the hadronization model. Large differences between UrQMD and experiment, however, are visible in the $\phi/(\rho + \omega)$, K^0_S/Λ and Ω/Ξ ratios. Those discrepancies can be traced back to the elementary UrQMD input. A comparison with figure 1a) shows e.g. the underestimation of the elementary ϕ-yield in proton-proton reactions by a factor of 2.

A thermal and chemical equilibrium model can be even used to fit the hadron ratios of the UrQMD calculation displayed in the upper frame of figure 2. The parameters of the thermal model fit to the microscopic calculation in the $y_{lab} = 3 \pm 0.5$ region (a detailed discussion of the rapidity dependence of the ratios is given below) yields a temperature of $T = 145$ MeV and a baryo-chemical potential of $\mu_B = 165$ MeV. However, the assumption of global thermal and chemical equilibrium is not justified: Both, the discovery of directed collective flow of baryons and antiflow of mesons in Pb+Pb reactions at 160 GeV/nucleon energies [19] as well as transport model analyses, which show distinctly different freeze-out times and radii for different hadron species [20,21], indicate that the yields and ratios result from a complex non-equilibrium time evolution of the hadronic system. A thermal model fit to a nonequilibrium transport model (and to the data!) may therefore not seem meaningful.

Let's turn to the next question: To what extent do the hadron ratios depend on rapidity and transverse momentum? How strong is their sensitivity to experimental acceptance cuts? The rapidity dependence of individual hadron ratios R_i is shown in Figure 3: The p/π^+, η/π^0, K^+/K^-, $\bar{p}/p$, Λ/p and K^0_S/Λ ratios are plotted as a function of y_{lab}. A strong dependence of the ratios R_i on the rapidity is visible – some ratios, especially those involving (anti-)baryons, change by orders of magnitude when going from target rapidity to mid-rapidity. The y-dependence is enhanced by the heavy target which leads to strong absorption of mesons and antibaryons. The observed shapes of $R_i(y)$ are distinctly different from a fireball ansatz, incorporating additional longitudinal flow: There, the ratios would also be symmetric with respect to the rapidity of the central source. A broad plateau would only be visible for ratios of particles with similar masses. When fitting a thermal model to data, one must take this rapidity dependence into account and correct for different experimental acceptances.

The large difference in the $K_0/\bar{\Lambda}$ ratio (as calculated by UrQMD) visible between figure 2a) and figure 2b) exemplifies the strong dependence of the hadron ratios on the experimental acceptances: While the experimental acceptance in rapidity is similar to the cut employed in figure 2a), the additional cut in p_t, which has been performed in figure 2b), changes the ratio by one order of magnitude.

Figure 4, finally, shows the UrQMD prediction for the heavy system Pb+Pb. The ratios around midrapidity (full circles) are again compared to those stemming from isospin-weighted nucleon-nucleon calculation (open triangles). For this heavy system, rescattering effects are even larger than in the S+Au case: Due to the large number of baryons around midrapidity, antibaryon annihilation at midrapidity occurs more often and therefore ratios involving antibaryons may be suppressed stronger than in the S+Au case. Most prominent examples are (again) the $\bar{\Xi}/\Xi$ (factor 20 suppression), $\bar{p}/p$ (factor 8 suppression) and the $K^0_S/\bar{\Lambda}$ (factor 3 enhancement) ratios.

In terms of absolute yields, the enhancement of particle production due to secondary interactions can be seen in figure 1b). Here, a comparsion between hadron yields in elementary p+p interactions at $\sqrt{s} = 27$ GeV and a respective Pb+Pb calculation with the yields scaled down by the relative number of participating nucleon pairs, A_{Pb}, is plotted. The yields *per participating nucleon-pair* are enhanced by factors of 2-10, especially those of resonances, such as the Δ_{1232}, the ρ or the Σ^*. Anti-resonance or -hyperon production is enhanced as well, their large absorption cross sections, however, "counter" this enhancement (see the antiproton suppression by a factor of 3). Thus, their yields are similar to those found in proton-proton reactions.

Open questions, to be addressed in a forthcoming, more detailed publication, include the dependence of R_i on the azimuthal angle and the impact parameter. Both should play a major role for baryon to antibaryon ratios, since those ratios are extremely sensitive to the phase-space distribution of baryonic matter [22].

Details in the treatment of the baryon-antibaryon annihilation cross section may have a large influence on the final yield of antiprotons and antihyperons: If the proton-antiproton annihilation cross section as a function of $\sqrt{s}$ is used for all baryon-antibaryon annihilations, instead of rescaling the cross section to equivalent relative momenta, the $\bar{\Xi}$ yield in central Pb+Pb reactions at 200 GeV/nucleon would be enhanced by a factor of 3. The $\bar{p}$ and $\bar{Y}$ yields would then be enhanced by 50% and 25%, respectively.

A systematic study of different baryon to antibaryon ratios as functions of system size, impact parameter, transverse momentum and azimuthal angle may help to gain further insight into the antihyperon-nucleon and antihyperon-hyperon annihilation cross section.

In summary, ratios of hadronic abundances for $\sqrt{s} \sim 20$ GeV have been analyzed within a microscopic transport model. A comparison to data shows good agreement. Discrepancies can be found in the $\phi/(\rho + \omega)$, K_S^0/Λ and Ω/Ξ ratios. The resulting ratios have been compared to the primordial abundances from a cocktail of elementary pp, pn and nn interactions and then analyzed with respect to their dependence on secondary interactions and on rapidity. Their strong dependence on rapidity casts doubt on the assumption of thermal and chemical equilibrium, which has been prevalent in previous analyses. Finally, hadron ratios for the symmetric heavy system Pb+Pb far from the elementary primordial nucleon-nucleon values are predicted.

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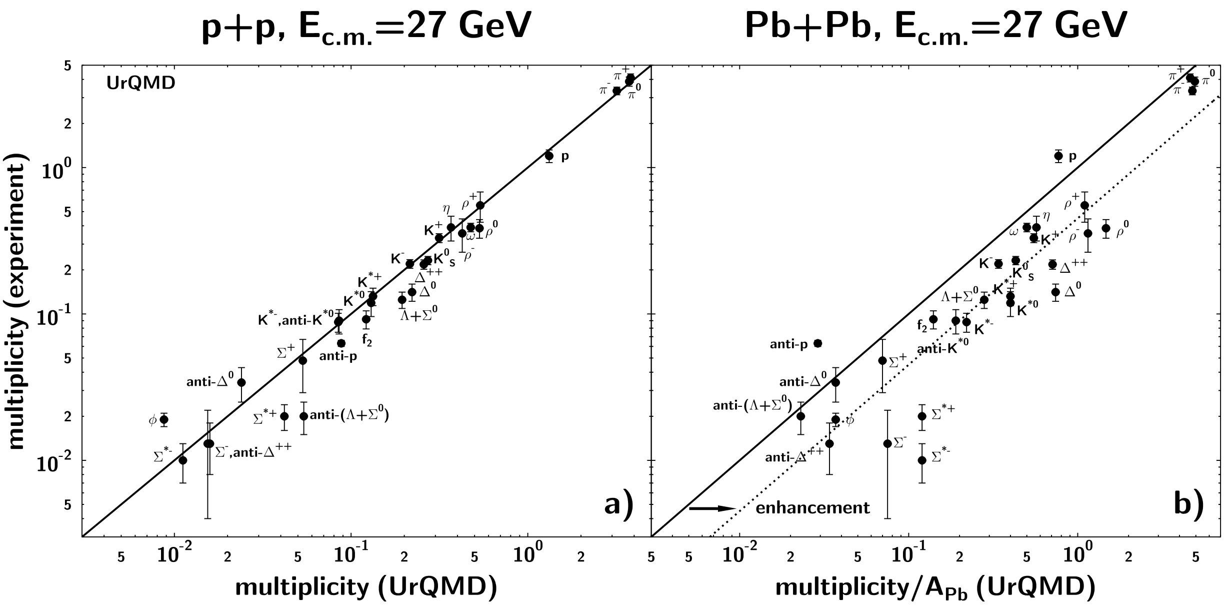

FIG. 1. Left: UrQMD hadron yields in elementary proton-proton reactions at $\sqrt{s} = 27$ GeV compared to data. The overall agreement spanning three orders of magnitude is good – the most prominent deviations from the experiment occur for the ϕ-meson and for (anti-)$\Lambda + \Sigma^0$. Right: UrQMD hadron yields in central Pb+Pb reactions *per participating nucleon pair* at the same energy versus proton-proton data. The large shift to the r.h.s. from the full diagonal line to the dotted diagonal line marks the enhancement of secondary particle production in AA reactions.

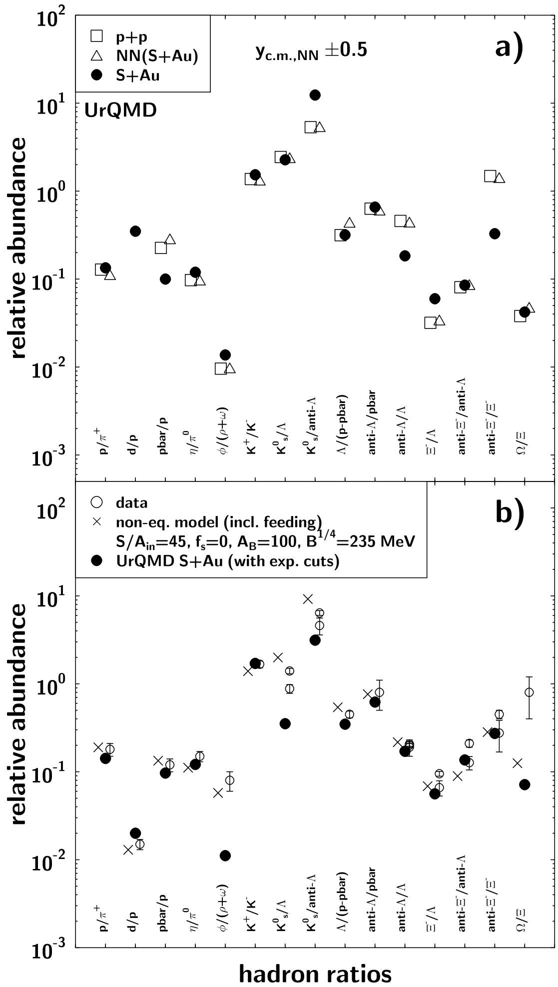

FIG. 2. Top: UrQMD calculation of hadron ratios in S+Au collisions at midrapidity (full circles). The ratios are compared to a proton-proton calculation (open squares) and a nucleon-nucleon calculation (correct isospin weighting) (open triangles). Bottom: Comparison between the UrQMD model (full circles) and data (open circles) for the system S+Au(W,Pb) at 200 GeV/nucleon. Also shown is a fit by a microscopic hadronization model (crosses). Both non-equilibrium models agree well with the data. Discrepancies are visible for the $\phi/(\rho+\omega)$, K_S^0/Λ and Ω/Ξ ratios.

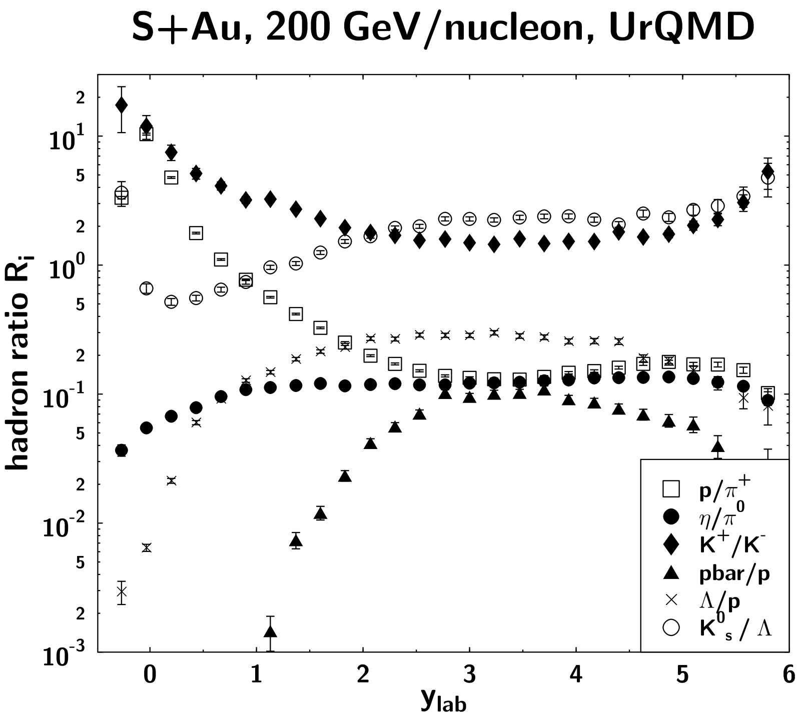

FIG. 3. Rapidity dependence of hadron ratios in the UrQMD model for the system S+Au(W,Pb) at CERN/SPS energies. The ratios vary by orders of magnitude, yielding different T and μ_B values for different rapidity intervals.

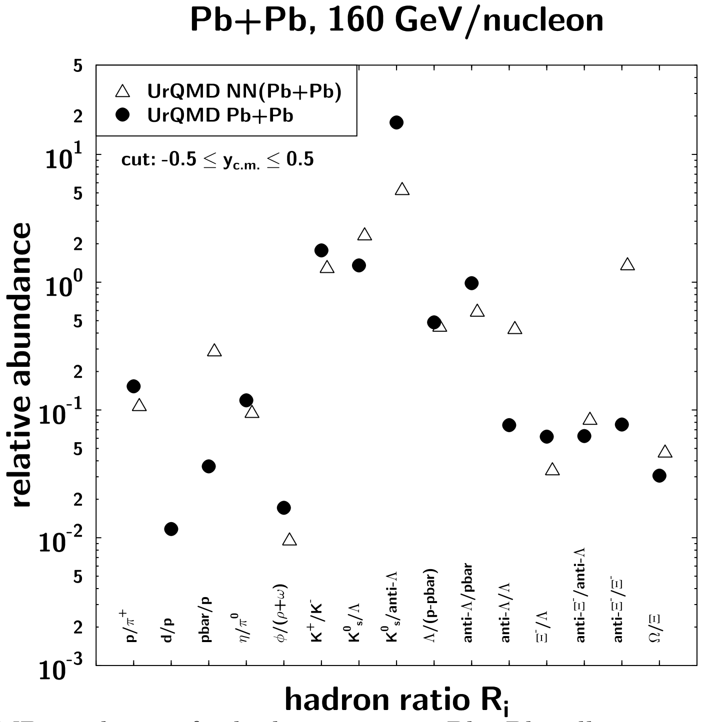

FIG. 4. UrQMD prediction for hadron ratios in Pb+Pb collisions at midrapidity (full circles). The ratios are compared to a superposition of pp, pn and nn reactions with the isospin weight of the Pb+Pb system (open triangles), i.e. a first collision approach. Especially in the sector of anti-baryons the ratios change by at least one order of magnitude due to the large anti-baryon annihilation cross section.