Transition to resonance-rich matter in heavy ion collisions at RHIC energies

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Abstract. The equilibration of hot and dense nuclear matter produced in the central region in central Au+Au collisions at $\sqrt{s} = 200A$ GeV is studied within the microscopic transport model UrQMD. The pressure here becomes isotropic at $t \approx 5$ fm/c. Within the next 15 fm/c the expansion of the matter proceeds almost isentropically with the entropy per baryon ratio $S/A \approx 150$. During this period the equation of state in the (P, ε)-plane has a very simple form, $P = 0.15\,\varepsilon$. Comparison with the statistical model (SM) of an ideal hadron gas reveals that the time of ≈ 20 fm/c may be too short to attain the fully equilibrated state. Particularly, the fractions of resonances are overpopulated in contrast to the SM values. The creation of such a long-lived resonance-rich state slows down the relaxation to chemical equilibrium and can be detected experimentally.

1. Introduction

The assumption that strongly interacting matter, produced in nucleus-nucleus collisions at high energy, can reach the state of local equilibrium (LE) [1, 2] is one of the most important topics in the relativistic heavy ion programme [3]. The degree of equilibration can be checked by fitting the measured particle yields and transverse momentum spectra to that of the thermal model in order to extract the conditions of the fireball at the chemical and thermal freeze-out [4–8]. Here the equilibrium particle abundances, which correspond to a certain temperature T, baryon chemical potential μ_B, and strangeness chemical potential μ_S, can be determined. However, the analysis is complicated, e.g., by the presence of collective flow and the non-homogeneity of the baryon charge distribution in the reaction volume. The volume of the fireball is also taken as a free parameter in the thermal model. Various non-equilibrium microscopic transport models have been applied to verify the appearance of at least local equilibrium in the course of heavy ion collisions at relativistic and ultra-relativistic energies [9–14]. To reduce the number of unknown parameters and simplify the analysis it has been suggested [15–17] to examine the equilibrium conditions in the central cell of relativistic heavy ion collisions. For this purpose the microscopic transport model UrQMD [18] is employed. Previous studies at energies

from $10.7A$ GeV (AGS) to $160A$ GeV (SPS) [15, 16] have shown that the cubic cell with volume $V = 125$ fm^3 is well suited for the analysis. The aim of the present paper is to study the relaxation of hot nuclear matter, simulated within the microscopic model, in the central cell in Au+Au interactions at $\sqrt{s} = 200A$ GeV.

2. Relaxation to thermal and chemical equilibrium

First, the kinetic equilibrium has to be verified. The collective flow in the cell should be isotropic and small, so it cannot significantly distort the momentum distributions of particles. Microscopic simulations show that the longitudinal flow rapidly drops and converges to the developing transverse flow [16, 17]. Isotropy of the velocity distributions results in the pressure isotropy. Pressure in longitudinal direction in the cell, calculated according to the virial theorem, is compared in figure 1(a) with the transverse pressure. The time of convergence of longitudinal pressure to the transverse one decreases from 10 fm/c to 5 fm/c with rising incident energy from AGS to RHIC, respectively. Thus, the kinetic equilibrium in the central cell in Au+Au collisions at RHIC energy is reached at $t \approx 5$ fm/c.
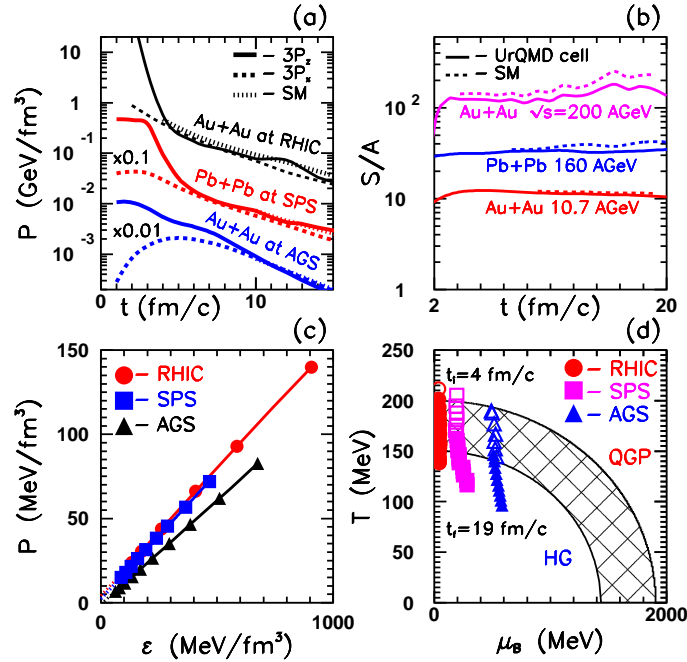
Figure 1. (a) The longitudinal (solid lines) and the transverse (dashed lines) diagonal components of the pressure tensor P in the central cell of heavy ion collisions at AGS, SPS, and RHIC energies compared to the SM results (dotted lines). (b) Time evolution of the entropy per baryon ratio, $s/\rho_{\rm B} = S/A$, in the central cell calculated with the UrQMD (solid lines) and the SM (dashed lines). (c) The evolution of pressure P and baryon density ε in the central cell. (d) The same as (c) but for the $(T, \mu_{\rm B})$-plane. Solid symbols correspond to the stage of kinetic equilibrium, open symbols indicate the pre-equilibrium stage. The hatched area shows the expected region of the quark-hadron phase transition.

To verify that the matter in the cell is in thermal and chemical equilibrium one has to compare the snapshot of hadron yields and energy spectra in the cell with the equilibrium spectra of hadrons obtained in the statistical model (SM) of an ideal

hadron gas. The description of the SM employed in our calculations can be found elsewhere [19]. The values of energy density ε, baryon density ρ_B, and strangeness density ρ_S, extracted from the microscopic calculations in the cell, are used as an input to the system of nonlinear equations of the SM [19] to determine the temperature T, baryon chemical potential μ_B, and strangeness chemical potential μ_S. This enables one to calculate the particle yields N_i^{SM}, total energy E_i^{SM}, pressure P^{SM}, and entropy density s. The thermal and chemical equilibrium is assumed to occur in the cell when the microscopic spectra of hadrons become close to the spectra predicted by the SM.

At the isotropic stage the total microscopic pressure is close to the grand canonical pressure, P^{SM}, as shown in figure 1(a). Therefore, the time $t = 5$ fm/c is chosen as a starting point for the comparison with the SM. The final time of the calculations, defined from the conventional freeze-out conditions $\varepsilon \approx 0.1$ GeV/fm^3 or $\rho_{tot} \approx 0.5\rho_0$ [16], corresponds to $t \approx 21$ fm/c. The hadron-string matter in the central cell expands nearly isentropically, see figure 1(b), with $s/\rho_B \equiv S/A \approx 12$ (AGS), 32 (SPS), and 150 (RHIC). The results of the simulations at AGS and SPS energies are intriguingly close to the entropy per baryon values extracted from the thermal model fits to experimental data, namely, $(S/A)^{AGS} \approx 14$ and $(S/A)^{SPS} \approx 36$ [7]. It is most interesting to compare the predicted value $(s/\rho_B)^{RHIC} = 150 - 170$ to the upcoming RHIC data.

The evolution of the pressure with the energy density is depicted in figure 1(c). The pressure drops linearly with the decreasing energy density for all three energies in question. Thus, the equation of state in the (P, ε)-plane has a very simple form: $P = 0.12\,\varepsilon$ at AGS, and $P = 0.15\,\varepsilon$ at SPS and RHIC, i.e. the ratio P/ε in the central cell is saturated already at SPS energies.

Figure 1(d) presents the evolution of the EOS in the (T, μ_B)-plane. In accordance with general estimates [7, 20] the baryon chemical potential at RHIC energies is small while the temperatures are well above the anticipated temperature of the QCD phase transition, $T \approx 150$ MeV. Note that the evolution of temperature as a function of ε/ρ_B and μ_B is mainly determined by the change of energy per baryon, which drops to $\approx 80 - 90\%$ of its initial value, but not by changing of the baryon chemical potential.

The slopes of energy spectra of particles in the cell are steeper compared to the predictions of the statistical model [17]. This means that the apparent temperatures of hadrons, especially pions, are lower than the temperature given by the SM. Since the energy density ε is the same in both models, one might expect that the fractions of mesons and resonances in the UrQMD cell are overpopulated. These extra-particles consume significant part of the total energy and effectively "cool" the hadron cocktail.

Figure 2 depicts the yields of the main hadron species in the cell within the time interval $5\,\mathrm{fm}/c \leq t \leq 19\,\mathrm{fm}/c$. It is interesting that microscopic spectra of pions, which are underestimated by the SM in the central cell at lower energies [16], converge to the SM predictions at $t \approx 15$ fm/c. Also, the statistical model overestimates yields of nucleons, lambdas, and kaons, while the yields of both baryon and meson resonances are reproduced quite well. Since the baryon number and the strangeness are conserved in strong interactions, where is the rest of the hypercharge, $Y = B + S$, in the UrQMD calculations in the cell? As a matter of fact, the total yields of baryons and antibaryons in the SM are larger than those of the UrQMD. For instance, at $t = 10$ fm/c the values of partial baryon and antibaryon density in the microscopic model are $R_B^{mic} = 0.05$ fm^{-3} and $R_{\bar{B}}^{mic} = 0.02$ fm^{-3}, respectively, while the SM predicts the values $R_B^{SM} = 0.08$ fm^{-3} and $R_{\bar{B}}^{SM} = 0.05$ fm^{-3}. The hadron-resonance-string matter in the cell is not in chemical equilibrium; that is why the density of antibaryons is 2-3 times smaller than the equilibrium values. Similarly, the SM predicts significantly larger abundances of
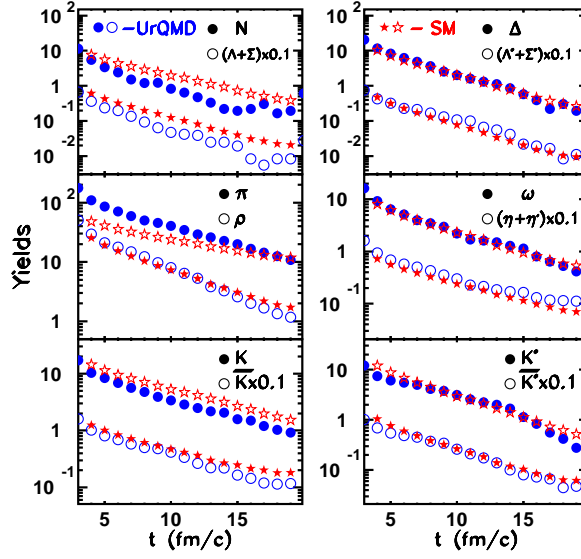
Figure 2. The yields of main hadron species in the central cell of Au+Au collisions at $\sqrt{s} = 200A$ GeV as a function of time as obtained in the model UrQMD (circles) together with the predictions of the SM (stars).

both strange baryons and strange antibaryons at $5 \leq t \leq 11$ fm/c in the cell, while the densities of strange mesons are nearly the same.

To check the relevance of the central cell results for a larger reaction volume at RHIC energies the rapidity distributions of baryon resonances are presented in figure 3 (other global observables have been studied in [21]). Here only those resonances that decay directly into groundstate hadrons (no final state interactions) are accounted for. These distributions are remarkably flat within the interval $|y| \leq 3.5$. More than 80% of the baryon non-strange resonances are Δ's (1232). The fraction of resonances reconstructible from the experimental data is quite large and, therefore, the formation of resonance-abundant state can be traced experimentally.
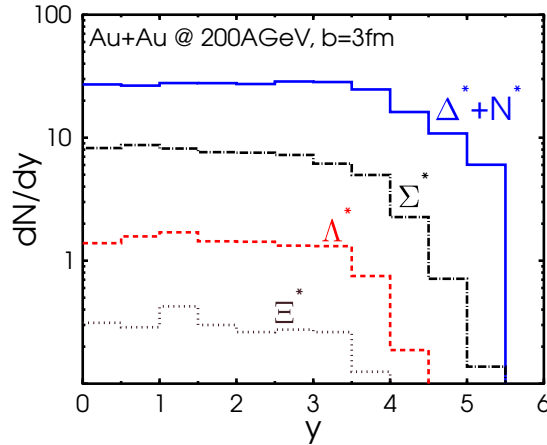
Figure 3. The rapidity distributions of baryon resonances in Au+Au ($\sqrt{s} = 200A$ GeV) interactions with the impact parameter $b = 3$ fm.

3. Conclusions

In summary, the following conclusions can be drawn. The expansion of matter in central Au+Au collisions at $\sqrt{s} = 200A$ GeV proceeds with constant entropy per baryon ratio in the central cell, $S/A = s/\rho_{\rm B} \cong 150$. Since the S/A ratios for the central cell in A+A collisions, calculated at AGS and SPS energies, are very close to the ratios extracted from the analysis of the experimental data, the expected value of the entropy per baryon ratio at RHIC lies within the range $150 \leq s/\rho_{\rm B} \leq 170$. The microscopic pressure in the cell is close to the SM pressure. It shows a linear dependence on the energy density in the cell, $P = 0.15\,\varepsilon$. The obtained result is in accord with the EOS $P \cong 0.2\,\varepsilon$, derived for an ideal gas of hadrons and hadron resonances [22]. The temperature $T^{\rm SM}$ in the cell at RHIC energies is shown to be nearly independent on the baryon chemical potential $\mu_{\rm B} \approx 50$ MeV.

The comparison of the energy spectra and yields of hadrons with those of the SM shows that the times $t \approx 20\,{\rm fm}/c$ may be too short to reach full thermal and chemical equilibrium. Particularly, the deceleration of the relaxation to equilibrium is attributed to the creation of the long-lived resonance-abundant matter. The yields of resonances are in accord with the SM spectra from the very early times $t \approx 5$ fm/c, while the densities of strange and non-strange baryons and their antiparticles are lower than the equilibrium values. (However, the fitting temperature of the thermal model is higher than the temperatures of hadron species in the cell.) According to microscopic calculations, the resonance-rich matter survives until the thermal freeze-out. It remains a challenging task to verify the formation of long-lived resonance-abundant matter in heavy ion collisions at $\sqrt{s} = 200A$ GeV experimentally.

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