Title
Chemical freeze-out parameters at RHIC from microscopic model calculations

Journal
Nuclear Physics A, 698

Author
Weber, H.

Publication Date
2001-04-06

Chemical freeze-out parameters at RHIC from microscopic model calculations

L. V. Bravina[a], E. E. Zabrodin[a,b], S. A. Bass[c,d], A. Faessler[b], C. Fuchs[b], M. I. Gorenstein[e,f], W. Greiner[e], S. Soff[g], H. Stöcker[e], H. Weber[e]

[a] *Institute for Nuclear Physics, Moscow State University, 119899 Moscow, Russia*

[b] *Institute for Theoretical Physics, University of Tübingen, D-72076 Tübingen, Germany*

[c] *Department of Physics, Duke University, Durham NC 27708, USA*

[d] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*

[e] *Institute for Theoretical Physics, University of Frankfurt, D-60054 Frankfurt, Germany*

[f] *Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*

[g] *Nuclear Science Division, Lawrence Berkeley National Laboratory, CA 94720, USA*

The relaxation of hot nuclear matter to an equilibrated state in the central zone of heavy-ion collisions at energies from AGS to RHIC is studied within the microscopic UrQMD model. It is found that the system reaches the (quasi)equilibrium stage for the period of 10-15 fm/c. Within this time the matter in the cell expands nearly isentropically with the entropy to baryon ratio $S/A = 150 - 170$. Thermodynamic characteristics of the system at AGS and at SPS energies at the endpoints of this stage are very close to the parameters of chemical and thermal freeze-out extracted from the thermal fit to experimental data. Predictions are made for the full RHIC energy $\sqrt{s} = 200$ AGeV. The formation of a resonance-rich state at RHIC energies is discussed.

Thermalization and chemical equilibration of hot and dense nuclear matter produced in ultrarelativistic heavy-ion collisions is a topic of great importance for the interpretation of current SPS and RHIC results. In our investigation we study the relaxation process in central Au+Au collisions at $\sqrt{s} = 200$ AGeV within the microscopic transport UrQMD model [1]. Earlier studies at AGS and SPS energies revealed that the central reaction volume defined by a cubic cell of volume $V = 125$ fm^3 is well suited for this kind of study [2]. It contains enough particles to be treated as a statistical system, and its macroscopic characteristics become isotropic after some time. Figure 1 depicts the velocity distributions of hadrons in the cell in transverse (x and y) and in longitudinal (z) directions. At $t = 3$ fm/c the longitudinal velocity distribution differs considerably from the distributions in the transverse plane, while at $t = 5$ fm/c the magnitudes and widths of all three distributions become very close to each other. Isotropy of the velocity distributions results in the isotropy of pressure in the cell. Pressure in longitudinal and in transverse direction is shown in Fig. 2(a) for AGS, SPS, and RHIC energies. It is widely believed that the thermalization at RHIC sets in quite early. Indeed, at RHIC the pressure in the cell becomes isotropic at $t \approx 5$ fm/c compared with $t \approx 8$ fm/c (SPS) and $t \approx 10$ fm/c (AGS). Starting from $t = 5$ fm/c the results of the microscopic calculations are compared with the predictions of the statistical model (SM) of an ideal hadron gas [3]. The values of the energy density ε, baryon density ρ_B, and strangeness density ρ_S, determined microscopically, are used as an input to obtain particle yields, partial energy densities, pressure, and entropy density via the temperature T, baryochemical potential μ_B, and strangeness chemical potential μ_S. As seen in Fig. 2(a), the microscopic pressure is very close to the grand canonical pressure after the onset of the (quasi)equilibrium stage.

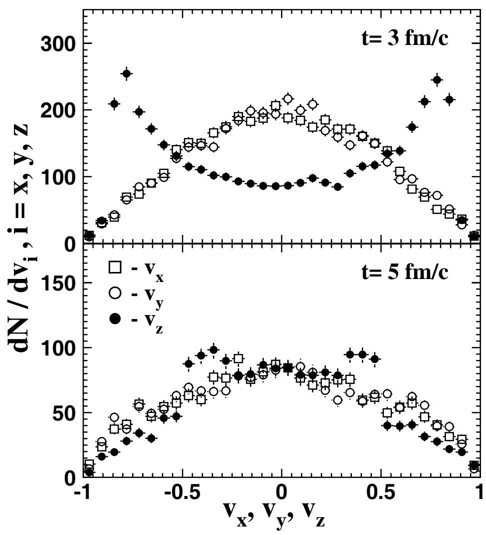

Figure 1. Hadron velocity distributions dN/dv_i, $i = x$ (□), y (◯), and z (•) at $t = 3$ fm/c and $t = 5$ fm/c in a central cell in Au+Au collisions at RHIC.

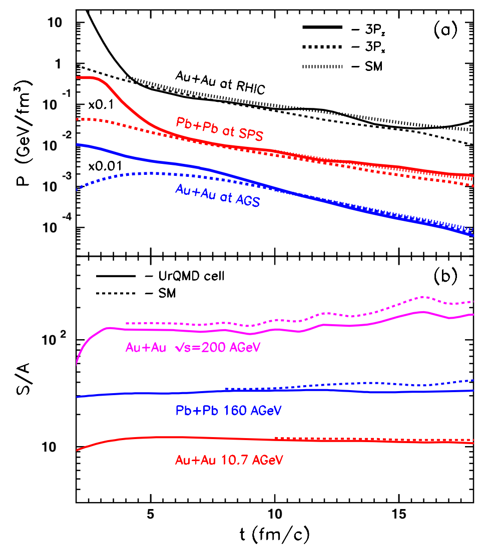

Figure 2. Time evolution of the components of the pressure tensor P (a) and of the entropy per baryon S/A (b) in the central cell of heavy ion collisions compared to the SM results.

The entropy density per baryon S/A, defined both microscopically and macroscopically (via the Gibbs thermodynamic identity $Ts = \varepsilon + P - \mu_B\rho_B - \mu_S\rho_S$) is presented in Fig. 2(b). The expansion in the cell proceeds nearly isentropically with $S/A = 12$ (AGS), 32 (SPS), and 150 (RHIC) (cf. $(S/A)^{\rm therm.fit} \cong 14$ (AGS) and $\cong 36$ (SPS) [4]). Therefore, it would be very interesting to compare the UrQMD estimate $(S/A)^{\rm RHIC} = 150 - 170$ with the value extracted from the thermal model fit to RHIC experimental data.

The equation of state (EOS) in the (P, ε)-plane is shown in Fig. 3. For all three energies it can be well approximated by a simple linear dependence $P/\varepsilon = 0.12$ (AGS), and 0.15 (SPS and RHIC). Note, that this version of the model does not imply the formation of the quark-gluon plasma, therefore, there are no kinks in this plot that can be attributed to quark-hadron phase transition. The evolution of the EOS in the (T, μ_B)-plane is depicted in Fig. 4 together with the chemical freeze-out and the thermal freeze-out parameters obtained from a thermal fit to experimental data at AGS and SPS energies. One can see that temperatures and chemical potentials in the cells at the beginning and at the end of the equilibrated stage are close to the thermodynamic parameters of chemical and thermal freeze-out, respectively. The UrQMD predicts that at chemical freeze-out $T^{\rm RHIC}_{\rm chem.FO} = 195 \pm 5$ MeV and $\mu^{\rm RHIC}_{\rm chem.FO} = 43 \pm 2$ MeV, while at thermal freeze-out $T^{\rm RHIC}_{\rm therm.FO} = 130 \pm 5$ MeV and $\mu^{\rm RHIC}_{\rm therm.FO} = 43 \pm 3$ MeV, i.e., the evolution of nuclear matter in the cell proceeds at constant baryon chemical potential. Calculations show very weak (within few MeV) difference between the results for Au+Au at $\sqrt{s} = 130$ AGeV and at $\sqrt{s} = 200$ AGeV. A thermal fit to particle ratios measured by the STAR

Collaboration (preliminary data) yields $T_{\rm chem.FO} = 190 \pm 20$ MeV and $\mu_q = 15 \pm 5$ MeV [6], i.e. $\mu_B = 45 \pm 15$ MeV, which is in remarkable agreement with the UrQMD calculations.

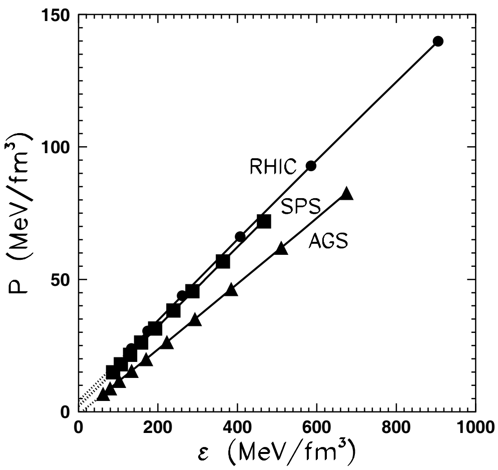

Figure 3. The evolution of pressure P and baryon density ε in the central cells of the heavy-ion collisions at AGS, SPS, and RHIC energies.

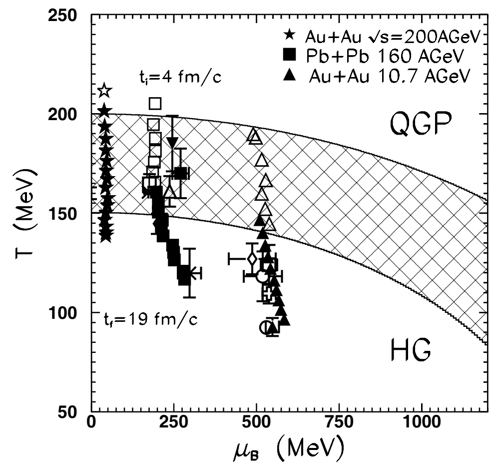

Figure 4. The same as Fig.3 but for the $(T, \mu_{\rm B})$-plane. Solid symbols correspond to the stage of kinetic equilibrium, open symbols indicate the pree-quilibrium stage. Symbols with error bars are chemical and thermal freeze-out parameters obtained from the SM fit [4]. The hatched area shows the expected region of the quark-hadron phase transition.

It is interesting to check the correspondence of the cell conditions at chemical freeze-out to the criterion $\langle E\rangle/\langle N_h\rangle \approx \langle M_h\rangle + 3/2T \approx 1$ GeV introduced in [4]. The mean energy per particle at the beginning of the equilibration in the cell at AGS, SPS, and RHIC energies is listed in Table 1. With rising bombarding energy from AGS to SPS there is a transition from baryon to meson dominated matter. It leads to the drop of $\langle M_h\rangle$ from nucleon mass to mass of ρ meson in accord with [4]. With further increase of the freeze-out temperature the yields of heavy meson resonances rise faster than that of light mesons, thus leading to the rise of $\langle M_h\rangle$ with $\sqrt{s}$.

Table 1
Energy per hadron $\langle E\rangle/\langle N_h\rangle$, energy density ε, and temperature T in the cell at the beginning of kinetic equilibrium.

	time fm/c	ε GeV/fm^3	$\langle E\rangle/\langle N_h\rangle$ GeV	T MeV
AGS	10	0.68	1.11	129
AGS	12	0.39	1.06	116
SPS	8	0.74	0.88	170
SPS	10	0.46	0.80	161
RHIC	5	2.33	1.08	201
RHIC	6	1.70	1.01	193

This means that not only the temperature, but also the mean mass of a particle is increased in the cell at RHIC energies, i.e., there should be more heavy resonances compared with the SPS cell. Therefore, the ratios of hadronic abundances are studied (see Fig. 5). Here the results are presented separately for non-strange and strange baryons and mesons. In the baryon sector the resonances dominate over the strange and non-strange baryons until the end of the simulations. This can be taken as an indication of the creation of long-lived resonance-rich matter. The fraction of baryon resonances is almost 70% of all baryons in the cell at RHIC at $5 \leq t \leq 19$ fm/c, while at SPS and AGS the number of baryon resonances decreases from 70% to 35%, and from 60% to 25%, respectively. The meson fractions of resonances shrink within the time interval $5 \leq t \leq 19$ fm/c from 60% to 30% (RHIC), 50% to 20% (SPS), and 40% to 15% (AGS). But at RHIC energies the hot hadronic matter in the cell as well as in the whole volume of the reaction is meson dominated. The mesons, baryons, and antibaryons carry 90%, 7%, and 3% of the total number of particles in the RHIC cell at $t \geq 10$ fm/c (cf. 85%, 14.5%, 0.5% at SPS and 50%, 50%, 0% at AGS). The microscopic ratios for mesons (Fig. 5, right panels) seem to be very close to the SM ratios. Since the freeze-out occurs at $t \approx 21$ fm/c in the central cell at RHIC energies, the matter in the cell is frozen before reaching complete chemical equilibrium. This circumstance complicates the extraction of the chemical and thermal freeze-out parameters by means of the standard thermal model fit.

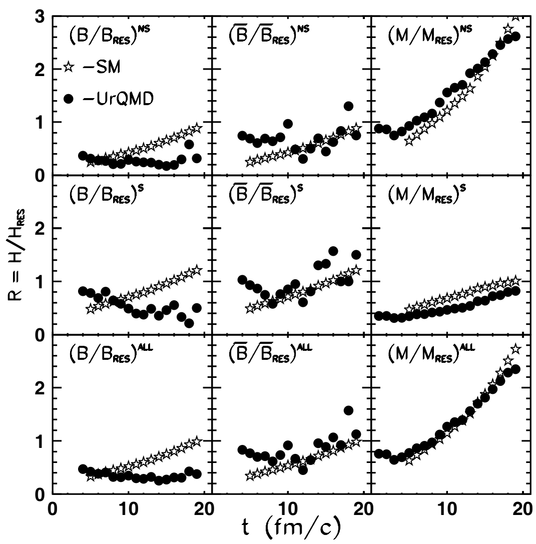

Figure 5. Time evolution of the hadron to resonance ratio $R = H/H_{res}$ in the central cell of Au+Au collisions at RHIC shown separately for baryons, antibaryons, and mesons as well as for non-strange hadrons, strange hadrons, and total hadron yields. Circles denote the UrQMD predictions, stars correspond to the SM results.

The rapidity distributions of baryon resonances in Au+Au collisions at $\sqrt{s} = 200$ AGeV are found to be nearly flat in the rapidity interval $|y| \leq 3.5$ [5]. More than 80% of the baryon non-strange resonances are still Δ's (1232). The density of directly reconstructible baryon resonances, that decay into final state hadrons, per unit rapidity at RHIC is quite high, and the resonance rich matter can be detected experimentally.

The results of our study can be summarised as follows. The formation of long lived resonance-abundant matter is found. UrQMD predicts that $T = 195 \pm 5$ MeV, $\mu_B = 43 \pm 2$ MeV, $150 \leq S/A \leq 170$, and $\langle E \rangle / \langle N_h \rangle \approx 1$ GeV at chemical freeze-out in central Au+Au collisions at RHIC. The equation of state has a linear dependence $P = 0.15\,\varepsilon$. The UrQMD cell calculations show that strangeness to entropy ratio monotonically increases with rising $\sqrt{s}$ as $R_S \cong 0.025$ (AGS), 0.04 (SPS), and 0.05 (RHIC).

REFERENCES

1. S.A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998) 255; M. Bleicher et al., J. Phys. G 25 (1999) 1859.
2. L.V. Bravina et al., Phys. Lett. B 434 (1998) 379; J. Phys. G 25 (1999) 351; Phys. Rev. C 60 (1999) 024904; Nucl. Phys. A 661 (1999) 600c; Phys. Rev. C 62 (2000) 064906.
3. M. Belkacem et al., Phys. Rev. C 58 (1998) 1727.
4. J. Cleymans and K. Redlich, Phys. Rev. C 60 (1999) 054908.
5. L.V. Bravina et al., J. Phys. G 27 (2001) 421; nucl-th/0010172 (Phys. Rev. C, in press).
6. N. Xu, STAR Collaboration, these proceedings.