Hadron and hadron-cluster production in a hydrodynamical model including particle evaporation

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We discuss the evolution of the mixed phase at RHIC and SPS within boost-invariant hydrodynamics. In addition to the hydrodynamical expansion, we also consider evaporation of particles off the surface of the fluid. The back reaction of this evaporation process on the dynamics of the fluid shortens the lifetime of the mixed phase. In our model this lifetime of the mixed phase is $\leqslant 12$ fm/c in Au+Au at RHIC and $\leqslant 8$ fm/c in Pb+Pb at SPS, even in the limit of vanishing transverse expansion velocity. Strong separation of strangeness occurs, especially in events (or at rapidities) with relatively high initial net baryon and strangeness number, enhancing the multiplicity of multiply strange nuclear clusters. If antiquarks and antibaryons reach saturation in the course of the pure QGP or mixed phase, we find that at RHIC the ratio of antideuterons to deuterons may exceed 0.3 and even $\overline{^4\mathrm{He}}/^4\mathrm{He}>0.1$. In S+Au at SPS we find only $\overline{N}/N\approx 0.1$. As a result of fluctuations, at RHIC even a negative baryon number at midrapidity is possible in individual events, so that the antibaryon and antibaryon-cluster yields exceed those of the corresponding baryons and clusters. [S0556-2813(97)04610-4]

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I. INTRODUCTION

The initial (preequilibrium) stage of heavy-ion collisions at BNL-RHIC energies has been intensively studied during the last years within various models; see, e.g., Refs. [1–3]. As a consequence of the huge number of (sea) partons in the initial state and the large cross sections (especially for gg) already after a very short (proper) time $\tau_i \approx 0.1$–0.2 fm/c the parton momentum space distributions at midrapidity are isotropic. Their widths correspond to a very high temperature on the order of $T_i \simeq 500$ MeV. On the other hand, the approach to chemical equilibrium probably takes somewhat longer. Nevertheless, it appears reasonable to assume that at midrapidity a quark-gluon plasma (QGP) in thermal and chemical equilibrium emerges after a few fm/c. This QGP subsequently expands and cools. If equilibrium is maintained during the expansion and if the phase transition to the finally observed hadrons is of first order (with a sufficiently large latent heat), the system will spend a large part of its lifetime in the mixed phase [4–6].

In this paper we discuss a scenario for the hydrodynamical evolution of the mixed phase, also including particle evaporation off the surface of the system and the back reaction of this time-dependent freeze-out. We also account for net strangeness conservation to compute the multiplicities of strange hadrons and clusters. General aspects and thermodynamic properties of strange matter are discussed in Refs. [7–9].

We do not consider the evolution of the pure QGP phase since most calculations of the initial conditions indicate that at early times $\tau \leqslant 1-3$ fm/c the parton gas might not be in chemical equilibrium, even though it is thermalized [1–3]. Also, the lifetime of the mixed phase at RHIC exceeds that of the pure QGP by roughly a factor of 3. Thus, probably many more hadrons are evaporated from the mixed phase. Anyhow, the emission of hadrons from the pure QGP phase [10] would further increase the evaporation rates (cf. Sec. II) and the effects discussed here would be even stronger.

We consider the following dynamical picture. At (proper) time τ_M a chemically and thermally equilibrated system is formed, which is assumed to be in the mixed phase. The mixed phase consists of a quark-gluon plasma modeled by a MIT bag model equation of state (mass of s quark: $m_s = 150$ MeV), and a hadron gas that includes all well-established (strange and nonstrange) hadrons up to masses of 2 GeV (the list is given in [11]). For the hadron gas Hagedorn's eigenvolume correction is applied [12]. We employ a bag parameter of $B = 380$ MeV/fm^3, leading to a mixed phase temperature (at small μ_q and μ_s) of $T_C \approx 160$ MeV. The same equation of state was used in [13] to study hadron ratios, cluster abundancies, and strangeness distillation in S+Au reactions at CERN-SPS within a similar model [8,9,14]; see also [6]. However, in contrast to the model presented here, spherical symmetry was assumed and boost-invariant hydrodynamical expansion was not taken into account. Also, the evaporation rates (cf. Sec. II) are different in the two models.

Initially the fraction of volume occupied by quarks and gluons equals one, $\lambda(\tau_M) = V^{\mathrm{QGP}}/V^{\mathrm{tot}} = 1$. Hydrodynamic expansion and evaporation of hadrons from the surface set in, leading to a decrease of the total energy, entropy, and net baryon density. Except for the permanent decoupling of hadrons at the boundary to vacuum, the mixed phase is assumed to remain in equilibrium while hadronization proceeds.

At some (proper) time τ_H the quark-gluon content of the mixed phase (i.e., λ) vanishes and all energy, etc., has been converted into hadrons. In principle, the hydrodynamic evolution continues until the decoupling stage is reached. However, experimental data for heavy-ion collisions at AGS and SPS indicate that the chemical potentials and the temperature at the time of decoupling are close to the phase boundary [15], i.e., that the hydrodynamic expansion of the hadronic phase can be neglected. We therefore decouple all remaining hadrons from the hydrodynamic flow immediately after the conversion of mixed phase matter into hadrons is complete. Note, however, that especially the multiplicity of antibaryons and anticlusters may depend strongly on the volume and the lifetime of the hadronic phase (due to annihilation) [16,14], even if it is very short.

We also employ the same dynamical picture (with different initial conditions, of course) for S+Au and Pb+Pb collisions at SPS, although the assumptions of boost-invariant expansion and full strangeness saturation might only be moderately fulfilled at this energy. Nevertheless, by comparing our results to those of Ref. [13] (evaporation without boost-invariant expansion), we can give upper and lower limits for the time scale of chemical freeze-out.

II. HYDRODYNAMIC EXPANSION INCLUDING PARTICLE EVAPORATION

The dynamical evolution of the mixed phase is described within a simple hydrodynamical model which is consistent with the inside-outside cascade picture at high energies [17]. In this model, the thermodynamic state of the system is defined along proper time hyperbolas $\tau=\sqrt{t^2-z^2}$. The flow rapidity η is assumed to be equal to the space-time rapidity; i.e., the (longitudinal) flow velocity at the space-time point (t,z) equals $v_\parallel = z/t$. The space-time volume element is $d^4x = d^2x_T \tau d\tau d\eta$. In the case of a perfect fluid (i.e., disregarding viscosity and thermal conductivity), the rapidity density of each quantity corresponding to a conserved current is (proper) time independent,

$$\frac{\partial}{\partial \tau}\frac{\partial A(\tau)}{\partial \eta}=0. \tag{1}$$

In the case without explicit particle evaporation, this equation holds for the (total) entropy S, the net baryon number N_B, and the net strangeness N_s. The energy per rapidity interval decreases due to the work performed by the expansion according to

$$\frac{\partial}{\partial \tau}\frac{\partial E(\tau)}{\partial \eta}=-p\frac{\partial}{\partial \tau}\frac{\partial V(\tau)}{\partial \eta}=-\pi R_T^2 p, \tag{2}$$

where p denotes the pressure. For simplicity, we consider only longitudinal expansion, i.e., $\partial R_T/\partial\tau=0$, assuming that collective transverse expansion of the mixed phase is slow. The transverse shock wave, which can additionally produce up to $\approx 10\%$ of entropy (for almost net baryon free matter) [5,18], therefore is absent. A microscopic calculation of entropy production in the phase transition to hadronic matter can be found in Ref. [19]. In our case, this additional entropy can, however, be thought of as being absorbed in the initial entropy which has comparable uncertainties (see next section).

In addition to the hydrodynamic expansion we consider particle evaporation off the surface of the midrapidity cylinder with transverse radius R_T. For the evaporation rate in the local rest frame of the fluid we estimate

$$\begin{aligned}\frac{dN_i^{\mathrm{ev}}}{d\tau d\eta} &= O^H \int \frac{d^3p}{E} f_i(E) \frac{\vec{p}_T\cdot\vec{r}_T}{r_T}\Theta(\vec{p}_T\cdot\vec{r}_T) \\ &= O^H n_i^H \frac{1}{\pi}\left\langle \frac{p_T}{E}\right\rangle_i ,\end{aligned} \tag{3}$$

where $O^H = 2\pi R_T \tau$ denotes the surface of the expanding cylinder. n_i^H is the density of the hadron species i under consideration.

The evaporated particles carry away entropy, baryon number, strangeness, and energy:

$$\frac{dS^{\mathrm{ev}}}{d\tau d\eta}=\sum_i \mathcal{S}_i \frac{dN_i^{\mathrm{ev}}}{d\tau d\eta}, \tag{4}$$

$$\frac{dN_B^{\mathrm{ev}}}{d\tau d\eta}=\sum_i \mathcal{N}_{B,i} \frac{dN_i^{\mathrm{ev}}}{d\tau d\eta}, \tag{5}$$

$$\frac{dN_s^{\mathrm{ev}}}{d\tau d\eta}=\sum_i \mathcal{N}_{s,i} \frac{dN_i^{\mathrm{ev}}}{d\tau d\eta}. \tag{6}$$

$\mathcal{S}_i \equiv s_i^H/n_i^H$, $\mathcal{N}_{s,i}\equiv n_{s,i}^H/n_i^H$, and $\mathcal{N}_{B,i}\equiv n_{B,i}^H/n_i^H$ denote the entropy, strangeness, and baryon number per particle of the hadron species i (for the given values of μ_s, μ_B, and T), respectively. For the pions and temperatures around 160 MeV we compute $\langle p_T/E\rangle_\pi \approx 0.75$. For all other particles, we employ

$$\langle v_T\rangle_i = \sqrt{\frac{T}{m_i}}, \tag{7}$$

which is close to the nonrelativistic limit

$$\langle v_T\rangle_i^{\mathrm{nr}} = \sqrt{\frac{\pi T}{2m_i}}. \tag{8}$$

By numerical integration of Eq. (3) we have found that in the relevant temperature range Eq. (7) gives a better approximation of the exact value than Eq. (8), especially for kaons and nucleons.

The evaporated energy could be computed employing an expression similar to Eqs. (4)–(6),

$$\frac{dE^{\mathrm{ev}}}{d\tau d\eta}=\sum_i \mathcal{E}_i \frac{dN_i^{\mathrm{ev}}}{d\tau d\eta}, \tag{9}$$

with $\mathcal{E}_i \equiv \epsilon_i^H/n_i^H$ denoting the energy per hadron of species i. Equation (9) thus assumes that the energy per particle in the free-streaming regime is equal to that in the thermal ensemble. However, this would mean that the evaporation of hadrons performs mechanical work, i.e.,

$$-p\,dV^{\rm ev}=dE^{\rm ev}-T\,dS^{\rm ev}-\mu_i dN_i^{\rm ev}>0. \tag{10}$$

The volume of the hadron gas simply shrinks until it disappears, while the volume of the QGP stays constant. Thus, Eqs. (4)–(9) do not lead to conversion of QGP into hadronic matter, unless transverse expansion is also taken into account [by adding a term $-2\pi R_T\tau p\,\partial R_T/\partial\tau$ on the right-hand side of Eq. (2)]. We have found that for moderate transverse expansion velocities, $\partial R_T/\partial\tau\approx 0.2$, the shrinking of the transverse radius due to evaporation and the increase due to expansion cancel. The resulting evolution and lifetime of the mixed phase are very similar to that described below.

We therefore assume that evaporation causes only heat transfer ($T\,dS^{\rm ev}<0$) and chemical work ($\mu\,dN^{\rm ev}<0$) but does not perform mechanical work. In this case the evaporated energy is determined by the first law of thermodynamics (with $dV^{\rm ev}=0$),

$$\frac{dE^{\rm ev}}{d\tau d\eta}=T\frac{dS^{\rm ev}}{d\tau d\eta}+\mu_s\frac{dN_s^{\rm ev}}{d\tau d\eta}+\mu_q\frac{dN_q^{\rm ev}}{d\tau d\eta}. \tag{11}$$

The time evolution of the thermodynamic quantities due to particle evaporation and hydrodynamic expansion is

$$\frac{dA}{d\tau d\eta}=-\frac{dA^{\rm ev}}{d\tau d\eta}(A=S,N_s,N_B), \tag{12}$$

$$\frac{dE}{d\tau d\eta}=-\frac{dE^{\rm ev}}{d\tau d\eta}-\pi R_T^2 p. \tag{13}$$

These equations generalize Eqs. (1) and (2) to account for the back reaction of the freeze-out on the dynamics of the fluid. Note that there are two distinct time scales in this model, one given by the (longitudinal) hydrodynamic expansion and the other by the evaporation process.

The preequilibrium parton evolution yields the initial values of the entropy, the net baryon number, and the net strangeness, i.e., $dS(\tau_M)/d\eta$, $dN_B(\tau_M)/d\eta$, and $dN_s(\tau_M)/d\eta$ (see below). By virtue of the equation of state and the additional requirement that the system is in the mixed phase with a QGP fraction of 100% [i.e., $\lambda(\tau_M)=1$], the initial energy at midrapidity is also determined.

At later times $\tau>\tau_M$, Eqs. (12) and (13) yield $dE/d\eta$, $dS/d\eta$, $dN_B/d\eta$, and $dN_s/d\eta$. From these four quantities and Gibbs' condition of phase equilibrium, $p^{\rm QGP}=p^H$, we can compute $V^{\rm tot}$, μ_q, μ_s, T, and the volume fraction of QGP $\lambda\equiv V^{\rm QGP}/(V^H+V^{\rm QGP})$.

The evaporated particles are assumed to stream freely to the detector. The measured hadron multiplicities are thus given by the evaporation rates (3), integrated over (proper) time. In addition, at the time τ_H where the hadronization is complete [$\lambda(\tau_H)=0$], the entire remaining hadronic system is assumed to decouple instantaneously (i.e., on the hyperbola $\tau=\tau_H$) from thermal and chemical equilibrium.

III. INITIAL CONDITIONS

On average over many events, the natural choice for the initial net strangeness (at midrapidity) is $dN_s/d\eta=0$. In contrast to heavy-ion reactions at fixed-target energies, the net baryon number at midrapidity is expected to be relatively small at RHIC. This is due to the large number of secondary partons as compared to the number of valence quarks. Nevertheless, it is important to account for nonvanishing N_B, especially when studying the enrichment of the mixed phase with net strangeness. The models RQMD 1.07 [20], FRITIOF 7.02 [21], and the parton cascade model (PCM) [1] predict $dN_B/d\eta=20-35$ in Au+Au at RHIC.

The entropy per baryon created in the early evolution of the parton gas is $S/N_B=200$ in the PCM [1]. In Ref. [2] $S/N_B=110$ was estimated for the ''final'' (i.e., at the time where isentropic expansion sets in) entropy per net baryon by assuming perturbative QCD (PQCD) interactions (lowest order) between the partons in the initial state. However, in this calculation a transverse momentum cut off (which is necessary to render the lowest-order PQCD cross sections finite) of $p_0=2$ GeV was used. As discussed in [2], this might be appropriate for LHC but for lower energies like RHIC the saturation of the produced gluons should be reached already for a smaller cut off. Changing p_0 from 2 to 1 GeV increases the minijet cross sections and thus S/N_B to about 150 [22]. Also, the soft component was assumed to be constant from SPS to RHIC, $(S/N_B)_{\rm soft}\approx 50$. Multiplying this number by an *ad-hoc* factor of 2 increases the total S/N_B to about 150 for $p_0=2$ GeV and to 220 for $p_0=1$ GeV [22].

The RQMD 1.07 model, based on color-string formation and decay, predicts a central pion multiplicity of $dN_\pi/d\eta=1000$, leading to $S_\pi/N_B=3.6N_\pi/N_B=170$ [20]. If we assume that other particles (e.g., kaons) contribute about 10%–20% to the total entropy, we find a similar number for S/N_B as in the PCM. The microscopic phase-space model UrQMD 1.0 [11], which also approaches RHIC from below assuming that color-string formation and subsequent fragmentation is the dominant mechanism for secondary production (as at SPS), predicts about 30 net baryons, 900 pions, and 80–100 kaons at midrapidity in central ($b=2$ fm) Au+Au collisions at RHIC [23]. Thus, a value of $S/N_B=200$ (at midrapidity) for an average central Au+Au event at RHIC seems reasonable.

Considering τ_M (the initial time for the mixed phase), we first note that once the midrapidity numbers for N_B and S are fixed, the corresponding coordinate space densities n_B and s behave like $1/\tau$. Thus, τ_M must not be chosen too small for then the system cannot be in the mixed phase initially (the equation $p^{\rm QGP}=p^H$ cannot be fulfilled). Also, the initial transverse radius R_T, as given by the thermodynamic relations, depends on τ_M (through the volume of the midrapidity region $\partial V/\partial\eta=\pi R_T^2\tau$). For the parameter set $N_s=0$, $N_B=25$, $S/N_B=200$, we choose $\tau_M=5$ fm/c which leads to $R_T=5.4$ fm. A similar value for τ_M would emerge if an equilibrated QGP with temperature $T\approx 500$ MeV at the initial time $\tau_i=0.1-0.2$ fm/c was created [5,24].

For collisions at SPS we employ $N_s=0$ initially. The specific entropy required to fit the particle ratios measured in S+Au with our equation of state is $S/N_B=45$ [13]. For central Pb+Pb we employ the same value. In S+Au the net baryon number at midrapidity, as measured by the NA35 collaboration [25], is $dN_B/d\eta\approx 16$. For Pb+Pb we assume $dN_B/d\eta=80$ which results in ≈ 61 net nucleons at midrapidity (cf. Sec. V). If we simply scale by 1/2 (at high energies the initial isospin asymmetry is ''deposited'' in the pions and the nucleons become isospin symmetric), the net

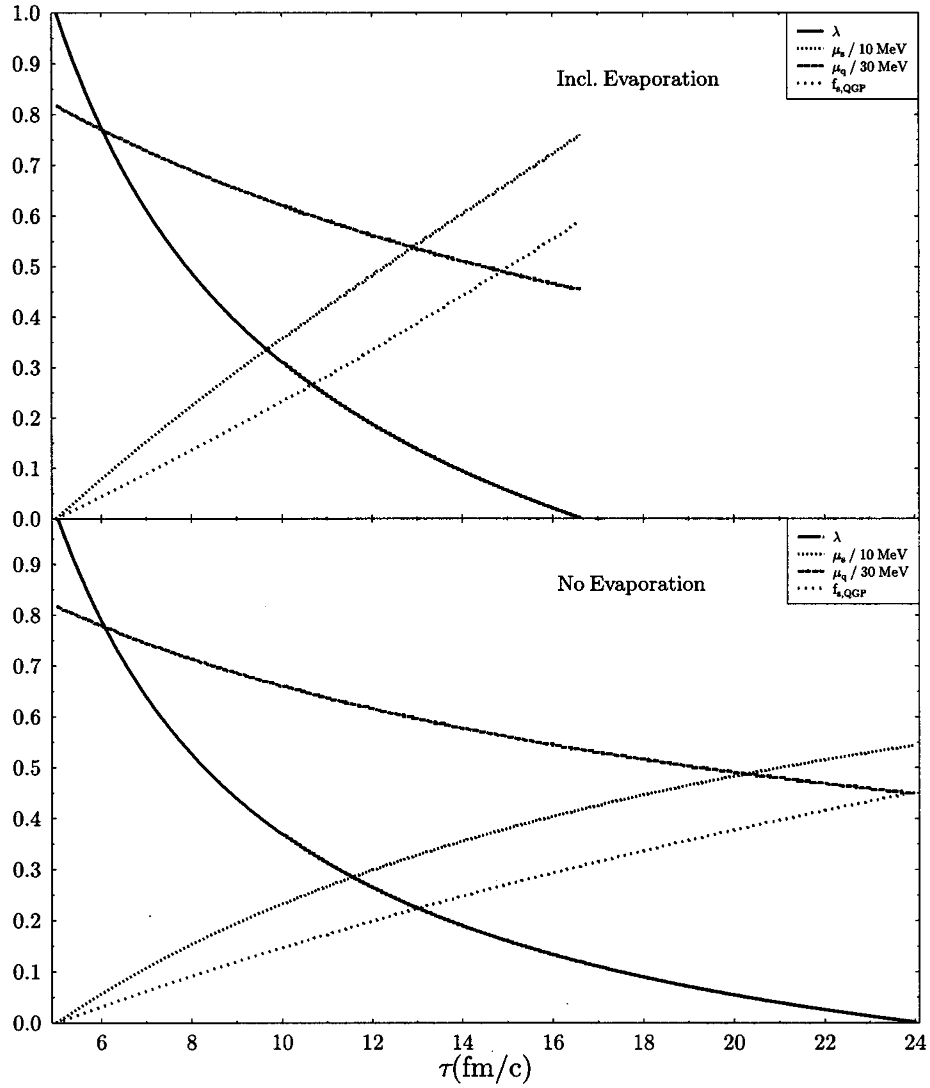

FIG. 1. Time evolution of the volume fraction occupied by QGP, the chemical potentials of s and u,d quarks, and the number of net strange quarks per baryon in the QGP. The initial conditions are as in Table I (average Au+Au at RHIC; bottom, only longitudinal hydrodynamic expansion without particle evaporation; top, including evaporation).

proton multiplicity is close to the preliminary NA49 data [26]. For the (proper) time where the evolution of the mixed phase starts we assume $\tau_M = 1.5$ fm/c (S+Au) and $\tau_M = 3$ fm/c (Pb+Pb) which leads to $R_T = 3.7$ fm and $R_T = 5.9$ fm, respectively.

IV. RESULTS FOR RHIC

Figure 1 shows the time evolution of λ, μ_s, μ_q, and $f_{s,\mathrm{QGP}} \equiv N_s^{\mathrm{QGP}}/N_B^{\mathrm{QGP}}$. Evaporation leads to a faster conversion of QGP into hadronic matter and reduces the lifetime of the mixed phase from $\tau_H - \tau_M = 19$ fm/c (only longitudinal boost-invariant expansion) to $\tau_H - \tau_M = 11.6$ fm/c. Thus, even if the transverse expansion of the mixed phase is extremely slow [5], the lifetime is considerably shortened by the permanent decoupling of particles close to the surface.

In contrast to the situation for lower vacuum pressure B and initial specific entropy [6,8,9,13,27], for $S/N_B \geqslant 40$ and $B = 380$ MeV/fm^3 the temperature in the mixed phase ($T \approx 160$ MeV) is essentially constant and does not increase significantly (although $S^{\mathrm{QGP}}/N_B^{\mathrm{QGP}}$ does increase). The variations of the chemical potentials μ_s and μ_q in time are much larger. Also, strangeness separation between QGP and hadrons occurs ($f_{s,\mathrm{QGP}} > 0$) even without evaporation ($N_s = 0$ in the total system in this case). This is a consequence of the fact that from $N_s = 0$ and $N_B > 0$ also $\mu_s > 0$ follows if hadrons are present (i.e., $\lambda < 1$) [8]. For the initial conditions as in Fig. 1 the evaporation of strangeness (which is mainly due to kaons) leads to a net strangeness at the final breakup (i.e., at the time where $\lambda = 0$) of $N_s/N_B = 11.5\%$.

As a result of the fact that (for these initial conditions) K, p, and Λ are more abundant in the hadron gas than the corresponding antiparticles, they are evaporated earlier and their average freeze-out times are smaller than those of the antiparticles [13,28,29]. As shown in Ref. [29], for low vacuum pressure $B^{1/4} = 160$ MeV (slow hadronization) this phenomenon affects the properties of the K-$\overline{K}$ correlation function. In our model, however, as a consequence of the boost-invariant expansion most particles are emitted in the breakup of the purely hadronic phase, washing out this signal completely. We obtain equal average freeze-out times for K and $\overline{K}$: $\langle \tau_{\mathrm{fo}} \rangle_{K,\overline{K}} = 15$ fm/c (these numbers include the kaons from the final breakup but not those from decays of higher-mass resonances).

TABLE I. Multiplicities of hadrons and clusters emitted from the expanding midrapidity cylinder. Feeding from decays of higher-mass resonances is included. The first line shows the total multiplicity (evaporated hadrons plus those from the final breakup at time $\tau=\tau_H$) while the second line shows only the evaporated particles. Initial conditions: $dS/d\eta/dN_B/d\eta=200$, $dN_B/d\eta=25$, $dN_s/d\eta=0$, $\tau_M=5$ fm/c (Au+Au at RHIC).

π	k	$\overline{K}$	N	$\overline{N}$	Λ	$\overline{\Lambda}$
830	100	92.6	44.4	25.8	13.2	8.67
267	31	27.1	11.4	5.97	3.19	2.05
d	$\overline{d}$	^{4}He	$\overline{^4\mathrm{He}}$	$\Lambda\Lambda$		
0.104	0.0355	1.20×10^{-6}	1.43×10^{-7}	0.0051		
0.024	0.0066	2.38×10^{-7}	1.79×10^{-8}	0.0010		

The initial conditions in individual events may strongly deviate from our standard set. There may well be large fluctuations [30] in N_s as well as in the net baryon number N_B, and the entropy per net baryon, S/N_B, if one considers only a small subinterval (e.g., ±0.5 around midrapidity) of the total rapidity gap. We assume that even in such events boost invariance around midrapidity is approximately valid.

In the tables we compile particle and cluster abundancies for our standard initial conditions and a calculation with higher initial net baryon number and an excess of s quarks. The first line gives the sum over evaporation and final breakup. Below, the contribution from evaporation only (without final breakup) is quoted. This latter part of antibaryons and clusters survives even if the space-time volume of the chemically equilibrated purely hadronic phase would be significant (which would lead to cooling below T_C). However, as already mentioned in the Introduction, this is probably not the case [13,15,19]. The pion multiplicity is perhaps somewhat underpredicted, which may be due to the fact that the effective volume correction should be done different for pions [31].

For the standard set of initial conditions (Table I), the higher initial specific entropy (as compared to BNL-AGS and CERN-SPS) leads to considerable antibaryon production ($\overline{N}/N$, $\overline{\Lambda}/\Lambda>0.5$). In S+Au at SPS one finds only $\overline{N}/N\approx0.1$. At RHIC, even the ratio of antideuterons to deuterons and antihelium to helium is larger than 0.1.

For the second set of initial conditions (Table II), of course, the initial values of μ_s and μ_q are considerably higher than in Fig. 1. The higher μ_q values enhance the multiplicity of deuterons by 40% and that of ^{4}He by a factor of 2. Also, a strong strangeness separation between the QGP and the hadrons in the mixed phase occurs, leading to $f_{s,\mathrm{QGP}}$ values up to ≈1.44. For example, in this calculation μ_s increases from 37 MeV initially to 48 MeV at the time where the transition to purely hadronic matter is complete. These μ_s values are comparable to those extracted in Ref. [13] for S+Au collisions at SPS (cf. Fig. 2), while at the same time μ_q is considerably lower. This can be clearly observed in the ratio $\Lambda/\overline{\Lambda}=3.6$, which is larger than $N/\overline{N}=2.5$ (S+Au at SPS: $N/\overline{N}\approx9$, while $\Lambda/\overline{\Lambda}\approx5$).

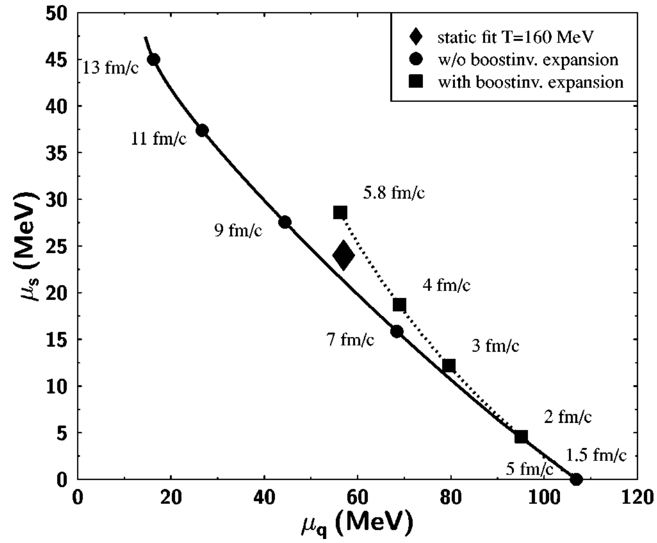

FIG. 2. Time evolution of μ_s and μ_q in the evaporation model of Ref. [13] (without boost-invariant hydrodynamic expansion), compared to our model. Our initial conditions for the midrapidity cylinder are $dS/d\eta/dN_B/d\eta=45$, $dN_B/d\eta=16$, $dN_s/d\eta=0$, and $\tau_M=1.5$ fm/c (S+Au at SPS). The parameters of the static fit are also indicated [13].

If experiments were able to trigger on events (or rapidities) with high net baryon and strangeness density, the detection of the so-called MEMO's (metastable multiple strange objects) [9,32] might be possible. As an example, note that for our second set of initial conditions the multiplicity of the lightest MEMO, the $\Lambda\Lambda$ cluster (for which we assume a mass of $m_{\Lambda\Lambda}=2200$ MeV, i.e., a binding energy of 30 MeV), increases by a factor of 2. A similar amount of $\Lambda\Lambda$ clusters as in Pb+Pb at SPS is emitted (cf. Table III), however, from a larger volume.

Since at RHIC the initial net baryon number is not very far from zero, even events with an excess of antiquarks

TABLE II. Same as in Table I but for the initial condition $dS/d\eta/dN_B/d\eta=100$, $dN_s/d\eta=dN_B/d\eta=50$, $\tau_M=5$ fm/c (Au+Au at RHIC).

π	K	$\overline{K}$	N	$\overline{N}$	Λ	$\overline{\Lambda}$
821	82.6	108	51.5	20.9	19.7	5.49
265	25.7	31.7	13.2	4.92	4.68	1.32
d	$\overline{d}$	^{4}He	$\overline{^4\mathrm{He}}$	$\Lambda\Lambda$		
0.144	0.0240	2.30×10^{-6}	6.54×10^{-8}	0.0102		
0.033	0.0045	4.36×10^{-7}	8.47×10^{-9}	0.0020		

TABLE III. Same as in Table I but for the initial condition $dS/d\eta/dN_B/d\eta=45$, $dN_B/d\eta=80$, $dN_s/d\eta=0$, $\tau_M=3$ fm/c (Pb+Pb at SPS).

π	K	$\overline{K}$	N	$\overline{N}$	Λ	$\overline{\Lambda}$
570	75.9	53.4	68.1	7.48	16.7	3.04
130	18.1	10.0	14.3	1.00	2.88	0.463
d	$\overline{d}$	^{4}He	$\overline{^4\mathrm{He}}$	$\Lambda\Lambda$		
0.373	4.57×10^{-3}	2.44×10^{-5}	3.54×10^{-9}	0.0130		
0.0873	4.20×10^{-4}	8.42×10^{-6}	1.71×10^{-10}	2.04×10^{-3}		

($N_B<0$) may not be too rare. The initial conditions $S=5000$, $N_s=0$, $N_B=-25$, and $\tau_M=5$ fm lead to the same particle and cluster yields as in Table I, except that particles and antiparticles have to be interchanged. As a result, the multiplicities of antibaryon clusters are enhanced by factors of ≈ 3 for antideuterons and ≈ 8 for antihelium.

V. RESULTS FOR SPS

As shown in Ref. [13], the hadron ratios measured in S+Au collisions at SPS can be fitted with our equation of state assuming isochronous chemical freeze-out (as in [15]) at $T=160$ MeV, $\mu_S=24$ MeV, and $\mu_q=56$ MeV (indicated by the diamond in Fig. 2). On the other hand, a reasonable fit was also obtained assuming formation of a mixed phase in equilibrium, which then hadronizes by evaporating hadrons from the surface, until the whole entropy, baryon number, etc., is converted into free-streaming hadrons. As a result of the neglect of hydrodynamic expansion, in this latter model the lifetime of the mixed phase, and thus the time interval in which the hadrons freeze out [13,29], is relatively large (8–9 fm/c; cf. Fig. 2). In contrast to the isochronous freeze-out scenario, the average freeze-out times for the various hadron species differ considerably. This is due to the fact that μ_s and μ_q are strongly time dependent and a transition to purely hadronic matter (which freezes out more or less instantaneously) does not take place.

Here, in our present model (including boost-invariant longitudinal expansion) the lifetime of the mixed phase is only 4.3 fm/c; the midrapidity region then enters the purely hadronic phase and breaks up. As can be seen in Fig. 2, this final breakup occurs close to the ''static-fit'' point. Most hadrons are emitted at this point, and only a few are evaporated.[1] In the other extreme case (only longitudinal expansion without evaporation) the lifetime of the mixed phase for our equation of state is $\tau_H-\tau_M=5.7$ fm/c and the breakup at the time $\tau_H=7.2$ fm/c occurs exactly at the ''static-fit'' point in Fig. 2. Our model thus is close to the sudden freeze-out scenario [at some specific (proper) time] and the freeze-out times of the various hadron species do not differ significantly. We repeat that for the considered high specific entropies and bag pressures the temperature is essentially time independent, $T=158\pm 2$ MeV, while the chemical potentials μ_s and μ_q vary considerably.

In Pb+Pb collisions, the lifetime of the mixed phase almost doubles (Fig. 3) but still is $2-3$ fm/c below the one at RHIC. The resulting hadron multiplicities are shown in Table III. The pion and net nucleon multiplicities fit well to the preliminary NA49 data [26]. Assuming isospin symmetry for the nucleons, $\overline{p}=\overline{N}/2$, we find a ratio $\overline{p}/\overline{\Lambda}=2.5$. As a result of the higher μ_q values, d and ^{4}He are more abundant than at RHIC, while the corresponding antinuclei are strongly suppressed. Note that we obtain fewer deuterons but many more helium nuclei than in the UrQMD model [23]. One also observes that the fraction of hadrons that are evaporated directly from the mixed phase (i.e., without those emitted at the breakup of the purely hadronic phase) is higher at RHIC than at SPS. The longer the lifetime of the mixed phase is, the more important evaporation gets. At LHC, a large part of (the entropy of) the mixed phase will probably be evaporated (i.e., directly converted into free-streaming hadrons) before the fluid reaches the purely hadronic phase.

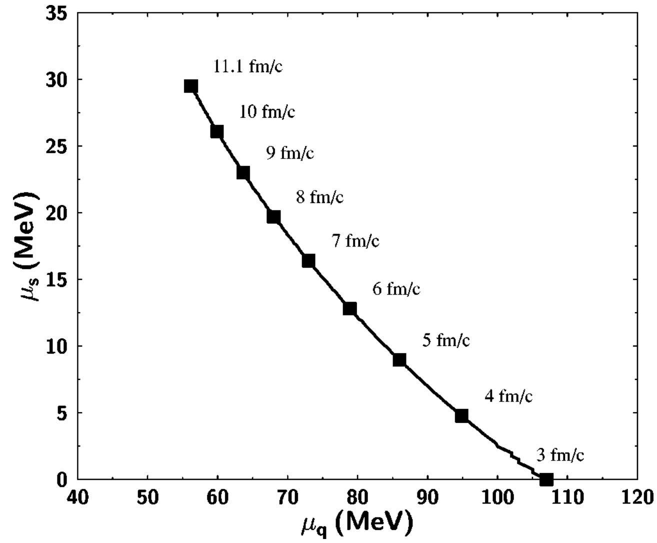

FIG. 3. Time evolution of μ_s and μ_q in our model (including evaporation and boost-invariant expansion). Initial conditions for the midrapidity cylinder as in Table III (Pb+Pb at SPS).

VI. SUMMARY

In this paper we discussed the evolution of the mixed phase presumably created in heavy-ion collisions at SPS and RHIC, employing a model that combines (boost-invariant) longitudinal hydrodynamical expansion and particle evaporation off the surface of the fluid. For reasonable choices of the initial conditions, our model reproduces the hadron ratios measured in S+Au at SPS (as compiled in [15]). The interplay of the evaporation process and the hydrodynamical expansion (and vice versa) leads to considerably shorter lifetimes of the mixed phase (i.e., to faster hadronization) as compared to the scenarios without evaporation (only hydrodynamical expansion [5,17,24,33]) or without hydrodynamical expansion (only evaporation [8,13]).

We have also calculated the multiplicities of various hadrons, clusters, and hyperon clusters in Pb+Pb at SPS and Au+Au at RHIC (our results for S+Au at SPS are not presented here since they are similar to those of Ref. [13]). At SPS, μ_q is large (and in particular larger than μ_s), implying that nucleon to antinucleon and hyperon to antihyperon ratios are large ($\geqslant 5$), in contrast to RHIC, where antinucleons and antihyperons are more abundant than at SPS by a factor of 3.

At RHIC, the initial conditions of the central region may fluctuate. This offers the very interesting opportunity to produce clusters of antibaryons and hyperons. In events with unusually high net baryon density or net strangeness (at midrapidity) the multiplicity of d, ^{4}He and MEMO's may be

[1]Therefore, it is obvious that the (midrapidity) particle ratios in our model are very close to those quoted in Refs. [13,15] and we do not need to repeat this discussion here.

enhanced by up to 100% (as compared to the average). In this case $\mu_s > \mu_q$ can be reached, leading to an emission of more hyperons per antihyperon than of nucleons per antinucleon. On the other hand, negative net baryon number (excess of antiquarks) at midrapidity increases antinuclei abundancies by up to a factor of 10.

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