Nonperturbative effects in a rapidly expanding quark gluon plasma

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Within first-order phase transitions, we investigate pretransitional effects due to the nonperturbative, large-amplitude thermal fluctuations which can promote phase mixing before the critical temperature is reached from above. In contrast with the cosmological quark-hadron transition, we find that the rapid cooling typical of the relativistic heavy ion collider and large hadron collider experiments and the fact that the quark-gluon plasma is chemically unsaturated suppress the role of nonperturbative effects at current collider energies. Significant supercooling is possible in a (nearly) homogeneous state of quark gluon plasma.

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I. INTRODUCTION

It is possible to model the gross general features of a phase transition from a quark-gluon plasma (QGP) to a hadronic phase through a phenomenological potential with a scalar order parameter [1]. Assuming the transition to be discontinuous, or first order, as suggested by some recent lattice QCD simulations [2], the QGP is cooled to a temperature T_1, where a second minimum appears, indicating the presence of a hadronic phase. With further cooling, the two phases become degenerate at a critical temperature T_c, with a free-energy barrier which depends on the physical parameters characterizing the system, such as the surface tension (σ) and the correlation length (ξ). This general behavior models both the cosmological quark-hadron phase transition and the production of a QGP during heavy-ion collision experiments, as those under way at the relativistic heavy ion collider (RHIC) and planned for the large hadron collider (LHC). In the latter case, the plasma generated by the collision expands and cools, relaxing back to the hadronic phase. Recent interest has been sparked by the possibility that this relaxation process is characterized by the formation of disoriented chiral condensates (DCC's), which are coherent pion condensates similar to the domains typical of quenched ferromagnetic phase transitions [3,4]. The nonequilibrium properties of this relaxation process and DCC formation were also studied as a first-order chiral phase transition where the supercooled phase may naturally lead to a "quenched" initial condition [5].

Recent work on the dynamics of weak first-order phase transitions showed that, in certain cases, it is possible to have nonperturbative, large-amplitude fluctuations before the critical temperature is reached, which promote phase mixing [6]. Studies performed in the context of the cosmological electroweak phase transition [7] and quark-hadron phase transition [8] indicated that, for a range of physical parameters controlling the transition, these effects are present. It is thus natural to consider if similar effects are present during heavy-ion collisions [9].

Whenever pretransitional phenomena are relevant, one should expect modifications from the usual homogeneous nucleation scenario, which is based on the assumption that critical bubbles of the hadronic phase appear within a homogeneous background of the QGP phase. The dynamics of weakly first-order transitions will be sensitive to the amount of phase mixing at T_c: for large phase mixing, above the so-called percolation threshold, the transition may proceed through percolation of the hadronic phase, while for small amounts of phase mixing they will proceed via the nucleation of critical bubbles in the (inhomogeneous) background of isolated hadronic domains, which grow as T drops below T_c. An ideal quark gluon plasma in one dimension expands according to the Bjorken scaling, where T^3t is constant [10]. Assuming the initial temperature of the plasma produced at RHIC and LHC energies to be 2–3 times T_c, scaling implies that the time (Δt) taken by the plasma to cool from T_1 to T_c is of order a few fm/c, which could be comparable with the time scale of the subcritical hadronic fluctuations. On the other hand, the expansion rate of the early universe in the range $T_1 \leqslant T \leqslant T_c$ is slow enough [11,12] (Δt could be of the order of a few μsec), that nonperturbative thermal fluctuations may achieve equilibrium. Another difference is that collisions at RHIC and LHC energies will lead to the formation of a highly (chemically) unsaturated plasma, i.e., the initial gluon and quark contents of the plasma remain much below their equilibrium values [13–16]. A chemically unsaturated plasma will cool at an even faster rate than what is predicted from Bjorken scaling [17,18]. The cooling rate will also be accelerated further if expansion in three dimensions is considered. Therefore, we will show that although the equilibrium density distribution of subcritical hadron bubbles is significant—particularly when the transition is weak—unlike the situation in cosmology, they do not contribute strongly to phase mixing. For the range of parameters we investigated, of relevance for RHIC and LHC energies, the plasma cools so rapidly that the subcritical bubbles do not have time to reach their equilibrium distribution and promote substantial phase mixing: significant supercooling is possible in a (nearly) homogeneous quark gluon state.

II. SUBCRITICAL BUBBLE FORMALISM

To study the dynamics of a first-order phase transition, we use a generic form of the potential in terms of a real scalar order parameter ϕ, given by [1,8]

$$V(\phi)=a(T)\phi^2-bT\phi^3+c\phi^4. \tag{1}$$

The parameters a, b, and c are determined from physical quantities, such as the surface tension (σ) and the correlation length (ξ) of the fluctuations, and also from the requirement that the second minimum of the above potential should be equal to the pressure difference between the two phases [8]. The bag equation of state is used to calculate the pressure in the two phases. The potential $V(\phi)$ has a minimum at $\phi=0$ and a metastable second minimum at

$$\phi_+=\frac{3bT+\sqrt{9b^2T^2-32ac}}{8c} \tag{2}$$

below $T\leqslant T_1$. In the thin wall approximation [19], b, c, and T_1 can be written as [8]

$$b=\frac{1}{\sqrt{6\sigma\xi^5T_c^2}},\quad c=\frac{1}{12\xi^3\sigma},\quad T_1=\left[\frac{BT_c^4}{B-\frac{27}{16}V_b}\right]^{1/4}, \tag{3}$$

where B is the bag constant and

$$V_b(\phi_m)=\frac{3\sigma}{16\xi(T_c)} \tag{4}$$

is the height of the degenerate barrier at $T=T_c$ or at $a(T_c)=b^2T_c^2/4c$. A wide spectrum of first-order phase transitions, ranging from very weak to strong, can be studied by either changing σ or ξ or both. For example, for a fixed value of ξ, the strength of the transition is controlled by σ, becoming very weakly first order or second order when $\sigma\rightarrow 0$.

We follow Ref. [6] to obtain the equilibrium number density of subcritical bubbles. Let $n(R,t)$ be the number density of bubbles with a radius between R and $R+dR$ at a time t that satisfies the Boltzmann equation

$$\frac{\partial n}{\partial t}=-|v|\frac{\partial n}{\partial R}+(1-\gamma)\Gamma_0-\gamma\Gamma_+ . \tag{5}$$

The first term on the right-hand side is the shrinking term with velocity $v=\partial R/\partial t$. The term Γ_0 is the rate per unit volume for the thermal nucleation of a bubble of radius R of phase $\phi=\phi_+$ (hadron phase) within the phase $\phi=0$ (QGP phase). Similarly, Γ_+ is the corresponding rate of the phase $\phi=0$ within the phase $\phi=\phi_+$. The factor γ is defined as the volume fraction in the hadron phase. Assuming $\Gamma_0\approx\Gamma_+(=\Gamma)$ for a degenerate potential at $T=T_c$, for the rate we write

$$\Gamma=AT^4\exp\left[-\frac{F(\phi_+)}{T}\right], \tag{6}$$

where A is a constant of order unity. Using the Gaussian ansatz for subcritical configurations,

$$\phi(r)=\phi_+\exp\left(-\frac{r^2}{R^2}\right), \tag{7}$$

the free energy functional

$$F(\phi)=4\pi\int r^2dr\left[\frac{1}{2}\left(\frac{\partial\phi}{\partial r}\right)^2+V(\phi,T)\right] \tag{8}$$

can be written as [6]

$$F(\phi_+)=\alpha R+\beta R^3, \tag{9}$$

where

$$\alpha=\frac{3\sqrt{2}\pi^{3/2}\phi_+^2}{8} \tag{10}$$

and

$$\beta=\pi^{3/2}\phi_+^2\left[\sqrt{\frac{2a}{4}}-\frac{\sqrt{3}bT\phi_+}{9}+\frac{c\phi_+^2}{8}\right]. \tag{11}$$

The equilibrium number density (n_0) of subcritical bubbles is found by solving Eq. (5) with $\partial n/\partial t=0$, and imposing the physical boundary condition $n(R\rightarrow\infty)=0$. Using $\gamma_0\approx 4\pi R^3n_0/3$, we obtain a coupled equation for γ_0, which can be solved to obtain

$$\gamma_0=\frac{I}{1+2I} \tag{12}$$

where

$$I=\int_R^\infty\frac{4\pi}{3v}R^3\Gamma(R',\phi_+)dR'. \tag{13}$$

We will consider the statistically dominant fluctuations with $R\approx\xi$, and estimate γ_0, integrating Eq. (13) from ξ to ∞. Neglecting the shrinking term in Eq. (5), the time-dependent solution of $n(\xi,t)$ can be written as [6]

$$n(\xi,t)=n_0(\xi)[1-\exp\{-q(\xi)t\}], \tag{14}$$

where $q(\xi)=[(8\pi\xi^3/3)\Gamma]$ and $n_0(\xi)=\Gamma(\xi)/q(\xi)$. Alternatively, in terms of γ, the above solution has the form

$$\gamma(\xi,t)=\gamma_0(\xi)[1-\exp(-q_0t)], \tag{15}$$

where $q_0=(4\pi\xi^3/3)\Gamma/\gamma_0$. The relaxation time $\tau=q_0^{-1}$ depends on two factors γ_0 and Γ, out of which only the γ_0 is affected by shrinking (if included). Since we know the complete solution of γ_0 that includes shrinking [Eq. (12)], Eq. (15) can also be used to estimate its time dependence. Note that the presence of a shrinking term in Eq. (5) results in a reduction of γ_0, and also in a faster relaxation process.

III. RESULT AND DISCUSSION

First we consider the slow evolution of the medium as in the case of early universe [11,12], so that the equilibrium scenario is applicable. Figure 1 shows the plot of γ_0 as a

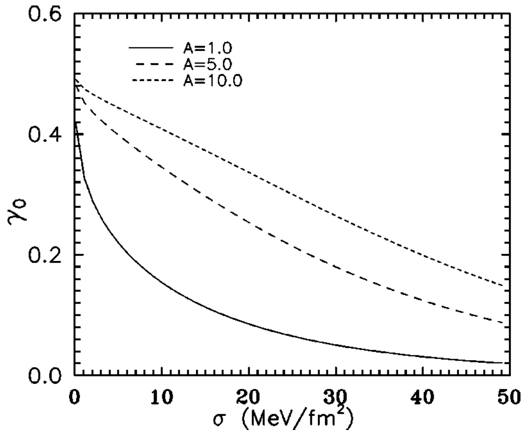

FIG. 1. γ_0 vs σ at $T=T_c$ for a few typical values of A. ξ is fixed at 0.5 fm and T_c at 160 MeV.

function of σ at $T=T_c$ for a few typical values of the prefactor A. We have fixed ξ at 0.5 fm and T_c at 160 MeV, and $v=1/\sqrt{3}$. As expected, the equilibrium hadronic fraction increases with decreasing σ, and becomes as large as 0.5 for weak transitions. Recent lattice QCD predictions [2] suggested that the quark-hadron phase transition could be weakly first order with σ values in the range 2–10 MeV/fm^2. Therefore, the choice of σ in the above range and $A\sim 1$ [19] would imply a significant amount of phase mixing at $T=T_c$ so that homogeneous nucleation becomes inapplicable [8].

Next we consider the plasma expected to be formed at RHIC and LHC energies. Since the expansion of such plasma is much faster compared to the plasma of the early universe, it will be interesting to know the amount of phase mixing (the value of γ) built up by the time the plasma cools from T_1 to T_c. Assuming ideal scaling, we can estimate the time Δt taken by the plasma to cool from T_1 to T_c as

$$\Delta t=\frac{T_0^\nu}{T_c^\nu}t_0\left[1-\frac{T_c^\nu}{T_1^\nu}\right], \tag{16}$$

where $\nu=3$ in $1+1$ dimensions. Since T_1 depends on σ [see Eq. (3)], Δt will also depend on σ, being smaller the weaker the transition. In the standard scenario, we can assume the initial temperature $T_0\approx 320$ MeV and the formation time $t_0\approx 1$ fm. However, several perturbative-inspired QCD models [14–16] suggest a very different collision scenario at RHIC and LHC energies, which lead to the formation of unsaturated plasma with high gluon contents. Such a plasma will attain thermal equilibrium in a short time $t_0\approx 0.3$–0.7 fm, but will remain far from chemical equilibrium. Since the initial plasma is gluon rich, more quark and antiquark pairs will be needed in order to achieve chemical equilibration. The dynamical evolution of a plasma undergoing chemical equilibration was studied initially by Biro *et al.* [17], and subsequently by many others [18], by solving the hydrodynamical equations along with a set of rate equations governing chemical equilibration. It was found that a chemically unsaturated plasma cools faster than what is predicted by Bjorken scaling, since additional energy is consumed during chemical equilibrium. Following Ref. [18], we studied chemical equilibration and dynamical evolution of the QGP with two sets of initial conditions, HIJING [14] and self-screened parton cascade model (SSPM) [15], as listed in Table I. The Perturbative QCD inspired models like parton cascade model (PCM) [16] and HIJING (Heavy Ion Jet Interaction Generator) [14] are generally used to simulate the nuclear collisions at collider energies on the level of microscopic parton dynamics. The PCM calculations describe the space-time evolution of quark and gluon distributions by Monte Carlo simulations of relativistic transport equations. The HIJING model also incorporates the perturbative QCD approach and multiple minijet productions; however, it does not incorporate a direct space-time description. Early PCM calculations were done by assuming a p_T cutoff to ensure the applicability of the perturbative expansion of the QCD scattering process. In the recently formulated SSPM [15], early hard scattering produces a medium which screens the longer range color fields associated with softer interactions. The screening occurs on a length scale where perturbative QCD still applies, and the divergent cross sections in the calculation of the parton production can be regulated self-consistently without an *ad hoc* cutoff parameter. The numerical studies based on the parton cascade model suggest that the parton plasma produced in the central region is essentially a hot gluon plasma, and the dynamics is mostly dominated by gluons. Gluons thermalize rapidly, reaching approximately isotropic momentum distributions on a very short-time scale. The densities of quarks and antiquarks stay well below the gluon density, and cannot build up to the full equilibration values required for an ideal chemical mixture of gluons and quarks. Similar conclusions were also drawn from the calculations based on the HIJING approach. Though both PCM and HIJING models are QCD inspired models, the two still differ in quantitative predictions possibly due to different treatments of multiple parton interactions and collective effects. In the following, we take the initial conditions obtained both from HIJING and SSPM calculations at the time when the parton momentum distribution becomes isotropic. We consider two dominant reaction channels $q\bar{q}\rightleftharpoons gg$ and $gg\rightleftharpoons ggg$, that contribute to the chemical equilibrium. The fugacity $\lambda_{g(q)}(\leqslant 1)$ gives the measure of the deviation of the gluon (quark) density from the equilibrium value; chemical equilibrium is achieved when λ_i's $\rightarrow 1$. For a detail discussion of chemical equilibration, we refer further to Ref. [18].

TABLE I. Initial conditions are taken from Ref. [20] as predicted by SSPM and HIJING calculations. The fugacities λ_i's give a measure of the deviation of the gluon or quark densities from the equilibrium values.

Code	Energy	t_i (fm/c)	T_i(GeV)	λ_g	λ_q	ν
SSPM	RHIC	0.25	0.668	0.34	0.064	2.2
SSPM	LHC	0.25	1.02	0.43	0.082	2.2
HIJING	RHIC	0.7	0.55	0.05	0.008	1.9
HIJING	LHC	0.5	0.82	0.124	0.02	1.8

Figure 2 shows a typical example of the effect of chemical equilibration on the cooling rate for SSPM initial condi-

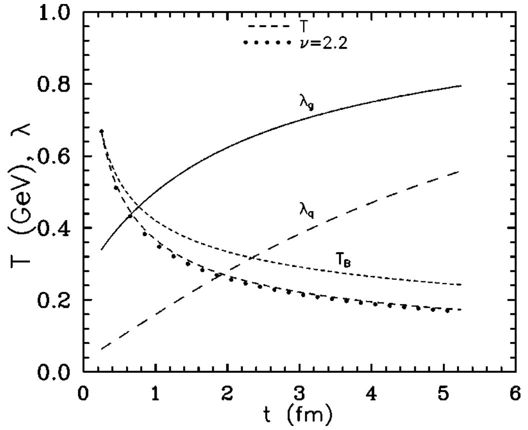

FIG. 2. The temperature T and fugacity λ as functions of time t. The description of the various curves are given in the text.

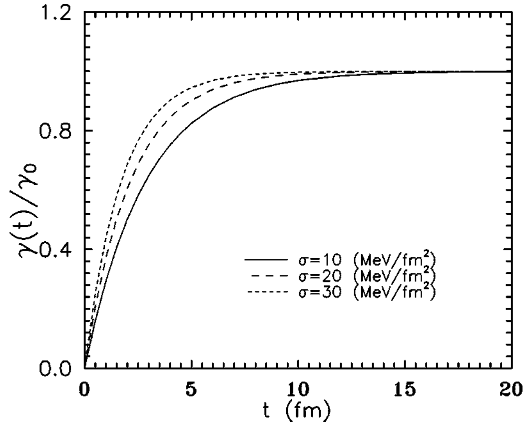

FIG. 4. The ratio $\gamma(t)/\gamma_0$ as a function of t at three typical values of σ for $A=1$.

tions at RHIC energy ($\lambda_{g0}=0.34$, $\lambda_{q0}=0.064$, $t_0=0.25$ fm, and $T_0=0.668$ GeV). The dotted curve (marked as T_B) shows the cooling rate as a function of time which obeys Bjorken's scaling ($T^3t=$const) corresponding to the case of an equilibrated plasma ($\lambda_g=\lambda_q=1.0$). In case of a chemically unsaturated plasma for which the values of initial fugacities are much less than unity, the hydrodynamical expansion of the plasma proceeds along with chemical equilibration. As a result, both λ_g and λ_q increase with time, and the temperature (shown by dashed curve) drops at a faster rate as compared to Bjorken's scaling. The solid circles show the temperature given by ($T^\nu t=$const for $\nu=2.2$). In this work, since we are interested only in the cooling rate, we skip the details of the calculation, and parametrize the cooling rate in terms of ν in the range $T_1\leqslant T\leqslant T_c$ (i.e., $T^\nu t=$const). In Table I, ν has been listed for two sets of initial conditions obtained using HIJING and SSPM models at RHIC and LHC energies. Note that $\nu<3$ implies a faster cooling. Figure 3 shows the plot of Δt as a function of σ as obtained from Eq. (16) for different ν values. The time Δt depends on the initial values of the temperature T_0, formation time t_0, and cooling rate ν. However, except for the SSPM initial conditions at LHC energies, values of Δt obtained with other initial conditions have nearly similar values.

Next we proceed to estimate the density of subcritical hadron bubbles built up at $t=\Delta t$. Figure 4 shows $\gamma(t)/\gamma_0$ as a function of t at three different σ values. The equilibration rate of subcritical hadron bubbles of a given radius depends on the ratio Γ/γ_0. Although both Γ and γ_0 are larger for weaker transitions, their ratio decreases with decreasing σ. Therefore, as can be seen, equilibration is faster for a stronger transition as compared to the weak one.

Figure 5 shows the fraction of the density built up at time $t=\Delta t$ as a function of σ with different initial conditions. Although the equilibrium density distribution of subcritical hadron bubbles increases with decreasing σ, the time Δt decreases with decreasing σ. As a result of these two competing effects, γ at $t=\Delta t$ shows a peak at around $\sigma\approx 20$ MeV/fm^2. The equilibrium fraction γ_0 depends on the ratio A/v, which increases due either to an increase in A or a decrease in v. However, the variation in A and v act differently on q_0 as the nucleation rate Γ depends only on A. Therefore, we study the effect of A and v on γ_0 and γ separately. Figure 6(a) shows the plot of γ_0 (upper curves) and $\gamma(t)$ (lower curves) as a function of σ at $A=5$, 10, and 20, respectively. Other parameters are $v=1/\sqrt{3}$, $T_c=160$ MeV, and $\xi=0.5$ fm. As expected, γ_0 goes up as A increases. The increase in γ_0 for A from 5 to 20 is about 1.5 to 2 times, but

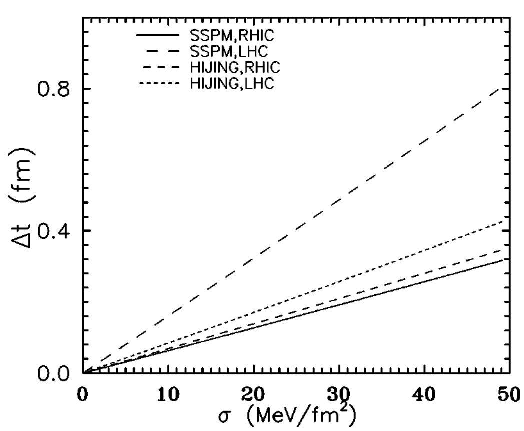

FIG. 3. Δt as a function of σ for various initial conditions as shown in Table I.

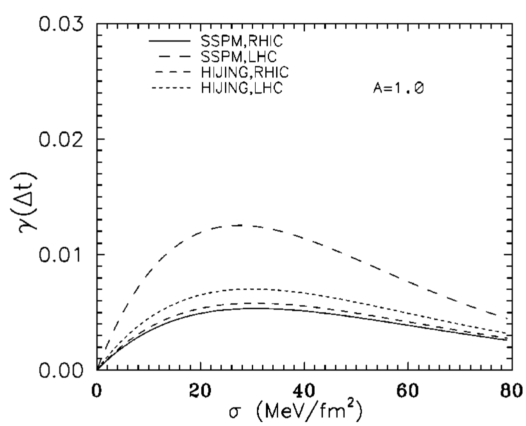

FIG. 5. The fraction γ at $t=\Delta t$ as a function of σ at $A=1$ and $v=0.577$.

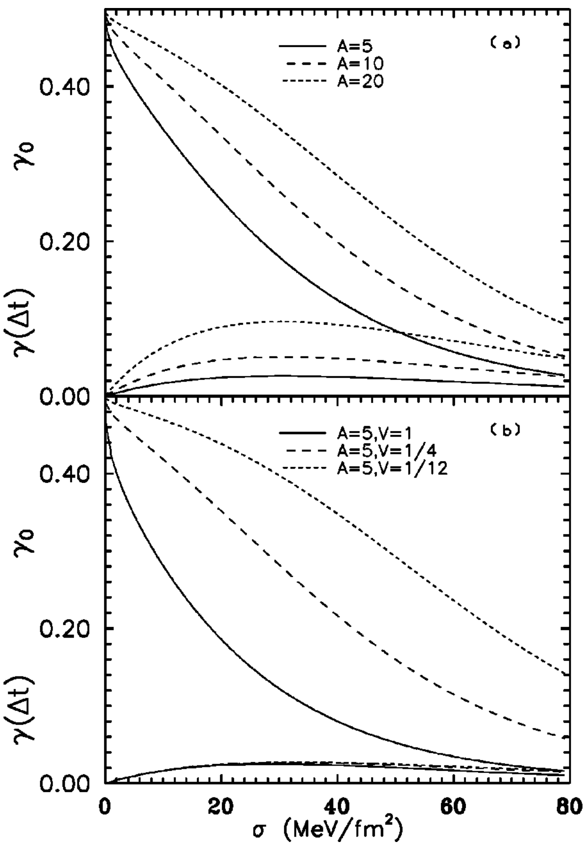

FIG. 6. (a) The fractions γ_0 (upper curve) and γ at $t=\Delta t$ (lower curve) as functions of σ at $A=5,10,20$, and $v=0.577$. (b) Same as above at $A=5$, but for different v values with SSPM initial conditions at RHIC energy.

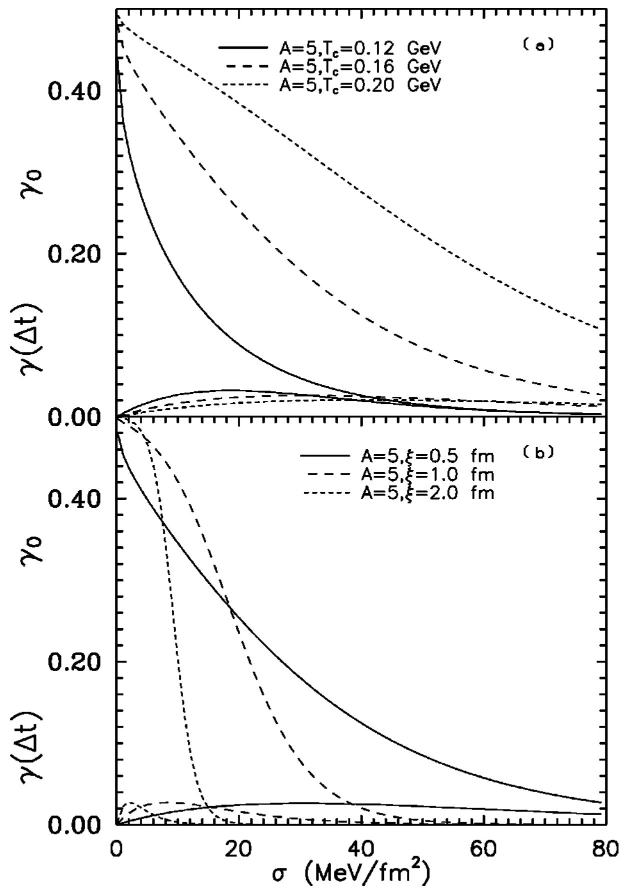

FIG. 7. (a) The fractions γ_0 (upper curve) and γ at $t=\Delta t$ (lower curve) as functions of σ for different values of T_c at $A=5$ and $v=0.577$. (b) Same as above at $A=5$, but for different ξ_c values with SSPM initial conditions at RHIC energy.

the nucleation rate Γ goes up by a factor of 4. Therefore, the ratio Γ/γ_0 also goes up, resulting in a faster equilibrium. The net consequence is both γ_0 and $\gamma(t)$ go up with increasing A. For the calculation of $\gamma(t)$, we have used SSPM and RHIC initial conditions. Further, we would like to mention here that, although we have varied A up to 20, the value of A more than unity is unrealistic. A recent work by us [21], as well as studies in Ref. [22] suggested $A \ll 1$. However, the ratio A/v can also go up with a decrease in v, which we study in Fig. 6(b). Figure 6(b) shows γ_0 and γ for $v=c=1$ (upper limit), 1/4, and 1/12. This corresponds to A/v ratios of 5, 20, and 60, respectively. Therefore, γ_0 goes up with decreasing v, as expected. Since A is fixed, Γ does not change, but q_0 decreases with increasing γ_0, resulting in slower equilibration. As a result, $\gamma(t)$ does not build up at all. It is also interesting to note that $\gamma(t)$ is not affected much by the choice of v, although γ_0 has a strong dependence on it. $\gamma(t)$ only depends on parameter A. This aspect is interesting.

From the above studies (Figs. 5 and 6), we can conclude that the fraction in the range $2\ \mathrm{MeV/fm}^2 \leqslant \sigma \leqslant 10\ \mathrm{MeV/fm}^2$ does not build up to a significant level due to the rapid cooling of the plasma, although the equilibrium concentration is fairly large. It may be mentioned here that we have considered expansion only in $1+1$ dimensions. Inclusion of transverse expansion, significant at RHIC and LHC energies, will accelerate the cooling rate further, reducing the amount of phase mixing considerably. Since phase mixing at $T=T_c$ is negligible, the plasma will supercool and the phase transition may proceed by the nucleation of critical-size hadron bubbles within a (nearly) homogeneous background of the metastable QGP phase.

We have also studied the effect of other parameters like T_c and ξ on γ. Figure 7(a) shows the plots for various T_c values at $A=5$. The nucleation rate decreases with decreasing T_C [see Eq. (6)] resulting in a decrease in γ_0. On the other hand, a smaller T_c will result in larger Δt, which may increase $\gamma(t)$. However, as shown in Fig. 7(a), the variation in $\gamma(t)$ with T_c is not very significant, although γ_0 depends on it. Similarly, Fig. 7(b) shows the plots at various ξ (0.5, 1.0, and 2.0). Increasing ξ suppresses γ_0 and $\gamma(t)$, particularly when the transition is strong. Therefore, the effect of other parameters like v, T_c, and ξ on γ are not very significant to promote phase mixing. The prefactor A is the only sensitive parameter on which $\gamma(\Delta t)$ depends. While the choice of $A \approx 1$ is quite reasonable [19], we also varied A from 1 to 20, and did not find significant phase mixing particularly when σ is small.

IV. CONCLUSION

In conclusion, we have studied the effect of phase mixing promoted by thermal subcritical hadron bubbles during a first-order quark-hadron phase transition, as predicted to occur during heavy-ion collisions. Although the equilibrium density distribution of these subcritical bubbles can be quite large, their equilibration time scale is larger than the cooling time scale for the QGP. As a consequence, for RHIC and LHC energies, they will not build up to a level capable of modifying the predictions from homogeneous nucleation theory. The phase transition may proceed either through the nucleation of critical size hadron bubbles in a (nearly) homogeneous background of the supercooled quark-gluon plasma or through spinodal decomposition if nucleation rate is not significant [23]. This situation is to be contrasted with the cosmological quark-hadron transition, where substantial phase mixing may occur, altering the dynamics of the phase transition. We would also like to add here that even though our calculations rule out the role of subcritical bubbles, it is possible that impurities may decrease the decay time scale and that no real supercooling will be measured, as is the case with many condensed-matter systems. The question, however, remains as to what these impurities, if any, might be in this context. One possibility—ruled out in this work—-is that the subcritical bubbles, being seeds for nucleation, may act as impurities [24]. However, other possibilities, such as the presence of condensates, may exist, and should be considered in the near future. If there is supercooling there will be an extra entropy production which will reflect on the final hadron multiplicities. In this case, subcritical bubbles are not present, or are irrelevant. On the other hand, if the transition is known to be first order and no extra entropy is observed, subcritical bubbles (or unknown impurities) do play a role.

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