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Slow dynamics of nonequilibrium density fluctuations in hard-sphere suspensions

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The coupled diffusion equations recently proposed for concentrated hard-sphere suspensions are numerically solved to investigate the dynamics of density fluctuations around time-dependent nonequilibrium (spatially inhomogeneous) states. As the volume fraction of spheres \( \phi \) approaches the critical value \( \phi_c \) from below, the self-intermediate scattering function \( F_2(k,t) \) is shown to obey two different slow relaxations whose time scales \( t_\beta \) and \( t_\alpha \) diverge as the separation parameter \( \sigma = (\phi - \phi_c)/\phi_c \) approaches zero: \( t_\beta \sim |\sigma|^{-\beta} \) and \( t_\alpha \sim |\sigma|^{-\alpha} \), where \( \phi_c = (4/3)/(7 \ln 3 - 8 \ln 2 + 2) \). Thus, the importance of nonequilibrium effects on slow dynamics is stressed from a unifying viewpoint.

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Recent experimental works [1–3] show that concentrated hard-sphere suspensions also exhibit a transition from a fluid phase to a glass phase, similar to that in supercooled liquids. Many attempts to understand the dynamics of suspensions approaching the glass transition have been made by employing the mode-coupling theory (MCT) [4,5] for the dynamics of supercooled fluids. The most striking feature of MCT is the prediction of two different slow relaxations of density fluctuations, the so-called \( \beta \) and \( \alpha \) relaxations, whose time scales \( t_\beta \) and \( t_\alpha \) are singular as \( t_\beta \sim |1-\phi/\phi_c|^{-\beta} \) and \( t_\alpha \sim |1-\phi/\phi_c|^{-\alpha} \), where \( \phi_c \) is a critical packing fraction, and \( \beta \) and \( \alpha \) are exponents to be determined. In concentrated colloidal suspensions [2–4], MCT predicts \( \beta = 1.66 \) and \( \alpha = 2.58 \). Thus, MCT has stimulated much of the recent experimental, computational and theoretical works on colloidal suspensions. In this paper, we present a theoretical approach different from MCT in the following three basic view points. First, MCT has been applied mainly to equilibrium systems. On the other hand, the present theory deals with a nonequilibrium system and starts with the nonlinear deterministic diffusion equation for the average number density \( n(x,t) \), which was recently derived by Tokuyama and Oppenheim on the time scale much longer than the Brownian relaxation time \( t_B \) [6]. This is because most experimental measurements are, in general, done in quenched metastable fluid states prior to crystallization where the nonequilibrium effects may change the behavior of relaxation processes. The deterministic equation for \( n(x,t) \) then describes the nonequilibrium transitional behavior from a nonequilibrium initial state with \( n(x,0) = n_0 \), where \( n_0 = N/V \) is the equilibrium number density, \( N \) and \( V \) being the total number of Brownian particles and the total volume of the system, respectively. Second, MCT assumes that the density fluctuations obey the nonlinear stochastic equations for the density fluctuations \( \delta n(x,t) \). On the other hand, the present theory starts with the linear stochastic diffusion equation for the density fluctuations \( \delta n(x,t) \) recently pro-

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\[
\frac{\partial}{\partial t} n_k(t) = -k^2 D^L_\phi(\phi)n_k(t) - D^S_\phi(\phi) \sum_q \mathbf{k} \cdot \mathbf{q} M_{k-q}(t)n_q(t),
\]

\[
\frac{\partial}{\partial t} F_\phi(\mathbf{k},t) = -k^2 D^L_\phi(\phi) F_\phi(\mathbf{k},t) - k^2 D^S_\phi(\phi) \sum_q M_{k-q}(t) F_\phi(q,t),
\]

with the Fourier transform \(M_k(t)\) of the memory function

\[
M(z(\mathbf{x},t)) = \frac{(1-z)[\dot{D}^S_\phi(1 - \dot{\phi}^2 z) + u\{\dot{D}^S_\phi \dot{\phi}^2 z(1 + \dot{\phi} z + \sigma^2(1 - \dot{\phi}^2 z)^2\}]}{V(D^2_\phi + \sigma^2/\phi)[\dot{D}^S_\phi \dot{\phi} z + (1 - \dot{\phi}^2 z)]},
\]

where \(z(\mathbf{x},t) = n(\mathbf{x},t)/n_0\), \(\dot{D}^S_\phi = D^S_\phi/D_0\), \(\dot{\phi} = 4\pi a^3_0 n_0/3\), \(\dot{\phi} = \phi/\phi_e\), and \(\sigma = \phi - 1\). \(D_0\) and \(a_0\) being the single-particle diffusion coefficient and the particle radius, respectively. Here \(D^S_\phi(\phi)\) and \(D^L_\phi(\phi)\) denote the short- and the long-time self-diffusion coefficient, respectively (see Ref. [6] for details). The coupling factor \(u = (9/32)\phi_e\) denotes the coupled effect between the many-body short-range hydrodynamic interactions and the many-body direct interactions among particles. The long-time self-diffusion coefficient \(D^S_\phi\) and the memory function \(M(z)\) can be written, near \(\phi_e\), as

\[
D^S_\phi \sim D_0(1 - u)\sigma^2 + O(\sigma^3),
\]

\[
M(z) \sim 2\sigma(1 - z)\{1 - u/\dot{D}^S_\phi\} + O(\sigma^2(1 - z)^2).
\]

We should mention here that these properties result from the correlation effects due to the many-body long-range hydrodynamic interactions between particles [6], leading to the two different slow relaxations [7,8].

Equation (1) is the nonlinear diffusion equation for \(n_k(t)\) and describes a transient behavior of the average number density \(n_k(t)\) from a spatially inhomogeneous, nonequilibrium initial state described by \(n_q(0)\) to the spatially homogeneous, equilibrium state given by \(n_0\delta_{k,0}\) under the conservation law \(n_q(t) = n_0\). We should note here that the memory function \(M(z(\mathbf{x},t))\) describes the nonequilibrium effect. In fact, it becomes zero in the equilibrium state where \(z(\mathbf{x},t) = 1\). Thus, the diffusion field (or the relaxation time) changes in space and time if the initial state of the system is nonequilibrium.

Equation (2) is the linear diffusion equation for \(F_\phi(\mathbf{k},t)\) which describes a linear relaxation of the self-diffusion process around the time-dependent nonequilibrium states determined by Eq. (1). Solving it formally, we obtain

\[
F_\phi(\mathbf{k},t) = f(\mathbf{k},t;\phi)\exp(-k^2 D^L_\phi t)
\]

with the memory part

\[
f(\mathbf{k},t;\phi) = \left[\exp\{-m(t;\phi)\}\right]_{kk},
\]

where \(m(t;\phi)\) denotes the matrix whose \((\mathbf{k},\mathbf{q})\) component is given by

\[
m_{k,q}(t;\phi) = \int_0^t \exp(k^2 D^L_\phi s)[k^2 D^S_\phi M_{k-q}(s)]
\times \exp(-q^2 D^L_\phi s)\,ds.
\]

Here \(\exp_{-}\) denotes a time-ordered exponential, ordered from the left. Thus, the scattering function \(F_\phi(\mathbf{k},t)\) is factorized into a memory part, which depends on the initial conditions for \(n_k(0)\), and a long-time part, which is independent of such initial conditions.

For the short-time region of order \(t_\gamma = 2\pi/k^2 D^S_\phi\), the relaxation obeys the short-time decay \(F^S_\phi(\mathbf{k},t) = \left[\exp\{-m(0;\phi)t\}\right]_{kk}\), which is mainly governed by the

![FIG. 1. Self-intermediate scattering function \(F_\phi(\mathbf{k},t)\) vs \(\log(t/t_0)\) at (a) \(z_0=0.8\) and (b) \(z_0=0.5\) for different volume fractions (from left to right): 0.543, 0.566, 0.569, and 0.571, where \(ka_0=2.8\) and \(t_0=a_0^2/D_0\). The symbols indicate the time scales: \(t_\gamma\) (○), \(t_\mu\) (○), and \(t_\alpha\) (●).]
FIG. 2. Log-log plot of self-part of dynamic susceptibility $\chi_S^s(k,\omega)$ vs $\omega_0 t$ for different volume fractions (from left to right): 0.571, 0.569, 0.566, and 0.543. Details are the same as in Fig. 1. The symbols indicate the frequencies: $\omega_\gamma$ (●), $\omega_\beta$ (○), and $\omega_\alpha$ (▲).

short-time self-diffusion coefficient $D_S^s$. On the other hand, for the long-time region of order $t_a = 2\pi/k^2 D_S^s$, we have $n(x,t) = n_0$ and $M(z(x,t)) = 0$. Hence, the relaxation is described by the long-time decay $F_S^z(k,t) = \exp(-k^2 D_S^s t)$. Thus, there exists a crossover from the short-time relaxation process to the long-time relaxation process.

For the intermediate-time region $t_e < t < t_a$, the dynamical behavior of $F_S(k,t)$ becomes more complicated because of the memory function $M(z(x,t))$, which causes a structural arrest. In fact, near $\phi_x$, the number density $n(x,t)$ is expected to become almost $n_0$ after some time $t_e$ between $t_\gamma$ and $t_a$ [7,8]. Since $M(z(x,t))$ reduces to zero for $t \equiv t_e$, Eq. (5) can be approximately written as $F_S(k,t) = f(k,t_e;\phi)\exp(-k^2 D_S^s t)$. For intermediate times $t_e < t \ll t_a$, therefore, $F_S(k,t)$ becomes nearly constant for a while, since $k^2 D_S^s t \ll 1$. This continues up to the time $t_\beta$ where the term $k^2 D_S^s t$ becomes the same order as the term $m(t_e;\phi)$. On the time scale of order $t_\beta$, $F_S(k,t)$ then starts to decay again, obeying $F_S^{L}(k,t)$. Thus, $t_\beta$ denotes the crossover time from structural arrest to long-time decay and is found, using Eq. (4), as $t_\beta \sim |\sigma|^{-1}, t_e \ll t_\beta \ll t_a$. Near $\phi_x$, the nonequilibrium effect is thus expected to cause two different slow relaxations, the so-called $\beta$ and $\alpha$ relaxations, with the time scales $t_\beta \sim |\sigma|^{-1}$ and $t_a \sim |\sigma|^{-2}$.

We now solve the coupled diffusion equations (1) and (2) self-consistently under appropriate initial conditions and investigate the self-intermediate scattering function $F_S(k,t)$ and the self-part of the dynamic susceptibility given by $\chi_S^s(k,\omega) = \omega_0 \int_0^\infty \sin(\omega t)F_S(k,t)dt$ numerically. To integrate those equations, we employ the forward Euler difference scheme with the time step 0.01$D_0^s/0.01$ and the lattice spacing 0.5$a_0$ in the volume $(128a_0)^3$ of the simulation system. As the initial conditions, we fix the values of the particle volume fraction $\phi$ and the reduced initial number density $z(x,0) = n(x,0)/n_0$. In order to distinguish the initial states from each other qualitatively, it is convenient to introduce a parameter $z_0$, which measures how close the initial state of the system is to the equilibrium state and is given by

$$z_0 = 1 - \frac{1}{V} \int dx |1 - z(x,0)|,$$

where $0 \leq z_0 \leq 1$, and $z_0 = 1$ in equilibrium. Then, the initial value $z(x,0)$ is chosen at each position $x$ from a random number with a Gaussian distribution, which is characterized by a mean value 1 and a standard deviation $s$. Here the standard deviation $s$ is adjusted so as to satisfy Eq. (8) for a given value $z_0$. In the following, we thus discuss the numerical results for two typical states: (a) a near-equilibrium state with $z_0 = 0.8$, where $s = 0.235$, and (b) a nonequilibrium state with $z_0 = 0.5$, where $s = 0.591$.

In Figs. 1(a) and 1(b) we show the time evolution of $F_S(k,t)$ at (a) $z_0 = 0.8$ and (b) $z = 0.5$ for various volume fractions where $ka_0 = 2.8$. For small volume fractions where $\phi_\beta \equiv \phi_x$, the scattering function decays quickly to zero. As the volume fraction increases and $t_\beta$ becomes larger than $t_\gamma$, the shape of the scattering functions becomes very sensitive to the volume fraction, forming a shoulder, which becomes at $\phi_x$ a plateau with the height 2.8. There are two peaks and one minimum in $\chi_S^s(k,\omega)$. The first peak is the so-called $\alpha$ peak at $\omega = \omega_\alpha$ in the lower-frequency region and describes the long-time relaxation process on the time scale of order $t_\beta$. The second peak is the so-called $\beta$ peak at $\omega = \omega_\beta$ in the higher-frequency region and describes the short-time relaxation process on the time scale of order $t_\gamma$. The minimum at the frequency $\omega = \omega_\gamma$ corresponds to the crossover point in $F_S(k,t)$ at the time $t_\gamma$, where $\omega_\alpha < \omega_\beta < \omega_\gamma$. Then, the characteristic frequencies $\omega_\alpha, \omega_\beta,$ and $\omega_\gamma$ are related to the

<table>
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<tr>
<th>$z_0$</th>
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<td>0.42</td>
<td>0.46</td>
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<tr>
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<td>0.31</td>
<td>0.66</td>
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<td>0.74</td>
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TABLE I. Time exponents $b_0$ and $b$ for different values $z_0$ and $\phi$ at $ka_0 = 2.8$. 

In order to see the crossover behavior in the intermediate-time region more clearly, we also calculate the self-part of the dynamic susceptibility $\chi_S^s(k,\omega)$. In Figs. 2(a) and 2(b) we plot it at (a) $z_0 = 0.8$ and (b) $z_0 = 0.5$ for different volume fractions where $ka_0 = 2.8$. There are two peaks and one minimum in $\chi_S^s(k,\omega)$. The first peak is the so-called $\alpha$ peak at $\omega = \omega_\alpha$ in the lower-frequency region and describes the long-time relaxation process on the time scale of order $t_\beta$. The second peak is the so-called $\beta$ peak at $\omega = \omega_\beta$ in the higher-frequency region and describes the short-time relaxation process on the time scale of order $t_\gamma$. The minimum at the frequency $\omega = \omega_\gamma$ corresponds to the crossover point in $F_S(k,t)$ at the time $t_\gamma$, where $\omega_\alpha < \omega_\beta < \omega_\gamma$. Then, the characteristic frequencies $\omega_\alpha, \omega_\beta,$ and $\omega_\gamma$ are related to the
characteristic times $t_\alpha$, $t_\beta$, and $t_\gamma$ through $\omega_0 t_i = 2\pi$ ($i = \alpha, \beta, \gamma$), and are shown to be scaled with the separation parameter $\sigma$ as

$$\omega_\alpha \sim |\sigma|^{\alpha}, \quad \omega_\beta \sim |\sigma|^{\beta}, \quad \omega_\gamma \sim |\sigma|^{\gamma},$$

where $\alpha = 2.03$ (a) and 1.99 (b), and $\beta = 0.97$ (a) and 1.02 (b). Thus, the analytical values $\alpha = 2$ and $\beta = 1$ predicted previously in Ref. [8] are numerically verified to hold.

From Figs. 1 and 2, we see that the plateau height in the near-equilibrium state (a) is higher than that in the nonequilibrium state (b), and the $\alpha$ peak in (a) is higher than that in (b), while the $\beta$ peak in (a) is lower than that in (b). This is because the memory function $M(z(x,t))$ in (b) is much larger than that in (a) since in (b) it takes a longer time for $n(x,t)$ to become $n_0$ than in (a). This also shows that the crossover in (b) occurs more slowly than in (a). In fact, from Fig. 2, $\omega_\beta$ in (b) is smaller than that in (a). Thus, the plateau height and the peak heights turn out to depend on how far from equilibrium the initial state is.

In order to see the time dependence of $F_S(k,t)$ in terms of a power-law formula in the intermediate-time region, we also calculate the logarithmic derivative given by $\varphi = \partial \log[f_k^b - F_S(k,t)]/\partial \log t$. Then, the effective exponent $\varphi$ reveals two fairly plateau regions: $\varphi = b_0(\sigma, z_0)$ for $t_\gamma < t < t_\beta$ and $\varphi = b(\sigma, z_0)$ for $t_\beta < t < t_\alpha$, where the exponents $b_0$ and $b$ are listed in Table I. For intermediate times, therefore, the relaxation proceeds in the following two time stages in the fluid state ($\sigma < 0$): one is the so-called $\beta$-relaxation stage for $t_\beta < t < t_\alpha$ ($\omega_\beta \ll \omega \ll \omega_\alpha$), where the power laws hold

$$F_S^b(k,t) = F^b_0 - A_\beta(t/t_\beta)^{b_0}, \quad \chi^b_S(k,\omega) = A^b_\beta(\omega/\omega_\beta)^{b_0},$$

where $A_\beta$ and $A^b_\beta$ are weak functions of $k$ and $\sigma$. The other is the so-called $\alpha$-relaxation stage for $t_\alpha < t < t_\gamma$ ($\omega_\alpha \ll \omega \ll \omega_\gamma$), where the power laws hold

$$F_S^\alpha(k,t) = F^\alpha_0 - B_\alpha(t/t_\alpha)^{b}, \quad \chi^\alpha_S(k,\omega) = B^\alpha_\alpha(\omega/\omega_\alpha)^{b},$$

where $B_\alpha$ and $B^\alpha_\alpha$ are weak functions of $k$ and $\sigma$.

In conclusion, by solving the coupled diffusion equations numerically, we have shown how the initial inhomogeneities in space change the qualitative behavior of the relaxation processes near $\phi_0$, leading to the two different slow relaxations. Such inhomogeneities start to become smooth, obeying the nonlinear deterministic equation (1). For regions where the number density $n(x,t)$ is larger than the critical value $n_\lambda = 3\phi_0/(4 \pi a_0^3)$, however, the smoothing process is slowed down, leading to a structural arrest. Thus, the density fluctuations undergo a slow relaxation, although they are governed by the linear stochastic equation (2). The detailed analysis will be discussed elsewhere.

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