Viscosity of a Strongly Coupled Dust Component in a Weakly Ionized Plasma

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(Received 7 March 2012; published 2 August 2012)

An experimental study of the kinematic viscosity has been carried out for dust particles of size 0.95 and 3.92 μm, in weakly ionized plasma over a wide range of dust coupling parameters. Measurements of viscosity for weakly correlated dusty-plasma systems are presented for the first time. An approximation for the estimation of viscosity constants is proposed. The measured viscosity constants are compared with theoretical estimates and numerical data.

DOI: 10.1103/PhysRevLett.109.055002 PACS numbers: 52.27.Lw, 52.27.Gr, 52.35.Fp

Transport phenomena in dissipative systems of interacting particles are of significant interest in various fields of science and technology (plasma physics, medical industry, physics of polymers, etc.) [1–7]. In particular, viscosity is a fundamental parameter that reflects the nature of the interparticle potentials and the phase state of the system [7–11].

There has been much recent work on the determination of viscosity minimum in classical systems with strongly interacting particles [12–14]. In Ref [13] it has been assumed that the shear viscosity $\eta = \rho\nu$ in classical strongly coupled systems may be so low that it is effectively negligible. Here ν is the kinematic viscosity, $\rho = nM$ is the mass density, n is the particle density, and M is the particle mass. Nevertheless, a string theory (AdS/CFT, anti–de Sitter/conformal field theory) predicts the existence of a lower limit for the ratio for viscosity to entropy density [12,13], which (for classical systems) may be presented in the form $\nu/s^* \geq A_{\lim} \cong 6.08 \times 10^{-13}$ K s, where $s^* = S/M$ is the specific entropy. But the theory and experiments show that for ordinary molecular fluids the values of the ν/s^* ratio lie well above the $A_{\lim}$ limit [13,14].

It is well known that for most ordinary single-atomic molecular fluids the viscosity coefficients (η and ν) decrease with decreasing temperature T in the gaseous state but increase with decreasing T in the liquid state. Thus a minimal value of viscosity is usually observed around a critical point of the medium [15,16]. Numerical simulations for the frictionless one-component plasma (OCP) and Yukawa systems with $\kappa = l_p/\lambda < 6$ predict a minimum of the shear/kinematic viscosity at $\Gamma/\Gamma_m \approx 0.11$ [11,17–20]; here, $\Gamma = (eZ)^2/(T l_p)$ is the Coulomb coupling parameter, $\Gamma_m \cong \Gamma_m^* \exp(\kappa)/(1 + \kappa + \kappa^2/2)$ is the value of Γ at a melting line [5–7], eZ is the particle charge, l_p is the mean interparticle distance, λ is the screening radius, and $\Gamma_m^* \cong 106$ for three-dimensional systems [5–7,17–19] and $\Gamma_m^* \cong 70$ for the two-dimensional case [11,20].

A dusty plasma is an ionized gas containing micron-sized charged particles. A dusty plasma is ubiquitous in nature (in space, in upper layers of the atmosphere, etc.) and is produced in many technological processes [5–7]. Laboratory experiments on dusty plasma, which are carried out in various types of partially ionized gas discharges, provide a good experimental model for studying nonideal systems.

The first results on the measurements of viscosity constants in dusty plasma were reported in Refs. [9,10]. In the Ref. [9] measurements of the shear viscosity of a monolayer dust component, within a capacitive radio frequency (rf) discharge plasma were presented. The subsequent analysis of measured constants showed essential differences between the experimental data [9] and the results of simulations of viscosity for equilibrium two-dimensional systems [11]. Viscosity measurements for three-dimensional multilayer dust structures were described in Ref. [10]. However, these measurements were performed only for strongly correlated dust systems ($\Gamma/\Gamma_m > 0.35$) and do not allow a detailed comparison of experiments with the existing results of numerical simulations. Additionally, all of the existing numerical results were obtained for the case of frictionless systems, and none of these references discuss the possible influence of dissipation (friction) on dust viscosity.

However, the effect of the friction on the viscous properties of dusty plasma was studied and/or discussed in several recent papers [21–27]. It was found that with increasing friction the viscosity constants decrease at low Γ and increase at high Γ [21,22,25]. Nevertheless, the temperature dependence of viscosity (including the existence, position, and value of a minimum) is still an open question in dissipative systems.

Here we present the results of an experimental study of the viscosity constants for strongly coupled dust in weakly ionized gas discharge plasma, where the collisions between the dust particles and atoms or molecules of surrounding neutral gas exert a considerable influence on the transport properties of the systems. For analysis of this influence we will use the scaling parameter $\xi = \omega^*/\nu_{\mathrm{fr}}$ and the effective coupling parameter $\Gamma^* = \pi(\omega^* l_p)^2/T$, where ν_{fr} is the friction coefficient due to the dust-neutral collisions, $\omega^* = [U''/(2\pi M)]^{1/2}$ is the characteristic dust-dust frequency, and U'' is the second derivative of a pair

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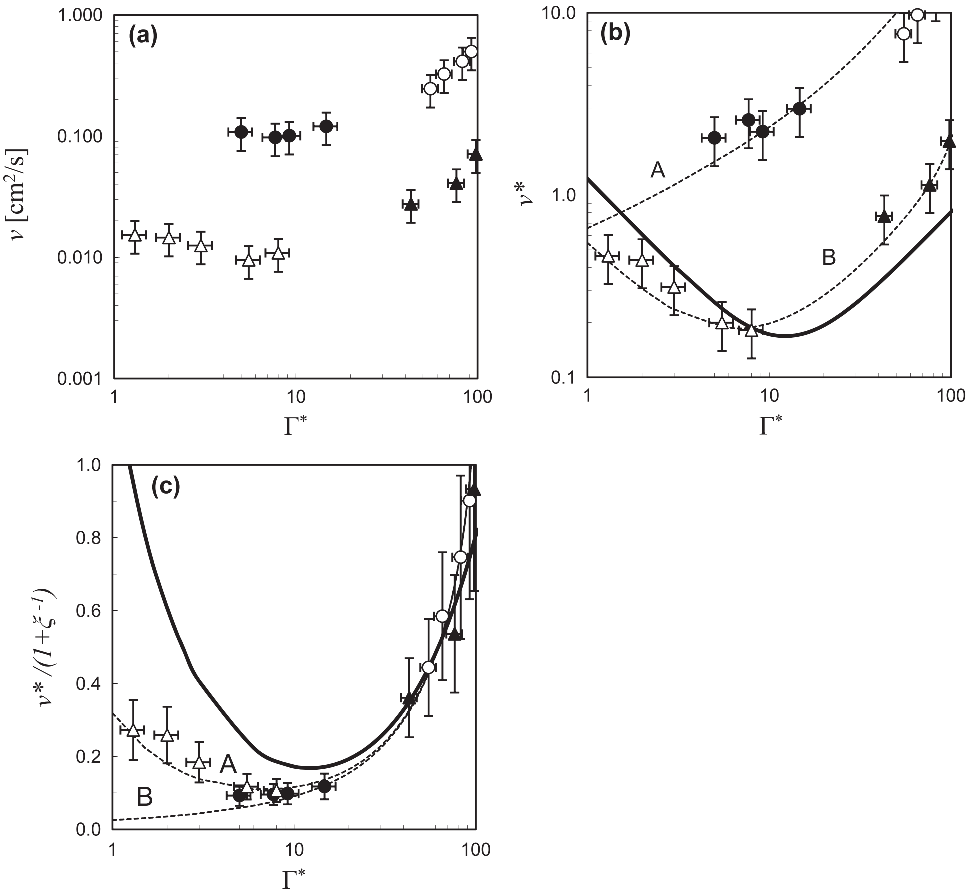

FIG. 1. The values of ν (a), ν^* (b), and $\nu^*(1+\xi^{-1})$ (c) vs Γ^* for various experiments: (●) $a = 0.95$ μm ($P = 35$ Pa, $W = 15$–22 W); (○) $a = 0.95$ μm ($P = 25$ Pa, $W = 6$–13 W); (▲) $a = 3.92$ μm ($P = 9$ Pa, $W = 8$–13 W); (△) $a = 3.92$ μm ($P = 5$ Pa, $W = 3.8$–6 W). Continuous curve is the averaged data of numerical simulations [17–19]. Dotted curves are Eq. (1): (A) $\xi = 0.04$, (B) $\xi = 1.4$.

potential energy at the particle separation l_p. We note here that the value of ω^* may be easily determined in experiments by the various diagnostic techniques [28,29] and that the Γ^* value is equal to Γ^*_m at the melting line of the system [5–7,20].

The experiments were performed in a rf discharge in argon, at pressure P from 5 to 35 Pa, with discharge power W from 2 to 25 W. The dust particles were formaldehyde melamine, of density $\rho_d \approx 1.5$ g cm^{-3}, with radius a either 0.95 or 3.92 μm. The scheme of the experiment was detailed in Refs. [10,21]. The observed dust cloud consisted of several ($\sim$ 15–20) dust layers. The radiation pressure of an Ar^+ laser was used to drive a laminar flow of dust particles through an undisturbed area of dusty plasma. The Ar^+ laser beam was preexpanded by a telescope, and the central part of this beam was cut out by a diaphragm of diameter $\sim$0.3 cm. The Ar^+ laser power W_L was varied from $\sim$5 to 150 mW. For diagnostics, a plane beam of a He-Ne laser (laser sheet $\sim$250 μm) illuminated the horizontal monolayer of dust particles. This monolayer was videotaped using a high-speed complementary metal-oxide-semiconductor camera (frame frequency 500 s^{-1}). The video records were analyzed using special computer codes. The coordinates, trajectories, and velocities of dust particles were obtained. Then the pair correlation functions $g(l)$, the mean separation l_p, the temperature T, and the mass-transfer functions $[D(t) = \langle \Delta l^2 \rangle/(4t)$, where $\langle \Delta l^2 \rangle$ is the mean-square displacement] for dust particles in an undisturbed area of dusty plasma were obtained. For diagnostics of dust parameters (Γ^* and $\xi = \omega^*/\nu_{\mathrm{fr}}$), the technique based on analysis of the mass-transfer processes for a small observation time [29] was used. Under experimental conditions the Γ^* values were varied from $\sim$1 to $\sim$100, the mean interparticle distances, l_p, was about 550 $\pm$ 100 μm, and the ξ parameters were varied within the limits $\sim$1–1.5 for particles with $a = 3.92$ μm, and $\xi \sim 0.04$–0.06 for particles with $a = 0.95$ μm.

Estimates of the viscosity constant ν were obtained from the Navier-Stokes equation $[\nu \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial V_y(r)}{\partial r} = \nu_{\mathrm{fr}} V_y(r) - F(r)/M$, where $F(r)$ is the radial distribution of laser radiation force], by fitting the experimental laminar flow velocity profile $V_y = V(y)$ of macroparticles through an undisturbed area of dusty plasma, under exposure to the Ar^+ laser beam.

This technique for a determination of viscosity and its specific conditions were detailed in [10,21].

The kinematic viscosity $\nu(\Gamma^*)$, its normalized value $\nu^* = \nu/(\omega^* l_p^2)$, and $\nu^*(1 + \xi^{-1})$ are plotted against Γ^* for various experiments, in Figs. 1(a)–1(c), respectively. Comparisons of the measured viscosity constants with the averaged data of numerical simulations for three-dimensional frictionless OCP [18,19] and Yukawa [17] systems are shown in Figs. 1(b) and 1(c). (The minimum of the viscosity constant, $\nu^* \approx 0.18$, in the above-mentioned numerical simulations is observed at $\Gamma^* = 12$ [17–19]).

We now summarize the conclusions to be drawn from our measurements, focusing on the position and value of the viscosity minimum, the influence of friction on viscosity constants, and the minimal ratio of viscosity to entropy density.

Figures 1(a) and 1(b) clearly show that the measured values $\nu(\Gamma^*)$ vary by more than an order of magnitude for various experimental conditions, i.e., for different Γ^* and $\xi \propto 1/\nu_{\mathrm{fr}}$. For the big particles ($a \approx 3.92$ μm, $\xi \sim 1$–1.5), a minimum of the viscosity constant (where its temperature dependence varies) is observed. The experimental results differ considerably from the results of numerical simulations for frictionless systems [17–19]. However, the normalized viscosity constants $\nu^*(1 + \xi^{-1})$ in the range of $\Gamma^* =$ 10–100 are in accordance with the numerical simulation of frictionless ($\xi^{-1} = 0$) Yukawa systems; see Fig. 1(c). The last result is in agreement with the numerical simulation of strongly correlated dissipative Yukawa systems [20] and with the experimental data presented in Ref. [21].

Analytical estimates of the temperature dependence of the viscosity constants, for various values of Γ^* and ξ, can be obtained from analyses of numerical simulations of the diffusion coefficient D and the viscosity coefficient ν. The viscosity coefficient ν can be written as $\nu = \nu_{\mathrm{kin}} + \nu_{\mathrm{pot}} + \nu_{\mathrm{cross}}$ [17], where ν_{kin}, ν_{pot}, and ν_{cross} are the kinetic, potential, and cross parts of viscosity. Taking into account that the value of $\nu_{\mathrm{kin}} \cong 2D/3$ for $\Gamma^* < 30$ and that the value of $(\nu_{\mathrm{cross}} + \nu_{\mathrm{pot}})D \approx (\omega^* l_p^2)^2/(32\sqrt{\Gamma^*})$ for $90 > \Gamma^* > 1$ [17,30], we find the following approximation for $\nu^* = \nu/(\omega^* l_p^2)$:

$$\nu^* \approx 2\sqrt{\pi}D^*/(3\Gamma^*\{1 + \xi^{-1}\}) + \sqrt{\Gamma^*}(1 + \xi^{-1})/(32\sqrt{\pi}D^*). \tag{1}$$

Here, $D^* = D(\nu_{\mathrm{fr}} + \omega^*)M/T$ may be obtained by direct measurements, or from the numerical simulations, or (in the three-dimensional case) as the approximation [31]

$$D^* \cong 1 - [4\varepsilon/\{1 + \exp(\varepsilon)\} + 2\Gamma^*/\Gamma_c^*]/3. \tag{2}$$

Here, $\varepsilon = 0.5 + 2.5\Gamma^*/\Gamma_c^*$, and $\Gamma_c^* \cong 102$ is the Γ^* value at a crystallization point. The calculations of ν^* from Eqs. (1) and (2) for the various ξ parameters are presented in Fig. 2 together with the data from the frictionless ($\xi^{-1} = 0$) simulations [17–19]. Thus the viscosity constant ν increases with increasing the friction coefficient (with the ξ decreasing), and the minimal value of ν also increases and occurs at lower values of Γ^*. Our experimental data clearly agree well with these theoretical predictions [see Figs. 1(b) and 1(c)]. We can also clearly see that with increasing friction (i.e., with the ξ decreasing) the viscosity constants decrease at low Γ and increase at high Γ in accordance with the results presented in Refs. [20–22,25]; see Fig. 2.

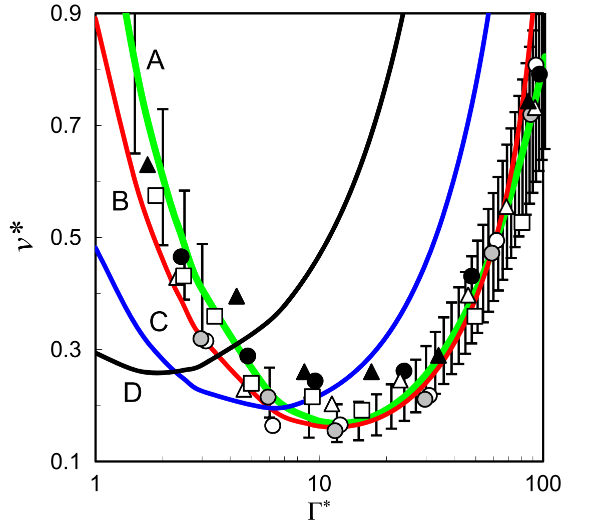

FIG. 2 (color online). The $\nu^*(\Gamma^*)$ functions for frictionless systems ($\xi \rightarrow \infty$) in OCP model: (□) [18,19], and for Yukawa systems [17]: (○) $\kappa = 0.16$; (gray ●) $\kappa = 0.81$; (●) $\kappa = 1.61$; (△) $\kappa = 3.2$; (▲) $\kappa = 4.8$. Lines are (*A*), the averaged data of numerical simulations [17–19] for the case of $\xi^{-1} = 0$ (with the relative errors of 20%), and the approximation, Eq. (1), for (*B*) $\xi^{-1} = 0$, (*C*) $\xi^{-1} = 1$ (*D*) $\xi^{-1} = 4$.

Notice that in most cases the kinematic viscosity ν of single-atomic molecular fluids is about $\sim 10^{-2}$ cm/s; i.e., ν is close to the kinematic viscosity of the dust component under conditions of weak dissipation of dust energy (with $\omega^* > \nu_{\mathrm{fr}}$, see Fig. 1(a), $a = 3.92$ μm). Nevertheless, the shear viscosity $\eta = \rho\nu$ may differ considerably, due to a difference in the density of media ($\rho = nM$), for example, for the gas and liquid state of the system due to their difference in the concentration n, or for different substances due to the difference in atomic/molecular mass M. So, for example, the mass density of liquid single-atomic metals is $\rho \sim 1$ g/cm^3 [15,16], while the mass density of the dust component in rf discharge plasma under typical conditions ($M = 10^{-12}$–10^{-9} g, $l_p \approx 500$ μm) varies from $\sim 10^{-8}$ to 10^{-5} g/cm^3. Thus the shear viscosity of the dust component of plasma is negligible with respect to the η coefficients for molecular fluids. The entropy $\{Sk_B\}$ for the ordinary molecular fluids is usually in the range from ~ 1 to ~ 10 [15,16]. Calculations of entropy for dust components under typical experimental conditions from the equations of Refs. [14,32] give $\{Sk_B\} \approx 36 \pm 10$. Thus the basic influence on the ratio of ν/s^* gives the difference in the mass of the particles M in analyzed media, and thus, the ratio $\nu/s^* = M\nu/S$ for dusty plasma is well above (more than of 10 orders) the ν/s^* value for molecular fluids.

In conclusion, an experimental study of the kinematic viscosity has been carried out for dust particles of different sizes in weakly ionized plasma. Nonmonotonic dependence (a minimum) of the viscosity constants on the dusty-plasma coupling parameter has been observed. Measurements of viscosity for weakly correlated dusty-plasma systems are presented for the first time. A decrease in viscosity constants with the temperature has been observed for small dust coupling parameters. The influence of the neutral component (friction) on the viscosity of dusty plasma has been investigated. An approximation for the viscosity constants (which is suitable for estimation of its minimum) has been proposed for nonideal dissipative systems.

This work was partially supported by the Russian Foundation for Basic Research (Projects No. 10-08-00389 and No. 10-02-1428), by the Research Program of the Presidium of the Russian Academy of Sciences "Matter under High Energy Densities." The authors are grateful to Dr. Martin Lampe for helpful discussions and comments.

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