Experimental Observations of Transverse Shear Waves in Strongly Coupled Dusty Plasmas

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We report experimental observations of transverse shear waves in a three-dimensional dusty plasma that is in the strongly coupled fluid regime. These spontaneous oscillations occur when the ambient neutral pressure is reduced below a threshold value and the measured dispersion characteristics of these waves are found to be in good agreement with predictions of a viscoelastic theory of dusty plasmas.

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Dust grains suspended in a plasma medium can acquire large amounts of charge such that the parameter $\Gamma = \frac{(Z_d e)^2}{T_d a} e^{-a/\lambda_p}$ can become of order unity or larger [here $(-Z_d e)$ is the charge on the dust particle, $a \simeq (4\pi n_d/3)^{-1/3}$ is the interdust distance, T_d is the dust temperature, and λ_p is the Debye length of the background plasma]. The parameter Γ is a measure of the ratio of the average Coulomb potential energy of the dust component to its average thermal energy. When $\Gamma \geq 1$ strong correlations develop between the dust particles investing liquidlike or solidlike properties to the medium and providing the possibility of exciting new collective oscillations. For example, beyond a certain critical value of Γ, ($\Gamma > \Gamma_c$), the dust component can freeze into an ordered solid phase—the so called "plasma crystal" state—which can support a variety of dust lattice modes. Such lattice modes have been identified and studied in a number of recent experiments [1–5]. In the regime $1 \ll \Gamma < \Gamma_c$, when the system is still in the strongly coupled fluid state, the correlations lead to the development of short range order in the system which keeps decaying and reforming in time. As a result the system exhibits "memory" effects and acquires some solidlike properties—"elastic" effects—while still retaining its fluid nature and provides the novel possibility of exciting transverse shear modes in the fluid medium. The existence of such modes has been predicted in a number of recent theoretical studies [6–8]. While shear modes have been observed in numerical simulation studies of Yukawa systems [9], to the best of our knowledge there has been no experimental verification of these modes. In this Letter we report the first experimental observations of spontaneously excited transverse shear waves in a dusty plasma cloud that is in the strongly coupled fluid regime.

The experiment was carried out in the setup shown in Fig. 1. The stainless steel cylindical chamber of 95 cm length and 20 cm diam was pumped down to a base pressure of 10^{-3} mbar using a rotary pump. Argon gas was then introduced using a precision needle valve to attain an operating pressure range of 0.4 to 0.04 mbar. To begin with, a stratified glow discharge was produced by applying 500 V of electric potential between a constricted anode and the vessel wall (used as a cathode) at 1 mbar. Two cylindrical stratified double layers were observed throughout the operating pressure range of our experiment. The electric field in the double layer was used to levitate the dust particles [10–13]. The neutral pressure was slowly reduced to 0.2 mbar by reducing the leak rate of the gas and the pumping speed. Laboratory grade kaolin (hydrated aluminum silicate) particles with a size distribution in the range of 0.5 to a few microns were sprinkled in the chamber. The levitated dust particles were observed by shining a He-Ne laser (632.8 nm, 25 mW) light sheet (2 mm thick and 50 mm wide formed using a cylindrical lens). The scattered light from the dust particles was recorded using a video camera and the images were digitized with the help of a frame grabber card. The dust particle density was calculated by measuring the interparticle distances. Langmuir probe measurements of dust-free plasma were made to determine the ion density, the electron temperature, and the floating potential in the system. A stable three-dimensional dust cloud was observed above 0.25 mbar at a discharge voltage of 337 V and a discharge current of 100 mA (see Fig. 2a). The dust particles were levitated only in the lower half of the chamber confined between 12 and 15 cm from the top. The measured floating potential profile along the vertical (y) and radial (x) directions is shown in Fig. 3 and reveals the existence of a strong electric field near the cathode region of the discharge (3 cm close to the wall). The direction of the electric field (see vertical floating potential profile as given in Fig. 3) is opposed to the gravity in the region from 0 to 3 cm, whereas it is in the same direction of gravity from 12 to 15 cm. Thus the electrostatic

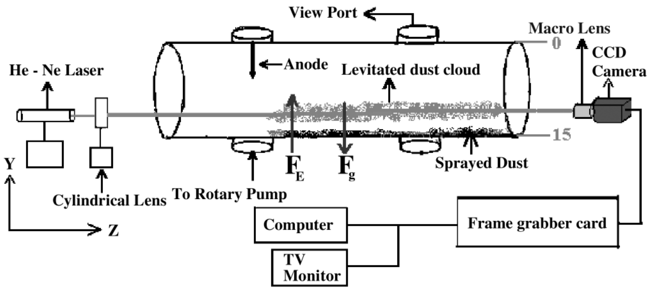

FIG. 1. Schematic representation of the experimental setup.

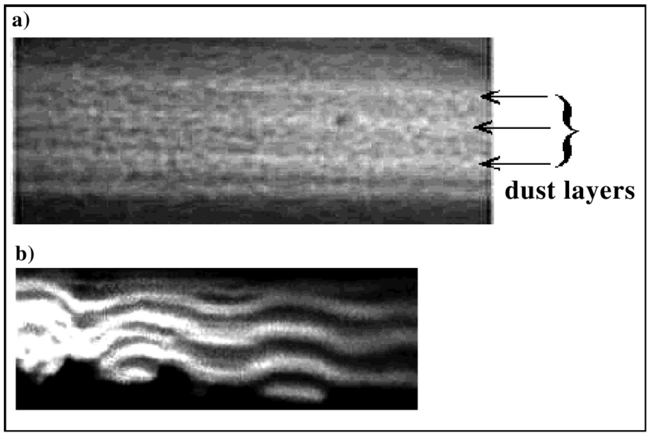

FIG. 2. (a) Stable three-dimensional dust cloud. (b) Typical shear oscillations at 0.1 mbar pressure.

force on the negatively charged dust particles is such that their levitation arising from a balance between opposing electrostatic and gravity forces can take place only in the region from 12 to 15 cm (the lower half of the chamber) and is consistent with the experimental observation. The equilibrium force balance condition in the vertical (y) direction is given by

$$eZ_d(y)E_0(y) = \frac{4}{3}\pi r_d^3(y)\rho g\,,$$

where g, $E_0(y)$, r_d, ρ, and $eZ_d(y)$ are the acceleration due to gravity, the electric field, the particle radius, the mass density, and the dust charge, respectively. Note that since the electric field is inhomogeneous near the wall region, particles of different sizes achieve equilibrium at different heights and the dust cloud has therefore a gradient in both the dust mass and the dust charge. The radial confinement of the layers is provided by the inward electric field arising from the radial gradient of the floating potential.

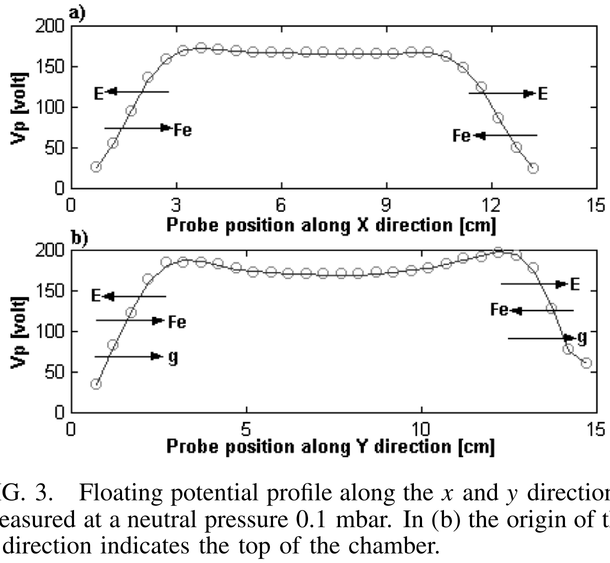

FIG. 3. Floating potential profile along the x and y directions, measured at a neutral pressure 0.1 mbar. In (b) the origin of the y direction indicates the top of the chamber.

As the neutral pressure is reduced to about 0.13 mbar the dust cloud shows spontaneous longitudinal oscillations of the acoustic type which propagate vertically downwards (in the direction of the gravity). From an analysis of consecutive video frames the typical wave number and phase velocity of this oscillation are found to be $\lambda_y \sim 0.2$ cm, $V_{\text{phy}} \sim 4$ cm/s so that the wave frequency $f_y \sim 20$ Hz. The wavelength and the frequency of this longitudinal wave are found to remain nearly the same when the discharge voltage is varied 300–350 V. We have compared the phase velocity of this wave to the theoretical expression of the phase velocity of the dust acoustic waves (DAW), which for $k\lambda_p \ll 1$ is approximately given as $C_{\text{da}} \sim \lambda_p \omega_{\text{pd}}$. In our experiment the typical plasma parameters are $n_i \sim 10^{16}$ m^{-3}, $T_i \sim 0.03$ eV, and the dust parameters are $n_d \sim 5 \times 10^{11}$ m^{-3}, $T_d \sim 0.03$ eV, $M_d \sim 5.4 \times 10^{-14}$ kg, $Z_d \sim (1\text{–}2) \times 10^4$. Thus on an average $\lambda_p \sim 13$ μm, $\omega_{\text{pd}} \sim (1.6\text{–}3.2) \times 10^3$ s^{-1} and the theoretically estimated value for C_{da} for our experimental parameters is $\sim$(2.1–4.2) cm/s. This is in close agreement with the experimentally measured value. The DAW mode has been experimentally identified and extensively analyzed in several recent studies [10–15], and we do not discuss its characteristics any further in this Letter.

When the pressure in the chamber is reduced to 0.1 mbar an additional wave motion appears in the dust cloud over and above the dust acoustic mode (see Fig. 2b). This mode has a significantly lower frequency, propagates along the z direction (i.e., along the horizontal axis of the chamber), and has a vertical polarization. It thus constitutes a transverse wave and our experimental investigation has been primarily devoted to the identification and elucidation of the propagation characteristics of this mode. A typical value of the measured wave number and phase velocity of this mode is $\lambda_z \sim 3.7$ mm, $V_{\text{phz}} \sim 4.2$ mm/s, leading to a frequency $f_z \sim 1$ Hz. For $\Gamma \gg 1$, a simple theoretical estimate of the frequency of the transverse shear mode [6], as explained shortly below, can be obtained using the expression $\omega \sim (kd)\omega_{\text{pd}}/\sqrt{3}$ where $d = ae^{(-a/2\lambda_p)}$ is the effective interaction distance of the dust particles. For our experimental parameters $a \sim 80$ μm, and thus for $\lambda_z \sim 3.7$ mm this gives us $\omega \sim 5.6$ s^{-1} and hence $f_z = \omega/2\pi \sim 1$ Hz, which is very close to the experimental value. For a more detailed confirmation we have measured the wavelength and frequency of the axially propagating mode over a wide range of parameters by varying the discharge voltage. These measured values are plotted in Fig. 4. It should be mentioned that, unlike in a driven wave experiment, the oscillations we observe are spontaneous ones and for a given value of the discharge voltage constitute a single set of values for ω and k. As we change the discharge voltage the equilibrium parameters also change; e.g., the electric field and plasma density increase with an increase in the operating voltage, and the dust particle density decreases leading to an increase in the

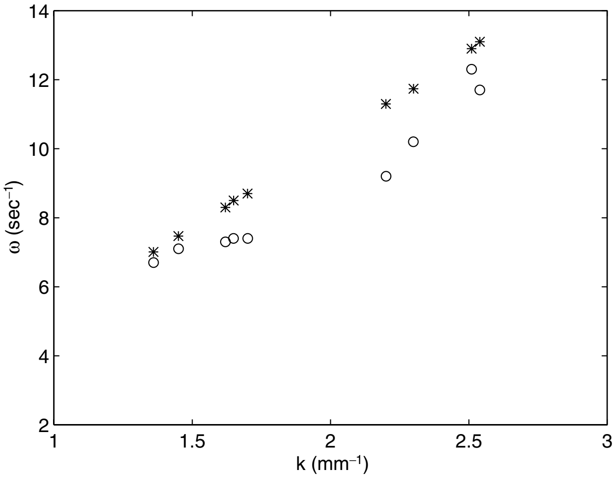

FIG. 4. Experimental (∘) and theoretically calculated (⋆) dispersion relations for the shear mode.

dust interparticle distance. The dispersion curve displayed in Fig. 4 has been generated by a series of measurements of spontaneous excitations observed over a range of discharge voltages. The open circles mark the experimental points. For comparison we have also plotted (with asterisks) the theoretical estimate of ω using the viscoelastic theory expression [6], $\omega = kC_{\mathrm{sh}}$, with

$$C_{\mathrm{sh}}^2 = \frac{3}{4}\frac{T_d}{M_d}\left(1 - \gamma_d\mu_d + \frac{4}{15}u\right). \tag{1}$$

Here μ_d is the compressibility, γ_d is the adiabatic constant depicting the ratio of specific heats, and u is the excess potential energy. γ_d has been taken to be 1.5 and u and μ_d have been estimated at each value of Γ from the following relations [6]:

$$\mu_d \equiv \frac{1}{T_d}\left(\frac{\partial P}{\partial n}\right)_T = 1 + \frac{u(\Gamma)}{3} + \frac{\Gamma}{9}\frac{\partial u(\Gamma)}{\partial \Gamma},$$
$$u(\Gamma) = -0.89\Gamma + 0.95\Gamma^{1/4} + 0.19\Gamma^{-1/4} - 0.81.$$

For $\Gamma \gg 1$, the expression for C_{sh}^2 in Eq. (1) can be approximated as $C_{\mathrm{sh}}^2 \sim \frac{T_d\Gamma}{M_d} \rightarrow \omega_{\mathrm{pd}}^2 a^2 e^{-a/\lambda_p}$. Hence $\omega \approx kC_{\mathrm{sh}} \sim ka\omega_{\mathrm{pd}}e^{-a/2\lambda_p}$, the expression we have used above for an approximate estimate of the shear wave frequency. As is seen in Fig. 4, the dispersion characteristics of the observed transverse wave agree quite well with the theoretical predictions of the shear mode in a strongly correlated dusty fluid. It should be mentioned here that transverse waves in a strongly coupled dusty plasma have been recently reported by Misawa *et al.* [4]. However, in their experiments the dust component was in a crystalline state—a single layer of ordered particles or multiple such layers which also displayed vertical alignment. The transverse modes of such an equilibrium are the transverse dust lattice waves (T-DLW) [16] which are supported by the vertical restoring force of the confining potential for the crystal. The frequency of the T-DLW is nearly independent of the wave number k for a large range of k and weakly decreases for increasing k in the regime where $kr_0 \ll 1$ (where r_0 is the average distance between the dust grains) [16]. The measured wave characteristics in the experiment of Misawa *et al.* [4] agree closely with the dispersion curve for a T-DLW. In our experiment the equilibrium conditions are quite different; the dust component displays no spatial order and resembles a fluid state. The wave dispersion relation (as shown in Fig. 4) has a strong linear dependence on k and increases with k. The underlying physical mechanism sustaining these transverse oscillations is therefore quite distinct from the T-DLW and appears to be best explained by the viscoelastic mechanism described in [6]. The theoretical estimate of the frequency corresponds to the pure shear mode and neglects corrections arising from finite mass gradient, finite charge gradient, dust charging effects, and linear coupling to the dust acoustic mode. Expressions for these corrections have been provided in detail in [7], and we find their values to be negligibly small for our experimental parameters. It has also been pointed out in [7] that a finite charge gradient coupled with finite dust charging time can drive the shear mode linearly unstable provided $E_0(dZ_d/dy) < 0$ and the neutral pressure (and consequently the dust neutral collision rate) is reduced below a threshold value. While the basic instability condition is satisfied in our experiment, we observe a large discrepancy in the threshold condition. The shear mode is found to appear spontaneously at pressure values which are much larger than the theoretically predicted value possibly due to other driving sources in the system. One possible driving source is the ion-dust streaming which is known to drive the compressional DAW unstable; linear and nonlinear coupling mechanisms may then transfer energy to the shear mode. A detailed theoretical explanation of additional driving mechanisms for making the shear wave unstable is beyond the scope of this Letter.

In conclusion we have observed the onset of spontaneous low frequency transverse oscillations in a strongly coupled dusty plasma in the regime characterized by $1 \ll \Gamma < \Gamma_c$. To the best of our knowledge this is the first experimental evidence of transverse shear waves in a three-dimensional dust cloud in the fluid regime and the dispersion characteristics of the wave agree quite well with theoretical predictions based on a viscoelastic mechanism. Further properties of these waves can be explored by controlled external excitations at desired frequencies (e.g., by current modulation [11]), and such experiments are currently under construction.

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