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Observation of the condensation of a gas of interacting grains

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Abstract. We consider an ensemble of grains that interact through a dipole-dipole interaction. A granular gas is formed by the vertical motion of a piston at the bottom boundary of the system. The interaction between the grains is controlled by an horizontally applied magnetic field. When the speed of the piston is decreased, we observe a transition from a low density to a high density phase. When the interaction between grains is weak, the transition is continuous. It is discontinuous for stronger interaction. The phase diagram displays strong similarities with the ones observed for usual equilibrium phase transitions.

In a fluid at equilibrium, the competition between attraction and thermal motion leads to a phase transition between a high density (liquid) phase and a low density (gas) phase. In a granular system driven out of equilibrium, transitions between phases with different densities have been observed in several experiments: in a three dimensional geometry for particles subject to gravity [1], in low gravity [2], in a monolayer subject to horizontal vibration [3], in a dense layer vertically shaken [4], and in an almost one dimensional granular media [5]. In these systems, the interactions are limited to contact events between grains, either through dissipative collisions or solid friction. Here we consider grains that carry an horizontal dipole and interact through dipole-dipole interaction. The granular medium is fluidized by the vertical motion of a piston at the bottom boundary of the experiment. Depending on the strength of the interaction, we study how the transition occurs.

The experimental system is made of stainless steel grains of monodispersed diameter $d = 2$ mm located in a vertical plexiglass cylinder of inner diameter $D = 53$ mm, see Figure 1. At the bottom of the experiment, a plexiglass piston performs a sinusoidal vertical displacement of amplitude 30 mm at a frequency F up to 12 Hz. The collisions of the piston with the grains inject energy into the system and for large enough F a gas of grains is formed. An horizontal magnetic field up to 160 G can be applied using two Helmoltz coils. The spheres are ferromagnetic and acquire a magnetic dipolar moment that is proportional to the applied magnetic field. This leads the spheres to interact by dipole-dipole interaction whose amplitude is thus tuned by the applied field. The competition between these interactions and the motion of the grains results in a transition between phases of different densities. For large enough vibration F, the piston fluidizes the granular layer and a low density phase, gas-like, is observed, see the upper snapshot in Figure 2. When the magnetic field is increased, a transition takes place, the granular gas collapses and a dense phase is formed as displayed in the bottom snapshot in Figure 2.

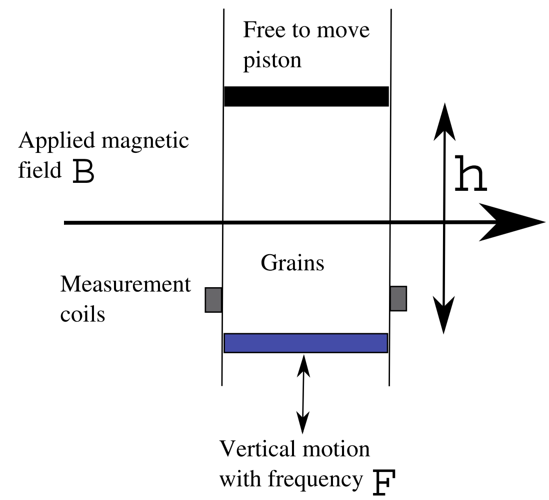

Fig. 1. (Color online) Sketch of the experiment. The grains are located in a glass cylinder of diameter 53 mm plunged into an horizontal magnetic field B. The bottom piston moves vertically at frequency F. The top lid is free to move and after transient reaches an height h measured from the upper position of the bottom piston. Two closely coupled coils allow to measure the local density of grains.

A lid of surface $S = \pi D^2/4$ can be placed at the top of the experiment and is adjusted so that its height h can vary: the position h is selected by the competition between a downward force Mg where M is the effective mass of the lid and the pressure force exerted by the collisions of the grains with the bottom face of the lid. After a transient,

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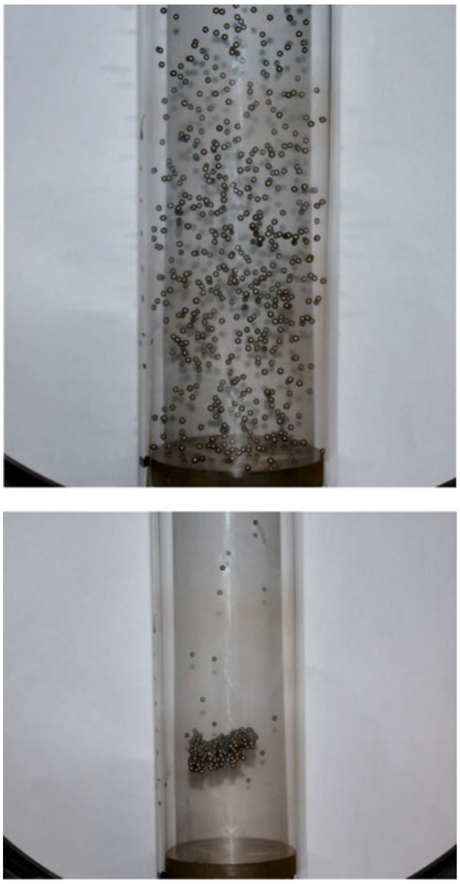

Fig. 2. Snapshot of the experiment when the top lid is removed. On the top, low density phase obtained for low magnetic field. On the bottom, dense phase obtained for high magnetic field.

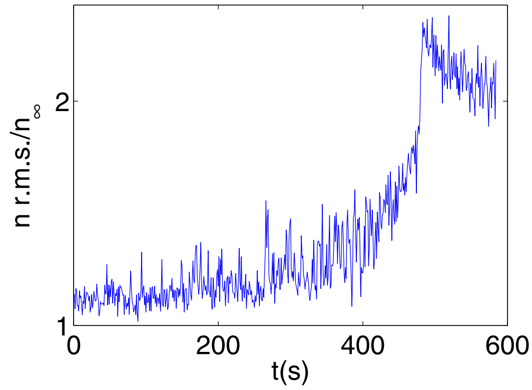

Fig. 3. (Color online) Density fluctuations n r.m.s. as a function of time for $B = 137$ G. The system is initially in the low density phase (large F) and at $t = 0$, the frequency is decreased to $F = 7.25$ Hz. The grains suffer a transition to the dense phase after a long transient. n_∞ is the value of the density fluctuation for large piston frequency ($F = 12$ Hz), see figure below.

the average lid position h can be measured. Experiments are thus performed with fixed pressure Mg/S as a control parameter while the volume of the system hS is measured. The transition is observed whether the top lid is present or not. In the absence of top lid, the gas occupies a large volume and is sensitive to magnetic field spatial variations. In the following, we present results obtained with the top lid, the charge of which corresponds to a mass $M = 5$ g and a pressure $P = Mg/S = 22$ kN m^{-2} . The total mass of grains is $m = 20$ g roughly corresponding to one monolayer. For these measurements, the maximum height of the lid is of the order of 50 mm corresponding to a magnetic field homogeneous within 3%.

Density measurements are performed following the method presented in [1]. Two closely coupled coils are fixed around the cylinder, at an height 10 mm above the upper position of the piston. An a.c. voltage with frequency 4 kHz is applied to one of the coils. Steel spheres in the vicinity of the measurement plane change the mutual between the two coils and induce a variation of the voltage of the second coil. The homodyne detection between the applied voltage and the a.c. voltage induced at the second coil gives a signal $n(t)$ which depends on the local density of spheres within the coils. More precisely, we have checked that this signal is roughly proportional to the number of grains in the vicinity of the coils (see [1] for detailed explanations). The density measurements display fluctuations. In the low density phase, this corresponds to the fluctuation of the number of single grains in the vicinity of the coil. When the system is in the dense phase, the fluctuations are larger because the collective motion of the grains is coherent and this results in large variations of the density measured in the plane of the coils. These variations are driven by the motion of the piston and thus occur at frequencies larger than F. The standard deviation of the density, n r. m. s., measured on a duration larger than $1/F$ (here 1 s) is a simple way to characterize the state of the system. It is displayed in Figure 3 for a case where the system is initially in the low density phase and, after a transient, it suffers a transition into the high density phase. We point out the short duration of the transition compared to the transient before and after it.

We measure n r.m.s. as a function of the piston frequency for different magnetic fields, see Figure 4. At low frequency F, large fluctuations are measured. This corresponds to the high density phase. At large frequency, we observe low fluctuations, i.e. the low density phase. When F is decreased the system changes from low to high density. This transition can occur in two different ways. At large magnetic field, here larger than 100 G, when a critical value of F is reached, the system first remains in its initial phase and suddenly transitions towards its stationary state (such a transition is reported in Fig. 3). This sudden change of state results in a large change of the properties of the system and we refer to this transition as discontinuous. In contrast for small magnetic field, the system does not display such a sudden transition and its properties evolve in a smooth manner when F is varied. We refer to this transition as continuous. Within measurement accuracy, the system reaches the same stationary state whether increasing or decreasing the frequency, apart for the highest magnetic field where a difference of F

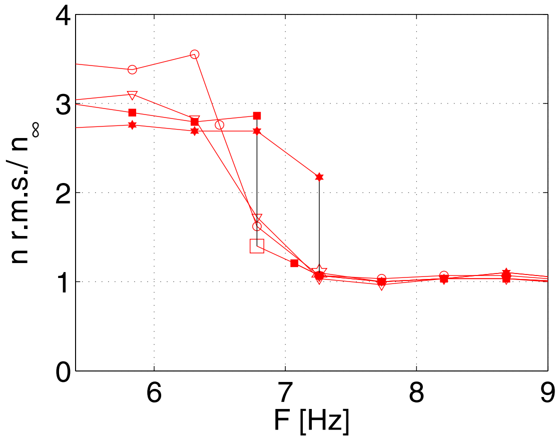

Fig. 4. (Color online) Density fluctuations n r.m.s. normalized by n_∞ its value at large piston frequency ($F = 12$ Hz), as a function of the piston frequency for ($\circ$): $B = 0$ G; ($\triangledown$): $B = 98$ G; ($\blacksquare$): $B = 117$ G and ($\star$): $B = 137$ G. In the last two cases (full symbols), the transition is discontinuous: when F is decreased, the system suddenly transitions into the high density state. We have marked with a large empty symbol the corresponding initial unstable state and a vertical line joins this state to the final stationary state.

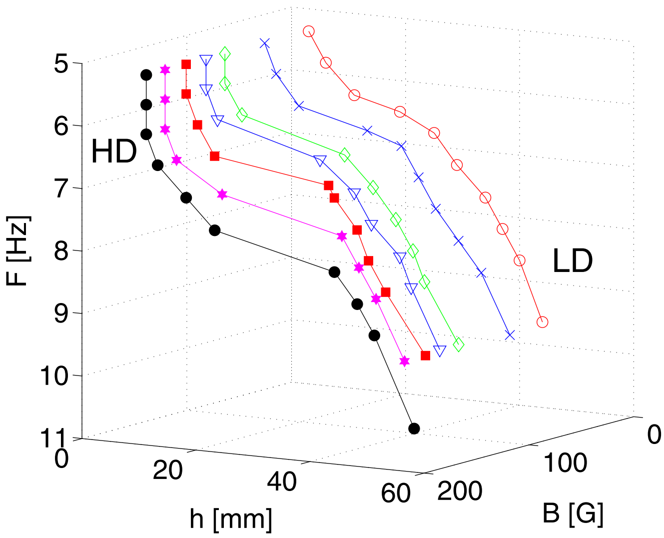

Fig. 5. (Color online) Equation of state in the B, F, h space. Magnetic field B is fixed to 0, 42, 80, 98, 117, 137 and 155 G.

at the transition up to 10% has been observed, probably because the transient time can be larger than the measurement duration (after a change of control parameters, we typically wait for hundred seconds before measuring the system properties).

The relation between the control parameters B, F and the system height h, the equivalent of a state equation, can be determined and is presented in Figure 5. The projection of these curves on the (F, h) plane is displayed in Figure 6. From these data also, we observe that up to roughly 100 G, the transition seems almost independent of the magnetic field. When the magnetic field is larger, the discontinuous transition results in a large variation of h for a small change of B, a plateau in the (h, F) plane within experimental accuracy. An increase of B postpones the transition to higher values of F. For large enough frequencies, the low density phase satisfies an equation of state of the form $h \propto F^{3/2}$, as displayed in Figure 6. This is in agreement with the behavior observed for particles that interact only through dissipative collisions [2] and this shows that the interactions have no effect on the state equation for frequencies even moderately large compared to the transition frequency.

Although our system is clearly out of equilibrium, it shares some features with the liquid-gas transition at equilibrium. There, the equation of state is in general expressed with the density, the pressure and the temperature. A possible way to compare the two systems, is to associate density to our measure of the height h[1], while temperature can be related to the frequency of the piston F.

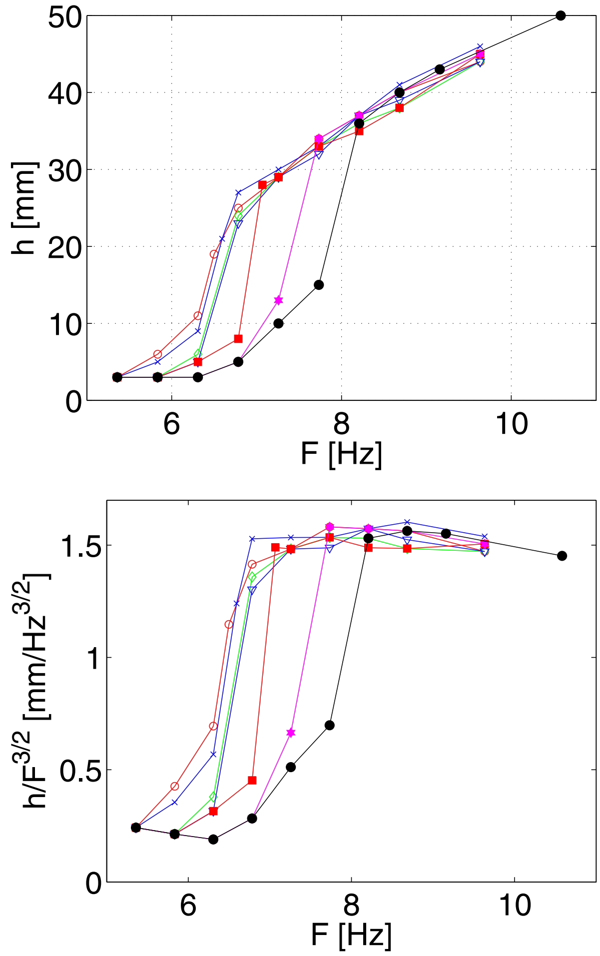

Fig. 6. (Color online) Projection of the equation of state in the (F, h) plane for different values of B. Same symbols as in Figure 5. On the bottom panel, a constant value of $h/F^{3/2}$ is shown to be the equation of state in the large F limit.

[1] In the high density phase, the grains are condensed and the local density is therefore non uniform. Then h is only a measure of the mean density $N/(hS)$.

Pressure is related to the interaction between the particles and, in our experiment, this depends on B. The experiments we present here can be described in the context of phase transition as the evolution from the liquid phase to the gas phase when the temperature is increased at fixed pressure. For high enough pressure, the change of phase is continuous and the fluid evolves through the supercritical state whereas at low pressure, a discontinuous transition takes place between the two phases. We point out that these results should not be considered as a definition of the temperature and pressure of our granular gas [6,7]. For instance a change in B at fixed volume results in both a change of the pressure and of the kinetic energy of the grains such that the similarity discussed above is only qualitative. Nevertheless it would be of great interest to investigate the behavior of the system close to the critical point: do some properties display anomalous exponent? Are these exponents dependent on the processes of dissipation? This would require higher accuracy measurements close to the point in the parameter space where the slope dF/dh vanishes.

For large enough magnetic field, the transition is discontinuous. We reported in [8], the experimental study of a granular gas fluidified by a turbulent flow. There the grains interact through a dipole-dipole interaction when the applied field and the induced dipoles are vertical. A continuous transition is observed to a time-dependent state where the density is roughly time-periodic. While the mechanism at work for the formation of the instability is in both cases the attractive interaction between the grains, we point out that the nature (continuous/discontinuous) of the instability can be different. This results from the difference in the way energy is injected into the granular system either in volume by a turbulent flow or at the boundary by the motion of the piston.

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