Light scattering from superfluid fog

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Abstract

The dynamics of the droplets of superfluid ^{4}He fog created by an ultrasonic transducer are investigated using a laser scattering technique. Diffusing-wave spectroscopy probes the motion of the droplets, which is found to be ballistic for times shorter than a characteristic viscous time $\tau_v = 10^{-5}$ s. The average relative velocity between the droplets is small compared to the velocity that the droplets are ejected from the surface into the fog, but increases proportionally to it.

Key words: superfluid fog; light scattering ; drop dynamics;

Very dense fogs of superfluid droplets can be generated by an ultrasonic transducer immersed in liquid helium [1]. The sound drives ripplons on the helium surface unstable above a critical surface acceleration, and droplets are ejected into the vapor. The size of the droplets is about the ripplon wavelength, ranging from a diameter of 100 μm at a drive frequency of 1 kHz to 10 μm at 124 kHz. Time of flight measurements [1] show that the droplets are emitted into the vapor with initial velocities of order 1 m/s, and this increases linearly with the surface velocity. The droplets reach a height of 4-6 cm above the liquid surface, and then drift back down under gravity, reaching a terminal velocity of a few cm/s. The dynamics of the fog creation process is still not well understood, and the interplay between the vapor and the droplets is complex [1].

To further investigate the dynamics of the droplets we employ the light-scattering technique of diffusing-wave spectroscopy [2]. A Nd-YAG laser producing 150 mW at 532 nm is directed through the width of a rectangular Plexiglass cell (2.5 cm width $\times$ 5 cm length $\times$ 7 cm height and closed at the top) in the helium vapor which contains the fog. The drive frequency was 124 kHz, producing 10 μm diameter droplets. The 1.5 K temperature of the sample helium and the droplets is determined by measuring the vapor pressure of the sample space in the optical dewar. The speckle-pattern fluctuations at a small angle from the exiting diffuse light are viewed with a photomultiplier through a 200 μm pinhole. Autocorrelation data of the fluctuations are collected for 20 minutes for each data set. The density of the fog was constant at about $5 \times 10^7/cm^3$, and data were taken at four different drive voltages between 39 and 57 V. This does not change the density, but increases the velocity that the droplets are being injected into the fog from the surface from about 1 m/s to 2 m/s [1]. The photon transport mean free path under these conditions was always at least a factor of 3 smaller than the width of the Plexiglass cell defining the fog region, as calculated from Mie scattering theory for 10 μm helium droplets and 532 nm wavelength, with an extinction efficiency of 1.8 and the average cosine of the scattering angle of 0.98, since the small dielectric constant of liquid helium results in strong forward scattering.

From the autocorrelation data we can extract the mean-square displacement between the drops [3], shown in Figure 1. At short times the displacement is proportional to t^2, showing that the droplets initially move in ballistic trajectories, since for that case one expects

$$< \triangle r_{rel}^2 > = < \triangle v_{rel}^2 > t^2 \qquad (1)$$

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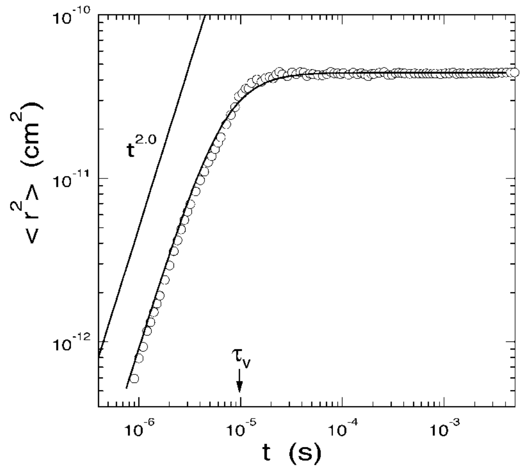

Fig. 1. The mean-square displacement as a function of the correlation time for a helium fog (57 V drive on the piezo, where the critical drive voltage to produce droplets was 15 V).

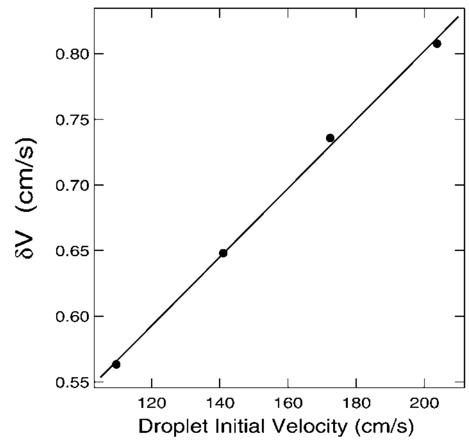

Fig. 2. The relative velocity of helium droplets vs the velocity that the helium droplets are being ejected from the helium surface. These are for drive voltages of 39, 45, 51, and 57 V, where the onset voltage for drop generation was 15 V. The line shows a linear fit, with the relative velocity linearly proportional to the initial droplet velocity.

where $\triangle v_{rel}$ is a randomly directed relative velocity between two drops. Ballistic behavior is expected for correlation times smaller than a characteristic viscous time [4] $\tau_v = R^2\rho_v/\eta_v$, where ρ_v and η_v are the density and viscosity of the vapor. For our conditions $\tau_v = 9.5{\times}10^{-6}$, which is marked with the arrow in Fig. 1, and it is seen that the ballistic regime indeed falls below this time. For larger times the displacement becomes nearly flat, but the data in this region is not particularly reliable because the autocorellation function is falling to zero and the extraction of the displacement becomes uncertain.

The relative velocities are found from the data of the mean-square displacement versus the correlation time (as in Fig. 1) by fitting to Eq. 1. In Fig. 2 the measured relative velocities $\delta v = \sqrt{\langle \Delta v_{rel}^2 \rangle}$ from the DWS data at different drive amplitudes are shown as a function of the initial velocity of the emitted droplets, calibrated from the onset drive voltage as in Ref. [1]. From Fig. 2 it is apparent that the relative velocity is proportional to the initial droplet velocity, but two orders of magnitude smaller. We believe that this magnitude can be understood from the steady-state dynamics of the fog. The fog is made up of essentially two classes of drops: the small fraction emitted from the surface on every cycle with velocities of order 1 m/s that increase with the drive, and the vast majority falling back to the surface with terminal velocities of a few cm/s that will be independent of the drive. A photon will occasionally scatter from both from a fast droplet and a slow one, giving a large relative velocity, but then when the mean-square average is taken over all the slow drops the net result is a greatly reduced value, but one which does increase with the drive amplitude. A complicating factor is the possibility of hydrodynamic motion of the helium vapor [1], which could exert viscous drag forces on the droplets.

This experiment is the initial application of DWS to understand the dynamics of superfluid fogs. The motion of the helium droplets is found to be ballistic when time scales short compared to the viscous time are probed, as expected. The fact that the droplets are superfluid does not appear to play any role in the dynamics, although the details of how the vapor helium atoms interact with a moving droplet may well not be completely classical. Further work is needed to examine the dynamics at longer correlation times where interactions between the droplets should become important.

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