Visualization Study of Counterflow in Superfluid ^{4}He using Metastable Helium Molecules

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Heat is transferred in superfluid ^{4}He via a process known as thermal counterflow. It has been known for many years that above a critical heat current the superfluid component in this counterflow becomes turbulent. It has been suspected that the normal-fluid component may become turbulent as well, but experimental verification is difficult without a technique for visualizing the flow. Here we report a series of visualization studies on the normal-fluid component in a thermal counterflow performed by imaging the motion of seeded metastable helium molecules using a laser-induced-fluorescence technique. We present evidence that the flow of the normal fluid is indeed turbulent at relatively large velocities. Thermal counterflow in which both components are turbulent presents us with a theoretically challenging type of turbulent behavior that is new to physics.

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The superfluid phase of liquid ^{4}He exhibits two-fluid behavior [1]: a normal fluid, carrying all the thermal energy, coexists with a superfluid component. The proportion of superfluid falls from unity to zero as the temperature T rises from zero to the λ transition [1]. In a thermal counterflow, the normal-fluid velocity v_n is related to the heat flux q by

$$q = \rho S T v_n, \tag{1}$$

where ρ is the total density and S is the entropy per unit mass [1]. Above a certain critical heat flux, superflow is known to become turbulent. This quantum turbulence takes the form of a disorganized tangle of quantized vortex lines [2,3]. A mutual friction force between the two fluids arises through the interaction between the quantized vortices and the normal fluid [4]. This type of quantum turbulence is maintained by the relative motion of the two fluids, through processes that are reasonably well understood [2,3]. Features in the observed relation between vortex density and heat flux suggest that the normal fluid may also become turbulent, and mutual friction has been shown theoretically to induce an instability in the laminar flow of the normal fluid [5]. Satisfactory evidence for such normal-fluid turbulence can come only from a visualization of the normal-fluid flow. Techniques for such visualization have recently started to be developed. Turbulence in both fluids has been observed in other types of flow in liquid helium [6], such as that behind a moving grid [7]. But in those cases the two fluids are not forced to have any relative motion and behave like a single classical fluid, exhibiting a Kolmogorov energy spectrum [1]. Simultaneous turbulence in both fluids in a counterflow must be different, and it would be a type of turbulence that is new to physics.

Past experiments on the visualization of thermal counterflow have used micron-sized tracer particles formed from polymer spheres or solid hydrogen, and they have been based on either particle image velocimetry [8] or particle tracking techniques [9]. The particle image velocimetry data obtained at large heat fluxes are hard to interpret since micron-sized particles can be trapped on the quantized vortex lines. However, particle tracking has yielded very interesting results, demonstrating that the normal fluid does move according to Eq. (1) and that information about the dynamical behavior of the quantized vortices can be obtained. However, these particle tracking experiments have been confined to small heat currents, at which there is no clear indication of any normal-fluid turbulence. The results at larger heat currents, when vortex density is high, may be harder to interpret [10]. In addition to micron-sized tracers, ^{3}He atoms have been used to study the flow in superfluid ^{4}He by using the neutron radiography technique, which requires a finely collimated neutron beam and the ability to raster the neutron beam through the region of interest [11]. Recently, we have demonstrated that metastable He_2^* triplet molecules, with a radiative lifetime of about 13 s in liquid helium [12], can be imaged by using a laser-induced-fluorescence technique, which involves only tabletop laser systems [13–16]. These molecules can act as tracers that follow the motion of the normal fluid. Their small size (~1 nm) means that they are not trapped by vortices at temperatures above 1 K [17], and scattering by vortices is likely to have a negligible effect. In this paper, we report the results of visualization studies, conducted at relatively high temperatures (1.8 and 1.95 K), on the normal fluid in a thermal counterflow using these molecules.

In one experiment, we used a molecule tagging technique [14,15] to visualize the velocity profile of the normal fluid. A counterflow channel, consisting of a square borosilicate glass tube (8 cm long, 5 mm inner side width) with one end sealed to a stainless steel flange, was installed in a superfluid-filled helium cell (see Fig. 1). Two sharp tungsten needles were mounted in the helium-filled cavity enclosed by the steel flange and surrounded by a grounded

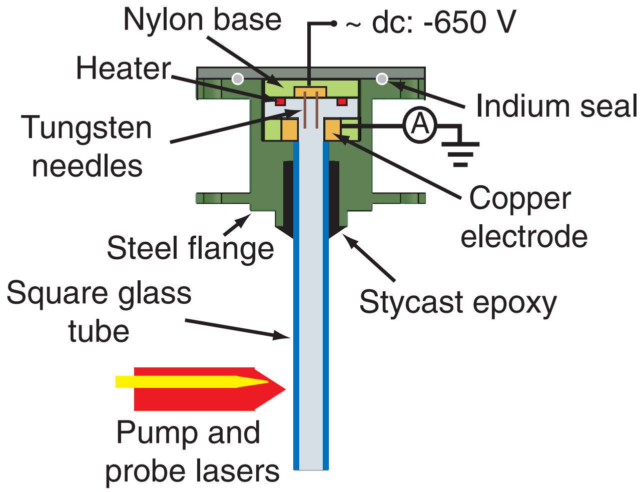

FIG. 1 (color online). Schematic diagram of the counterflow channel used in the molecule tagging experiment. The pump and probe lasers illuminate the channel at about 6 cm from the tungsten needles.

copper ring electrode as a field emission source. When a negative voltage with amplitude greater than the emission threshold (roughly −500 V) was applied to the needles, electrons were emitted from each needle and moved toward the copper electrode [18]. Metastable helium molecules were produced near the needle apexes with a rate of order $10^9\ s^{-1}$ [15,16]. A heater installed inside the cavity served to generate a counterflow in the channel. A focused pump laser pulse at 910 nm was used to drive the He_2^* molecules along the beam path into the first vibrational level of the triplet ground electronic state. At a given delay time, an expanded probe laser pulse at 925 nm was then used to image selectively the vibrationally excited line of molecules by driving them to an excited electronic state and inducing 640 nm fluorescent light [15]. In the absence of a heat current, we saw no molecules in the laser region while the field emission source was on. As we turned on the heater, helium molecules drifted with the normal fluid to the laser region and were imaged. At low heat fluxes, however, many molecules decayed radiatively before they could reach the observation region. The flow of the normal fluid was studied at heat fluxes that ranged from 160 to 1000 mW/cm^2, above the onset heat flux for quantum turbulence (about 20 mW/cm^2) observed in channels with similar geometry [19,20].

An intensified CCD camera was used to record the fluorescent light from the line of excited molecules. The camera was synchronized to each probe laser pulse and exposed for 6 μs so as to minimize the dark current. To achieve high image quality at each pump-probe delay time, up to 40 images were superimposed and an averaged line profile was obtained. Typical summed images showing the motion of a line of tagged molecules at a heat flux of 640 mW/cm^2 are shown in Fig. 2 in false color. For all studied heat fluxes, an initially straight line of molecules remains straight as it drifts, indicating a flat normal-fluid

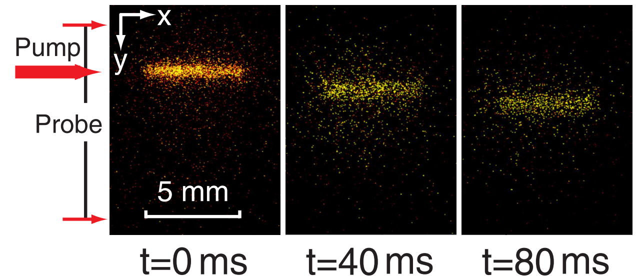

FIG. 2 (color online). Typical fluorescent images of a line of helium molecules taken at pump-probe delays of 0, 40, and 80 ms, respectively. A schematic of the widths and the positions of the pump and the probe lasers is also shown. The heat flux is 640 mW/cm^2. The temperature is 1.95 K. Each image is a superposition of 40 pump-probe trials.

velocity profile across the channel. For each image, we integrate the fluorescent signal in each pixel along the x axis for a given y value (see Fig. 2 for the axes) and plot the summed signal as a function of y to show the integrated cross-section profile of the tagged line. An example is shown in Fig. 3(a). The resulting line profile can be fit well by using a Lorentzian function, matching the

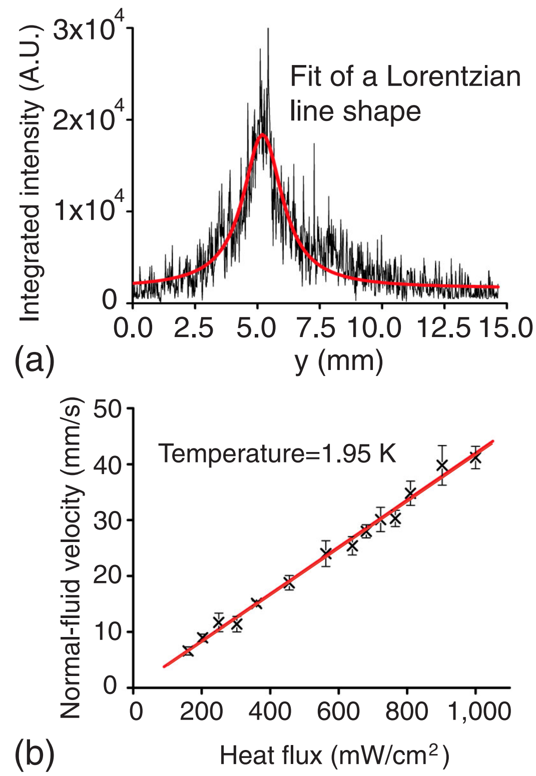

FIG. 3 (color online). (a) A typical integrated cross-section profile of a molecule line in arbitrary units. The heat flux is 640 mW/cm^2, and the pump-probe delay is 40 ms. The red line is a Lorentzian fit to the data. (b) The obtained normal-fluid velocity as a function of heat flux at 1.95 K. The black crosses are the data. The solid line shows the calculated velocity based on Eq. (1) in the text.

Lorentzian profile of the pump laser beam. From this fit, the center position and the mean width $\bar{w}$ (full width at half maximum) of a molecule line can be determined. At a given heat flux, multiple measurements were made as we varied the drift time. We then plotted the center positions versus drift time and fit to a straight line whose slope gives the corresponding normal-fluid velocity. The dispersion of these measurements contributes to the uncertainty of the slope, which gives the error in the measured velocity. The obtained velocities and error bars are plotted in Fig. 3(b) as a function of heat flux. By using the recommended values for entropy and helium density [21], the normal-fluid velocity predicted by Eq. (1) can be calculated and is shown in Fig. 3(b) as the solid line. The good agreement between our data and the calculated velocities demonstrates that the fluorescing helium molecules do track the normal fluid well. An approximately flat normal-fluid velocity profile in counterflow was also found by Awschalom *et al.* [22] by using a cluster of electrons as a tracer. The observation in our experiment agrees with their findings, with a simplification in interpretation due to the fact that, unlike electrons, helium molecules do not repel each other and interact less strongly with quantized vortices.

There remains the question of whether the flow of the normal fluid is turbulent. Two effects can cause a flattening of the normal-fluid velocity profile: turbulence and the nonlinear mutual friction acting on a laminar normal-fluid flow. It is therefore not clear whether the flat profile is clear evidence for turbulence. Better evidence comes from the observed broadening of the line of molecules with increasing time. We analyzed this broadening at a heat flux of 277 $\mathrm{mW/cm^2}$, although similar broadening is seen at all heat fluxes that we have studied. In Fig. 4, we plot the square of the mean width of the molecule line $\bar{w}^2(t)$ as a function of time t. The broadening of the molecule line occurs too rapidly for it to be explained by ordinary diffusion at the experimental temperature (1.95 K) [13]. We deduce that it is caused by turbulent diffusion [23], thus confirming that the flow of the normal fluid is turbulent.

The quantity $\bar{w}^2(t)$ is related in part to the time dependence of the separation of two particles in a turbulent flow, but it is influenced also by the way in which the line of molecules is distorted by turbulent motion on a length scale larger than the width of the molecular line. We note that if this second effect were absent, and if the energy spectrum $E(k)$ (dependence of energy on wave number k in a Fourier analysis of the velocity field) were to have the Kolmogorov form $E(k) \sim k^{-5/3}$, characteristic of classical homogeneous isotropic turbulence, then $\bar{w}^2(t)$ would be proportional to t^3 for large times [23], which compares with our observed dependence as t^4. However, further discussion must await a theoretical analysis that takes account of the distortion of the line. Owing to the action of mutual friction on the normal-fluid turbulence, the energy spectrum in our case is unlikely to have the Kolmogorov form, and it will be of great interest to discover the actual form of this spectrum. We emphasize that the heat fluxes at which we see evidence for turbulence in the normal fluid are significantly larger than those studied by Paoletti *et al.* [9].

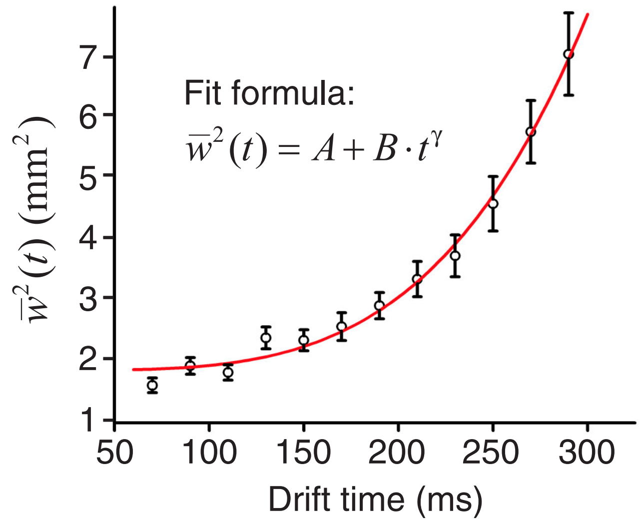

FIG. 4 (color online). The square of the width of a molecule line $\bar{w}^2(t)$ as a function of drift time t at a heat flux of 277 $\mathrm{mW/cm^2}$. Error bars are calculated by $2\bar{w}\delta\bar{w}$, where $\delta\bar{w}$ is the associated error in determining the line width $\bar{w}$. The solid curve is a power law fit to the data. The fit formula is shown in the figure with fitting parameters A, B, and γ. The best fit value of the power index is $\gamma = 4.0 \pm 0.3$.

To measure the normal-fluid velocity at small heat fluxes, we used a cluster tracking technique [15] in a narrower counterflow channel: a square glass tube 6 cm long with 2 mm inner side width [see Fig. 5(a)]. Two tungsten needles (0.1 mm in diameter) were precisely aligned along the central axis of the channel with a gap between them of about 1.5 mm. When a negative voltage pulse was applied to the cathode needle, a small cluster of helium molecules was created near its apex with an initial

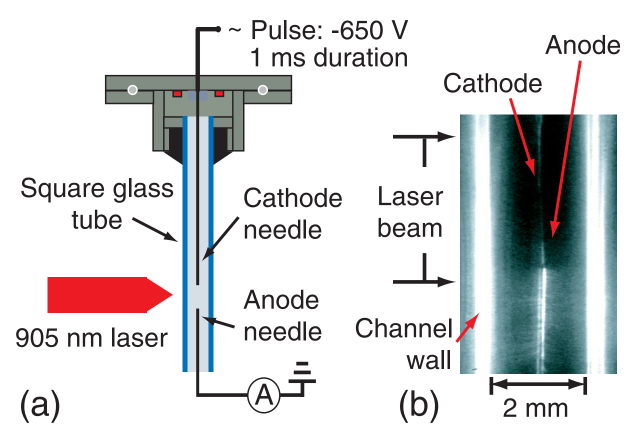

FIG. 5 (color online). (a) Schematic diagram of the counterflow channel used in the cluster tracking experiment. (b) An image of the square glass tube. A pulsed laser at 905 nm illuminates the needle apexes at about 2 cm from the open end of the channel.

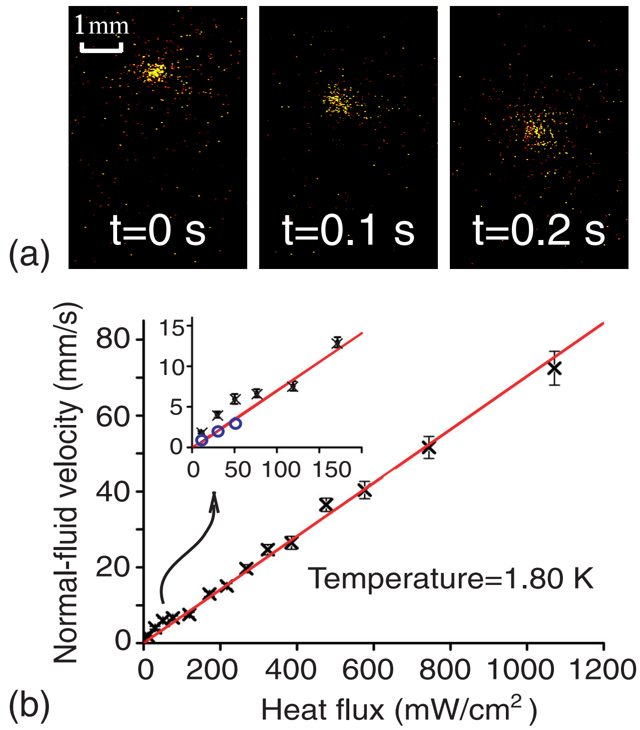

FIG. 6 (color online). (a) Typical fluorescent images of a cluster of helium molecules taken at 0, 0.1, and 0.2 s after the cluster was created. The heat flux is 119 mW/cm^2. The temperature is 1.80 K. The exposure time for each image is 20 ms. (b) The obtained normal-fluid velocity as a function of heat flux at 1.80 K. The black crosses are the data. The red line shows the calculated normal-fluid velocity based on Eq. (1) in the text. The blue circles in the inset for the small heat flux regime show the corresponding measured normal-fluid velocity divided by a factor of 2.

diameter in the range of 0.5–0.8 mm. This molecule cluster moves together and serves as a single tracer [15]. A pulsed laser at 905 nm (repetition rate 500 Hz) illuminated the needle apexes [see Fig. 5(b)] to drive the molecules to produce fluorescent light through a cycling transition [13–16]. Typical images of a molecule cluster at a heat flux of 119 mW/cm^2 are shown in Fig. 6(a) in false color. The normal-fluid velocity is determined by fitting the cluster center positions as a linear function of drift time as we did in a previous report [15]. The obtained normal-fluid velocities and their associated error bars are plotted in Fig. 6(b). Our data again follow the calculated normal-fluid velocity, except below a transition heat flux at about 50 mW/cm^2, which may correspond to the onset of quantum turbulence [19,20,24]. It is likely that, in the small heat flux regime, both the superfluid and the normal fluid are in a laminar flow state. A molecule cluster moving along the central axis should have a drift velocity roughly twice as large as the mean velocity given by Eq. (1) due to a Poiseuille profile [1] of the normal fluid [25]. Indeed, if we divide the measured velocities in the small heat flux regime by a factor of 2, the data fall back to the theory line [see the blue circles in the inset in Fig. 6(b)]. Above the transition heat flux, when the superfluid (and perhaps also the normal fluid) becomes turbulent, the normal-fluid profile is flattened [5] and a molecule cluster then moves at a velocity equal to the mean velocity.

More sophisticated studies of normal-fluid turbulence could be conducted in the future by using a well-focused femtosecond laser to create a thin line of molecules (through laser-field ionization [26]). The line of molecules can be created inside the observation region and, hence, can be imaged at any heat flux. By imaging molecules in the vibrational ground state through a cycling transition, high quality single-shot images of individual lines of molecules can be taken. The distortion of a molecule line will provide us information on the structure factors [27] of the normal-fluid turbulence.

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