Measuring the normal-fluid velocity in superfluid liquid Helium-4 using metastable helium molecules

W. Guo · J.D. Wright · S.B. Cahn · J.A. Nikkel · D.N. McKinsey

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Abstract We show in two demonstration experiments that metastable helium molecules can be visualized and used as tracers to quantitatively study the flow of the normal component in superfluid liquid $^4$He using a laser-induced-fluorescence technique. The methods we developed are useful in studying the role of the normal fluid component in quantum turbulence. A proposed experiment on imaging the normal-fluid velocity profile during the transition of quantum turbulence in a counterflow channel is discussed.

Keywords Visualization · Helium molecule · Superfluid · Quantum turbulence

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1 Introduction

Recently, particle image velocimetry with polymer micro-spheres and hydrogen isotopes has been used to study liquid helium flows [1, 2] and solid hydrogen tracers have been used to visualize the quantized vortices [3, 4]. However, the dynamics of micron-sized tracers in the presence of vortices are complex [1]. One must account for particle-vortex interactions [5, 6] in order to extract an accurate measurement of the local normal-fluid velocity. Furthermore, if the vortex-line density is too high then the possibility to use micron-sized particles to measure the normal-fluid velocity is lost. Another approach to imaging superfluid flow is neutron absorption tomography [7, 8], which uses $^3$He as a neutral tracer and requires a finely collimated neutron beam and the ability to raster the neutron beam through the region of interest. In this paper we shall introduce a new type of angstrom-sized neutral tracers, the metastable He$^*$$_2$ triplet molecules. Metastable He$^*$$_2$ molecules can be imaged using a laser-induced-fluorescence technique which involves only table-top laser systems [9, 10]. He$^*$$_2$ molecules follow the motion of the normal fluid without being affected by vortices at temperatures above 1 K [11] due to their small
effective mass in liquid $^4$He [12]. Although so far the sensitivity in imaging the molecules is not high enough to track the motions of individual molecules, useful studies can still be performed by tracking a group of molecules [13]. Two demonstration experiments are presented here [14]. In the first experiment, a small cloud of helium molecules is produced in liquid helium by pulsing a sharp tungsten tip. We can determine the normal-fluid velocity in a heat-induced counterflow by tracing the position of a single molecule cloud. In the second experiment, A focused 910 nm pump laser pulse is used to drive a small group of molecules to the first excited vibrational level of the triplet ground state. Subsequent imaging of the tagged molecules in the excited vibrational level with an expanded 925 nm probe laser pulse allows us to measure the velocity of the normal fluid.

2 Experimental details

Both experiments were conducted at 2.0 K. A sharp tungsten tip was used to produce the He$_2^*$ molecules in liquid helium. It is known that He$_2^*$ molecules in both spin singlet and triplet states are produced near the tip apex when a negative voltage with amplitude higher than the field-emission threshold is applied to the tip [15,16]. The singlet molecules radiatively decay in a few nanoseconds [17], while the triplet molecules are metastable with a radiative lifetime of about 13 s in liquid $^4$He [18]. The widths of the He$_2^*$ molecule absorption spectral lines in liquid helium (120 cm$^{-1}$ [19]) are considerably larger than the spacings of the rotational levels ($\sim 7$ cm$^{-1}$ [20]). A single pulsed laser at 905 nm is able to drive triplet molecules out of the $a^3\Sigma^+_u$ state to produce fluorescence through a cycling transition (see Fig. 1 (a)) [10]. However, the vibrational levels are separated by about 1500 cm$^{-1}$ [20], and the vibrational-relaxation time is on the order of 1 s [13]. Therefore, molecules falling to excited vibrational levels of the $a^3\Sigma^+_u$ state are trapped in off-resonant levels. Continuous fiber lasers at 1073 nm and 1099 nm were used to repump the molecules from the $a(1)$ to the $c(0)$ states and from the $a(2)$ to the $c(1)$ states respectively. Molecules in the $c$ states have a chance to decay back to the $a(0)$ state and can be used again. The schematic diagram of the experimental setup is shown in Fig. 1 (b). The tungsten tip was mounted at the center of a polytetrafluoroethylene (PTFE) plate. The PTFE plate had a diameter of 21 mm.
Fig. 2 (a) The motion of a molecule cloud with 15V on the heater. The images were taken at 0 s, 0.2 s and 0.4 s respectively after the cloud was created. The duration of the pulse on the tungsten tip was 5 ms. The images are a sum of 25 camera exposures. (b) The obtained normal-fluid velocity as a function of the heat power. The solid line and the dashed line are the theoretical curves as discussed in the text.

and a thickness of 1 mm. Four 100 Ω metal-film resistors were connected in series and attached to the PTFE plate around the tip on a 3 mm radius circle as a heater. A nickel mesh plate was placed 3 cm away from the PTFE plate and was grounded. The whole device was held at the center of a helium cell with total volume of about 250 cm³.

In the first experiment, the intensities of the fiber lasers at 1073 nm and 1099 nm were chosen to be 3 W/cm² and 1.5 W/cm² respectively. The intensity of the pulsed laser at 905 nm was 500 µJ/cm² per pulse, and the repetition rate was 500 Hz. To create a small cloud of He₂⁺ molecules, a −400 V pulse is delivered to the tungsten tip through a 0.1 µF capacitor in addition to a constant voltage of −450 V. Electrons are emitted from the tungsten tip and a small cloud of molecules is created near the apex of the tip when the total voltage crosses the field-emission threshold (around −550 V) during the pulse. At 2.0 K, a He₂⁺ molecule diffuses less than 1 mm during its lifetime [9]. Thus the molecule cloud stays together and serves as a single tracer. The size of the molecule cloud is of the order of 1 mm but becomes larger for longer pulse durations. With the heater off, the molecule cloud was observed to drift towards the nickel mesh plate due to a transient pulling force on the normal fluid created by the moving electron bubbles [16]. The drift velocity was typically of the order of 1 mm/s for a voltage pulse of 5 ms duration. As we turned on the heater, a thermal counterflow was set up in the liquid. The normal fluid flowed away from the heater with a speed \( v_n \) given in theory as \( v_n = Q/\rho ST A \) [21], where \( Q \) and \( A \) are the heater power and cross-section for heat transfer; \( \rho \), \( S \) and \( T \) are the helium density, entropy and temperature respectively. A typical set of images showing the motion of a molecule cloud with heater power of about 0.56 W is shown in Fig. 2 (a). These images were taken with an intensified CCD camera at 0 s, 0.2 s and 0.4 s respectively after the cloud was created. The camera was synchronized to each laser pulse and exposed for 6 µs so as to minimize the dark current. The number of camera exposures for each image was chosen to be 25 in order to obtain a good signal-to-noise ratio yet reduce image smearing. The heater was turned on a few seconds before the molecule cloud was generated so as to set up a steady flow of the normal fluid. We fit the image of each molecule cloud with a Gaussian function to determine its center position. For a given drift time, several images were taken and...
Fig. 3 (Color online) (a) Fluorescence images showing the positions of a small group of tagged $a(1)$ molecules at different delay times after they were created. The DC voltage on the tungsten tip was 805V. (b) Obtained normal-fluid velocity as a function of the square root of the current measured on the nickel mesh plate.

an averaged center position was determined. As a result, the normal-fluid velocity can be calculated. In Fig. 2 (b), we plot the normal-fluid velocity obtained as a function of the heat power. For low heat power, the normal fluid was believed to be in the laminar flow regime. Heat was transferred to all directions below the PTFE plate. The cross-section for heat transfer in this case was estimated to be about 6.2 cm$^2$. The solid line in Fig. 2 (b) shows the theoretical curve with $A=6.2$ cm$^2$. However, as one can see, the measured data starts to deviate from the theoretical curve when the heat power is above roughly 0.25 W. If we take the typical length scale for the flow to be 1 cm, then the measured fluid velocity (3 mm/s) gives a Reynolds number as high as 3000. It is likely that the normal-fluid flow started to become turbulent and caused a change in heat transfer pattern. When the heat power is higher than 0.8 W, the turbulent flow in the normal-fluid may be fully developed and the dispersion of the measured flow velocity is large. The dashed line in Fig. 2 (b) shows the theoretical curve assuming an effective heat transfer cross-section of 1.3 cm$^2$.

In the second experiment, we created a continuous molecular beam and selectively imaged a small group of molecules which were tagged using the first excited vibrational level of the $a^3\Sigma^+_u$ electronic state. To create the molecular beam, we ran the tungsten tip in a continuous mode by applying a DC voltage higher than the field-emission threshold. The emitted electrons moved from the tip to the nickel mesh plate leading to a continuous pulling force on the normal fluid. A normal fluid jet was formed from the tip to the nickel mesh plate carrying the He$^*_2$ molecules along [16]. Molecules created by field-emission initially occupy the $a(0)$, $a(1)$, and $a(2)$ excited states. To prepare a pure population of $a(0)$-state molecules for tagging and eliminate background signal for selective imaging, the 1073 nm and 1099 nm fiber lasers were used to illuminate a small volume near the tip and drive molecules from the $a(1)$ and $a(2)$ excited vibrational levels into the $a(0)$ state (see Fig. 3 (a)). A focused pump laser at 910 nm was then used to tag He$^*_2$ molecules by driving population from the $a(0)$ to the $c(0)$ state and relying on redistribution of the $c(0)$ population into the long-lived $a(1)$ state (see Fig. 1 (a)) via non-radiative transitions which occur naturally in a few nanoseconds [13]. An expanded probe laser at 925 nm was then used to selectively image the tagged molecules by driving the $a(1)$ population into the $d$ state and inducing 640 nm fluorescence via $d \rightarrow b$. 

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure3}
\caption{(Color online) (a) Fluorescence images showing the positions of a small group of tagged $a(1)$ molecules at different delay times after they were created. The DC voltage on the tungsten tip was 805V. (b) Obtained normal-fluid velocity as a function of the square root of the current measured on the nickel mesh plate.}
\end{figure}
radiative decay. In Fig. 3 (a), we show images for a group of tagged $\text{a}(1)$ molecules taken at pump-probe delay times of 0 ms, 10 ms, 40 ms and 70 ms respectively with 805 V on the tip. Both the pump laser and probe laser had a pulse energy of 5 mJ and repetition rate of 10 Hz. At each fixed pump-probe delay time, the camera was exposed ten times to obtain a single image with a good signal-to-noise ratio. The bright image obtained with zero delay time resulted from a two-photon transition induced by the pump laser alone at 910 nm [13]. The total driving force on the normal fluid exerted by the moving electron bubbles is proportional to the electric current $I$ [16]. In steady state the driving force on the jet is balanced by the drag force coming from the neighboring normal fluid. If we take the typical length for the jet flow to be 1 mm (the width of the jet), the Reynolds number is estimated to be $\sim 5 \times 10^3$. The flow should be in the turbulent regime, hence a drag force proportional to the square of the flow velocity is expected [21]. In Fig. 3 (b), the obtained flow velocity is plotted as a function of $I^{1/2}$. A linear dependence is observed which is similar to the time-of-flight measurements discussed in Mehrotra’s paper [16].

3 Discussion

The ability to quantitatively measure the normal-fluid velocity provides us the chance to better understand the role of the normal fluid in many hydrodynamical processes of the two-fluid system. For example, it has been known for many years that in a counterflow channel with small aspect ratio there exist two different states of quantum turbulence of Helium II denoted by Tough as T-1 and T-2 states [22]. The T-1 state appears at low values of heat flux while the T-2 state appears at higher heat flux and is characterized by a much higher vortex line density. Melotte and Barenghi studied the nature of the two turbulent states and proposed that this puzzle was related to the stability of the normal fluid [23]. In the T-1 state, the superfluid is turbulent, but the vortex line density is not sufficient to significantly alter the laminar Poiseuille-like profile of the normal fluid. As the heat flux is increased, eventually the line density becomes large enough to destabilize the normal fluid and the normal-fluid flow becomes turbulent in the T-2 state. So far, there is no direct experimental result to confirm Melotte and Barenghi’s idea. We propose that by using the molecule-tagging technique, we shall be able to provide useful experimental information. As shown in Fig. 4, a strong Beta source shall be used in a counterflow channel to continuously produce high density $\text{He}_2^*$ molecules [10]. A focused pump laser pulse prepares a straight line of tagged molecules. At an appropriate delay time, an expanded probe laser pulse can then be used to show the shape of the tagged-molecule line. When the normal fluid is in laminar flow, a straight molecule line should deform to a parabolic curve due to the Poiseuille-like velocity profile of the normal fluid in the channel. While when the normal fluid is in the turbulent state, a nearly straight broadened molecule line should be expected due to the flat, turbulent uniform normal-fluid velocity profile across most of the channel [21]. As a result, we should be able to determine the normal-fluid velocity profile in the channel, hence distinguish between the laminar flow and the turbulent flow states of the normal fluid. The vortex line density needs to be measured and one will know if the T-1 to T-2 transition of quantum turbulence is indeed coincident with the turbulent transition of the normal fluid as suggested by Melotte and Barenghi.
Fig. 4 (Color online) Schematic diagram showing the proposed experiment on imaging the normal-fluid velocity profile in a counterflow channel using the molecule-tagging technique as discussed in the text.

4 Conclusions

In conclusion, we have developed practical techniques to trace the normal-fluid component in superfluid $^4$He using metastable He$^*_2$ molecules. The ability to track the true normal-fluid flow provides direct understanding of the hydrodynamics of the normal-fluid component in superfluid $^4$He, which will in turn feed into a better understanding of this unique two fluid system.

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References