J Low Temp Phys (2011) 162: 329–339
DOI 10.1007/s10909-010-0237-9

A Study of the Motion of Particles in Superfluid Helium-4 and Interactions with Vortices

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Received: 21 June 2010 / Accepted: 28 September 2010 / Published online: 9 October 2010

Abstract We describe experiments in which a sound pulse is used to inject small particles into liquid helium at temperatures between 1 and 3 K. The motion of these particles is then observed. We are able to observe the effect of applying an impulse to a particle that is attached to a vortex. We also report on a number of surprising motions of particles and discuss possible explanations.

Keywords Superfluid helium-4 · Vortices · Particle motion

1 Introduction

During the last few years there has been an increasing interest in the study of the flow of the superfluid and normal fluid components of helium and of the dynamics of quantized vortices. One approach is to introduce small particles into the liquid and to record the position of these particles as a function of the time [1–14]. The particles used so far include solid hydrogen and electrons. In addition to the experimental work, there has been theoretical work directed to achieving an understanding of the relation between the particle motion and the flow of the fluid [15–19]. In this paper, we present the results of some new experiments in which we see some very unusual motions of particles in superfluid helium-4 and observe the effect of the interaction between a particle and a vortex line.

2 Experiment

The experiments that we report here use essentially the same apparatus that we have used previously to image the motion of single electrons in liquid helium (Fig. 1) [10–

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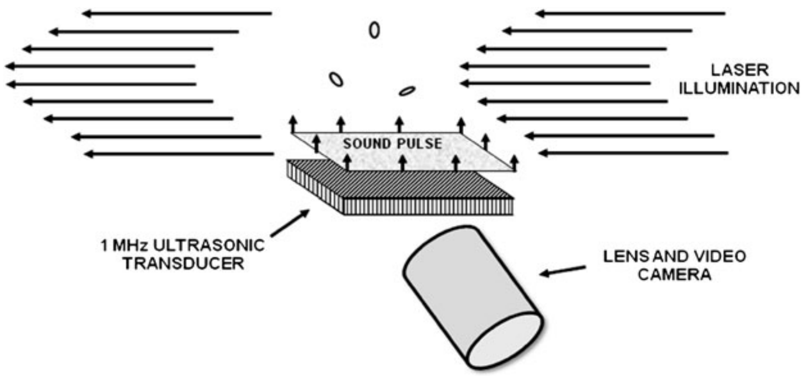

Fig. 1 Schematic diagram of the apparatus

14]. We have a large cell (volume ~ 200 cm^3) with several windows that can be used to introduce light from different sources or to make observations. The temperature of the cell can be controlled in the range from around 1 K to 4 K. As light sources, we have used a constant intensity helium-neon laser (power 30 mW), this laser operating in pulsed mode with a repetition rate of 160 Hz, a 500 mW 530 nm laser, and this laser with intensity modulated by means of a mechanical chopper of variable frequency. To minimize the heat input into the cell, we set up the light sources so that after passing through the cell the light leaves through an exit window. Images were recorded using a 5.5 cm lens and a video camera with pixel array 1388 by 1038 [20]. In order to increase the contrast on some images 2×2 pixel binning was used. The lens and camera were positioned at 90° to the illuminating beam.

A lithium niobate transducer with resonant frequency 1.3 MHz is placed near the bottom of the cell and generates sound pulses propagating upwards. The transducer is able to launch into the liquid a sound pulse with a pressure swing of 1 bar or more. In some of the experiments, the cell also contained a 5 mCi ^{63}Ni β-source to inject electrons into the liquid.

3 Results

In our previous experiments to study the motion of electrons a series of sound pulses was used [10–14]. During the negative pressure swing of each cycle of the sound pulse an electron bubble in the liquid became unstable and rapidly grew to a size large enough to be detected optically. In this way, it was possible to make stroboscopic movies of the motion of the electrons. The original intent of the present series of experiments was to make further studies of electron motion using this technique and to investigate in detail how electrons interact with quantized vortices. However, before starting this investigation we noticed that when just a single sound pulse was applied we were still able to see some particles in the liquid; these particles were stable and could be observed until they left the region of the cell that was within the field of view. Since the particles could be seen without the application of further sound pulses, they could not be electron bubbles. Moreover, the motion of these particles was unaffected or only weakly affected by applied electric fields. Assuming that the particles have a refractive index in the same general range as organic matter, the intensity of the light scattered by them indicates a particle size of the order of a few microns.

It appears that these particles may simply be dust that was left on the upper surface of the sound transducer and was ejected into the liquid when the transducer was driven. If no driving pulse is applied to the transducer, we cannot see any particles in the liquid. The particles could be driven upwards by acoustic radiation pressure, and we note that the heat dissipated in the transducer also results in an upward flow of the normal fluid which will drag particles along with it. In most of the experiments that we describe here the transducer is driven by a single electrical pulse lasting between 50 and 200 μs.

A typical image is shown in Fig. 2. This was taken at 1.37 K with continuous illumination and a camera exposure time of 1 s. The objects are seen to move through the cell along an irregular path and with a velocity of the order of 1 cm s $^{-1}$. Figure 3 shows an image taken at 1.34 K using the helium-neon laser pulsed at 160 Hz. From this type of picture one can determine values for the velocities of the particles, more precisely the velocity in the plane normal to the direction from the camera to the cell.

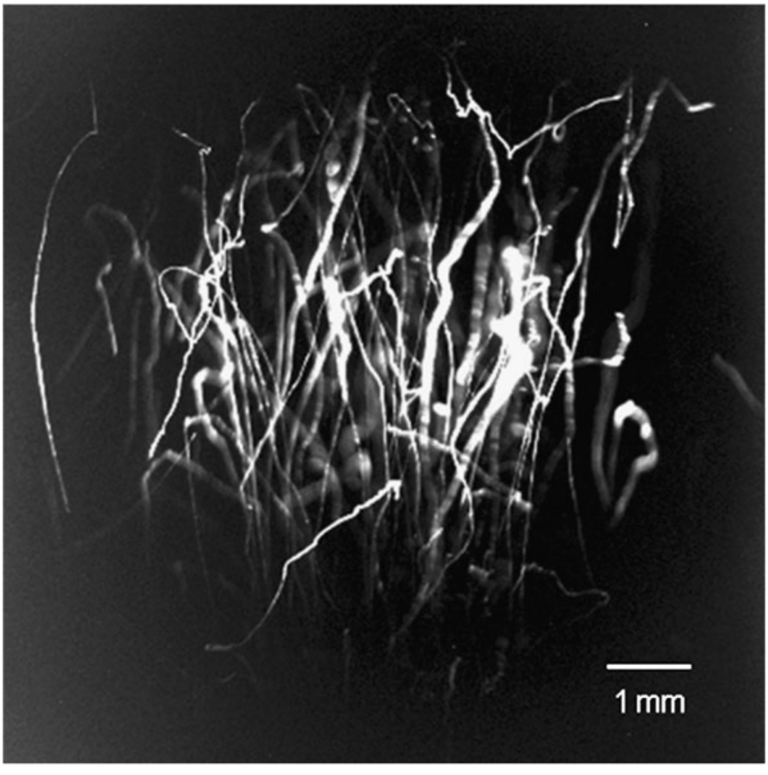

Fig. 2 Image taken at 1.37 K with continuous illumination and a 1 second exposure

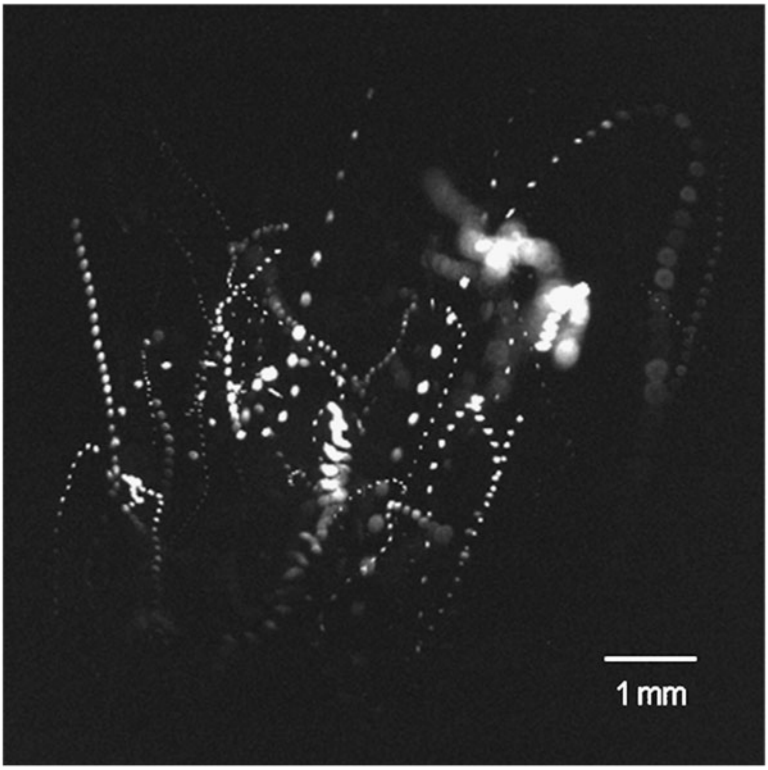

Fig. 3 Image taken at 1.34 K with illumination pulsed at 160 Hz and 0.5 second exposure

Note that the size of the particles as appearing in the image does not correspond to the true size; most of the particles are not in sharp focus.

One can ask whether the particle motion is the result of chaotic motion of the normal fluid or comes about because the particles are interacting with vortex lines. We have performed a simple experiment that demonstrates clearly that at least some of these objects are attached to vortices. We are able to see the effect of the vortex line tension on the particle motion and an example is shown in Fig. 4. In this experiment at 2.1 K instead of putting in a single sound pulse, we use a series of sound pulses with repetition rate 10 Hz. The first sound pulse drives a dust particle into the liquid, and the subsequent pulses scatter from the particle and give it an impulse in the vertical direction. In Fig. 4 the particle is moving from left to right along a vortex line. The particle suddenly acquires an upwards velocity when the sound pulse reaches it (the duration of the sound pulse is roughly 200 μs) and the tension of the vortex line then pulls the particle back to a height close to the starting height. The image shown in Fig. 4 was taken with the illuminating laser chopped at a frequency of 600 Hz. We can consider that the particle moves under the combined influence of the impulse provided by the sound pulse, the viscous drag due to the normal fluid and the line tension exerted by the vortex. Although we do not know the details of how the vortex responds, one can see from the figure that each time that a sound pulse is applied and

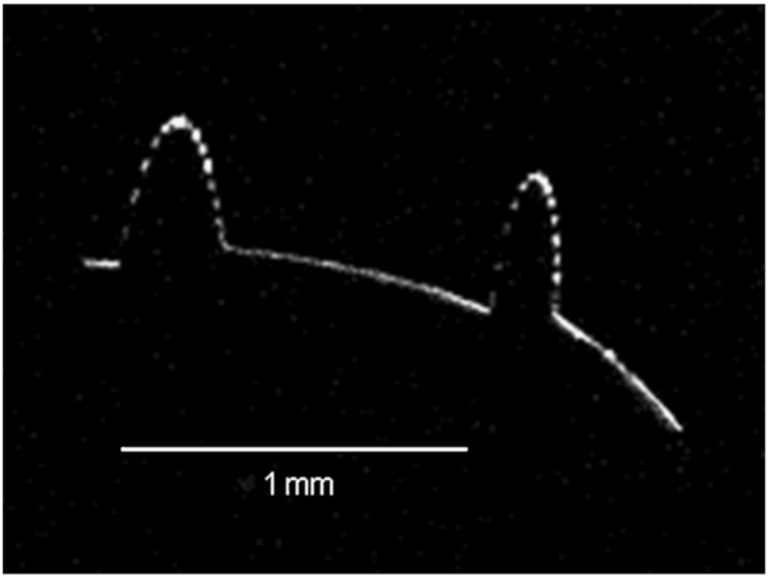

Fig. 4 Image showing the motion of a particle moving along a vortex line and subject to impulses provided by sound. The temperature is 2.1 K and the particle is moving from *left* to *right*. The laser illuminating the cell is chopped at a frequency of 600 Hz and the sound repetition rate is 10 Hz

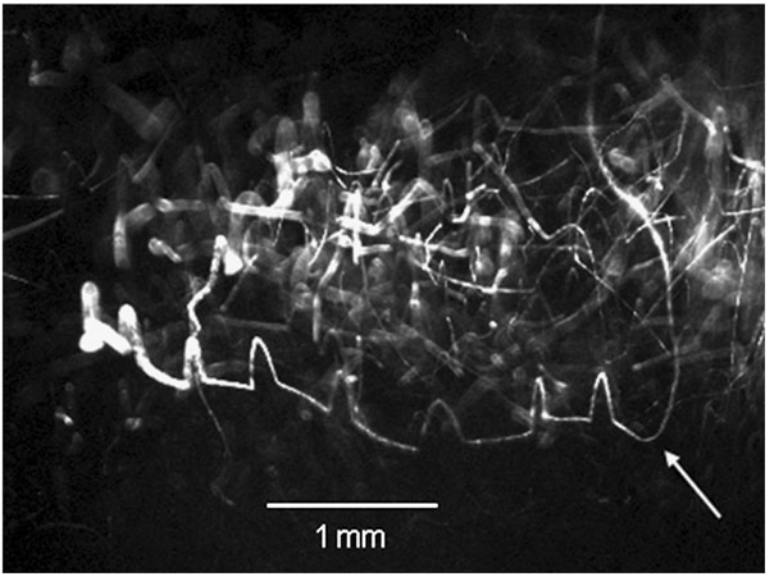

Fig. 5 Image showing a particle moving along a vortex. The particle is given upward impulses by a series of sound pulses and then appears to escape from the vortex at the location of the *arrow*. This image is for continuous illumination and a sound repetition rate of 10 Hz. The temperature is 1.38 K

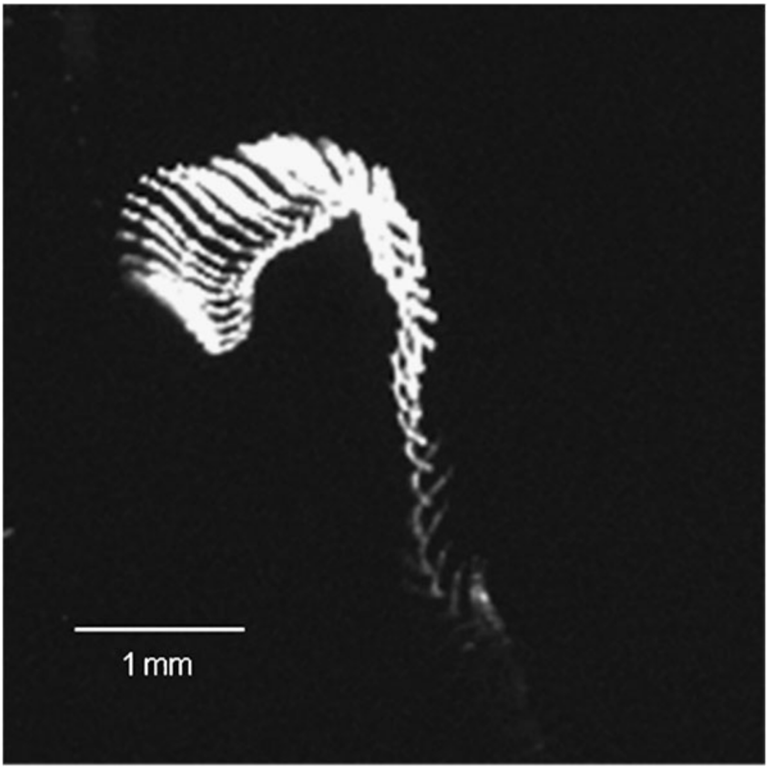

Fig. 6 Image showing the motion of a dust string at 1.36 K with illumination pulsed at 160 Hz

the particle is pulled back by the vortex, and the vortex is pulled upwards. Analysis of images such as this can be used to test theories of the interactions of particles and vortices.

Another interesting image is shown in Fig. 5. A particle is moving from left to right in the figure and is subjected to series of sound pulses. At the point indicated by the arrow a sound pulse knocks the particle off of the vortex and the particle then moves freely away.

A small percentage of the particles that we see are long fibers like this; one such is shown near the center of Fig. 3, and another is shown in more detail in Fig. 6. This particle has a length of approximately 1 mm. Such particles may come from the cotton swabs that are used to clean the cell.

We now turn to discuss several other interesting objects that we have observed. Occasionally we see "spiral objects", i.e., particles rising through the liquid as shown in Fig. 7. By way of caution, however, we note that we cannot tell for sure that the path is a spiral since it could possibly be simply a zigzag motion in a plane normal to the direction of observation. In this figure the pitch of the spiral is fairly constant at around 1 mm and the vertical component of the velocity is about 2 $\mathrm{cm\,s^{-1}}$. It is not clear what causes the spiral motion. At a temperature of around 1.4 K where we have

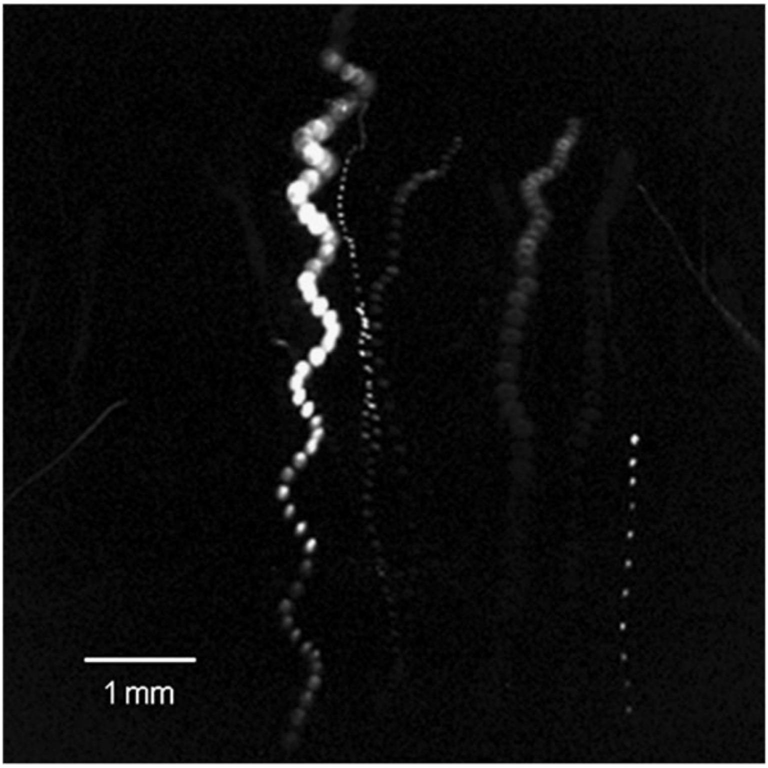

Fig. 7 Spiral motion of a particle at 1.34 K. Image was taken with illumination pulsed at 160 Hz

recorded many images, a spiral track is seen in about 1% of the images; we have not seen multiple spiral tracks on the same image.

The second interesting feature is shown in Fig. 8. The image shows parallel tracks (two sets in this particular case). This picture was taken with the laser pulsed at 160 Hz. Above the lambda point we see many such pairs of parallel tracks and the natural explanation is that these arise from gas bubbles rising in the normal liquid. The bubbles are produced as a result of the heat entering the cell from the transducer. The two images appear because light from the laser is reflected at the bubble surface both on entering and on leaving, i.e., is reflected from both the front and back of the bubble. Since the incident light is traveling in the horizontal plane, this results in the camera recording two spots that are separated by a distance of $R\sqrt{2}$ where R is the radius of the bubble.

This explains the double tracks seen above the lambda point. But the image shown in Fig. 8 was taken with the liquid temperature of 1.34 K! At this temperature the gas in a bubble will condense very quickly since the heat of condensation will be carried away by the high thermal conductivity of the liquid. An explanation of the image in terms of dust is implausible; dust is not usually spherical. At the present time the most likely explanation is that these objects are multi-electron bubbles. The source in our cell produces electrons at a rate of 10^8 s^{-1}. These electrons enter the

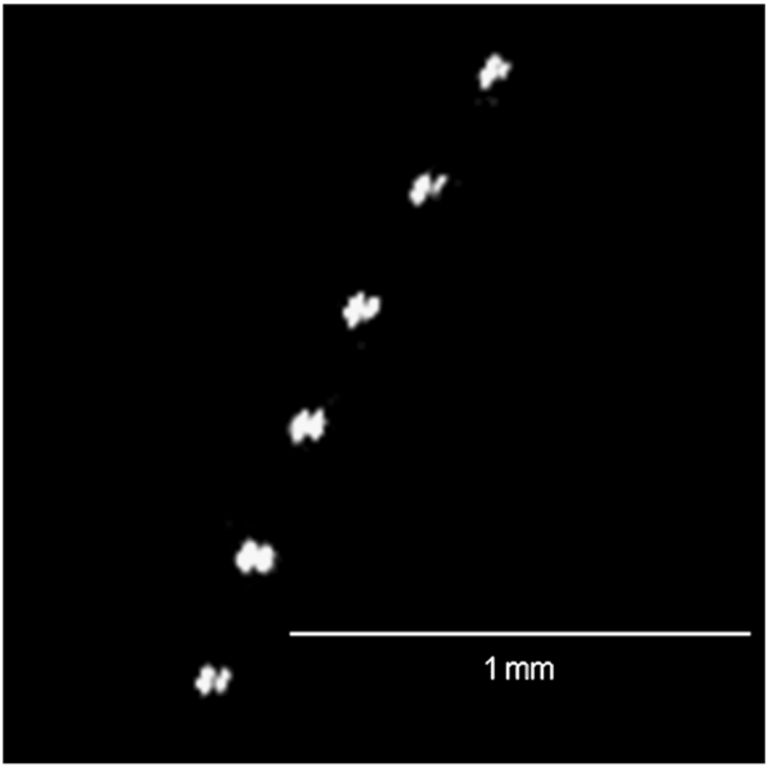

Fig. 8 Image showing double tracks apparently coming from light scattered from a bubble. The temperature is 1.34 K and the illumination was pulsed at 160 Hz

liquid and move under the influence of the space charge field and the flow of the normal fluid. It is possible that a layer of electrons accumulates at the upper surface of the transducer, held there by image forces, but unable to enter because of a layer of non-conducting material on the transducer surface. If the sound pulse has sufficient amplitude to explode one electron, it will be able to explode them all, and it seems possible that the resulting bubbles could coalesce into large bubbles containing many electrons. To be more specific we note that when an electron bubble explodes under the influence of a 1 MHz sound pulse it grows to a maximum size of around 8 µm [10–12]. Thus the cross-sectional area of the bubble is 2×10^{-6} cm^2. Hence, if the number of electrons per unit area is 10^6 or larger and all bubbles explode, the expanded bubbles will merge. The bubble for which the track is shown in Fig. 9 has a radius of 20 µm, which corresponds to a bubble containing 8×10^5 electrons [21].

The most curious feature we have seen is the "DNA" structure that appears at the right hand side of Fig. 9. This picture was taken at 1.52 K. We have seen only a few of these structures. The structure appears to consist of two objects each moving on a helix. We know of no theoretical explanation of this. Unfortunately, all of the DNA structures that we have seen so far have been found in images taken when there was continuous illumination rather than pulsed. In Fig. 10 we show two close ups of

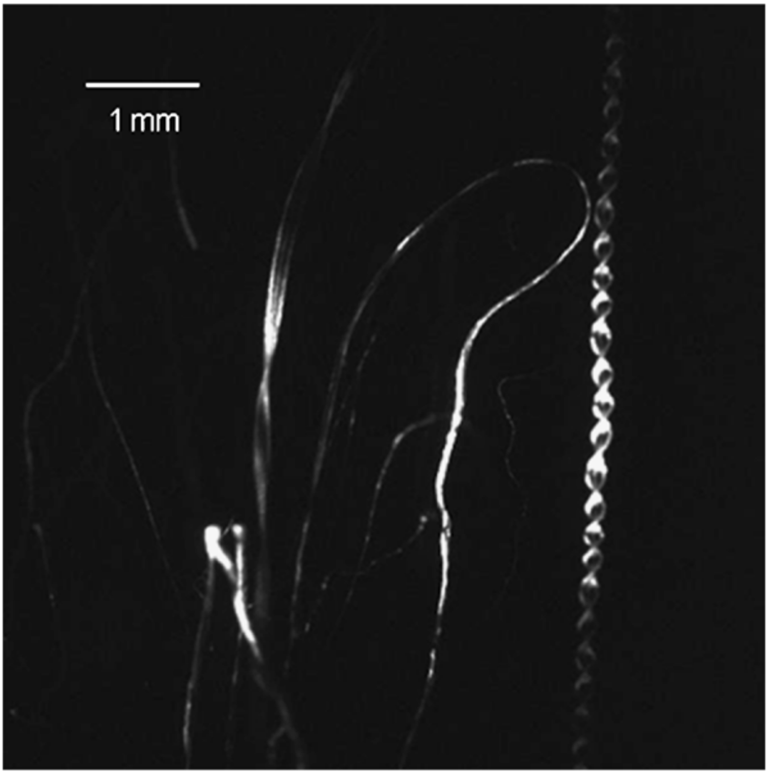

Fig. 9 Image of the motion of "DNA" in superfluid helium at 1.52 K. This was taken using continuous illumination

sections of the DNA. Figure 11 includes two other examples of DNA. In part A we show an example in which the DNA is twisted tightly over some part of its length and then appears to turn into two strands that remain together but run almost parallel for a while and then make one slow twist around each other (left hand part of the figure). Again, we note that because this image has been taken with continuous illumination, we cannot be sure in which direction along the recorded path that the structure is moving. The pitch of the twist is also changing in part B of the figure.

These pictures were taken with the radioactive source in the cell. We have made one short experimental run without the source and did not see any DNA structures, but this may just be chance and at this point cannot be taken to demonstrate a connection between the electron source and DNA.

4 Summary

We have described a number of experiments to investigate the motion of small particles in superfluid helium. We have been able to obtain images that show the interaction between a particle and a vortex. We have seen a number of interesting objects, including the spiral and DNA, whose physical nature requires further investigation.

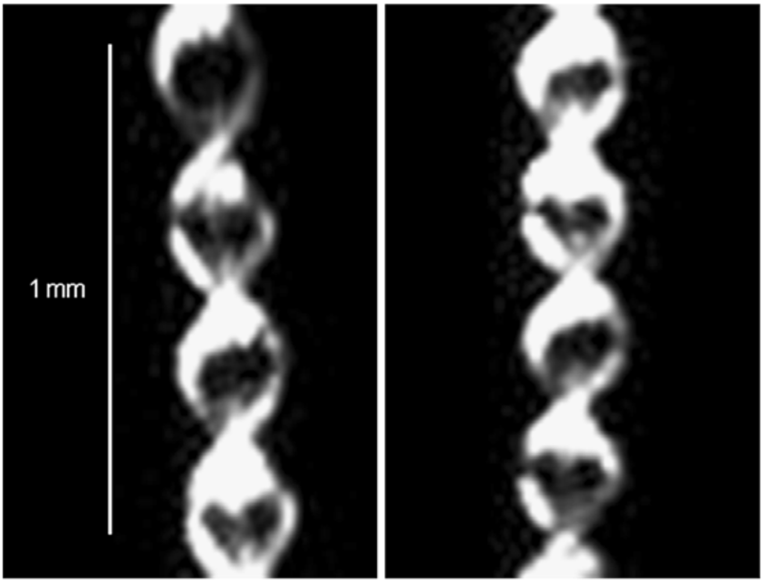

Fig. 10 Enlarged view of two sections of the "DNA" structure shown in Fig. 9

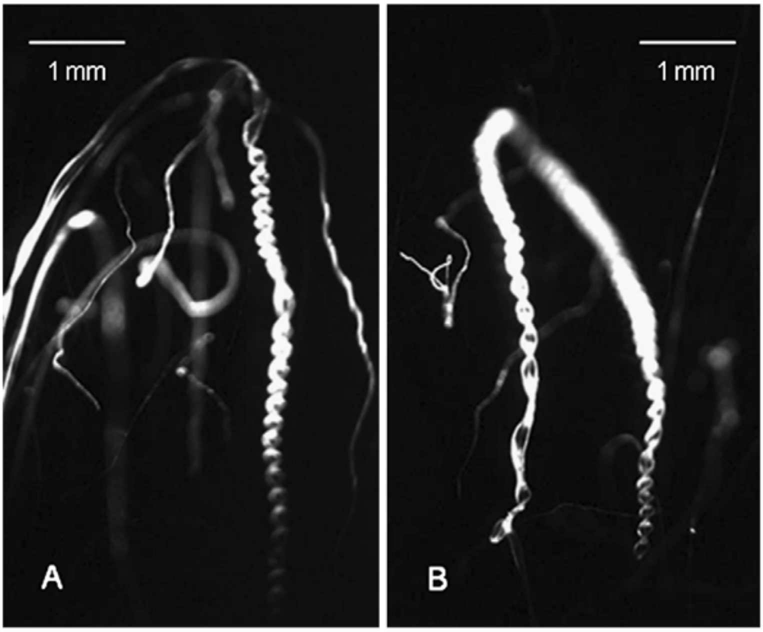

Fig. 11 Two examples of "DNA" structures taken at temperatures of 1.52 K for both **A** and **B**. These images were taken with continuous illumination

Acknowledgements We thank S. Balibar, G.M. Seidel, N. Svensson and W. Wei for helpful discussions. This work was supported in part by the National Science Foundation through grant number DMR-0605355.

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