A study of the motion of single electrons in liquid helium

2007 J. Phys.: Conf. Ser. 92 012001

(http://iopscience.iop.org/1742-6596/92/1/012001)

A study of the motion of single electrons in liquid helium

W Guo, D Jin and H J Maris[1]

Department of Physics, Brown University, Providence, Rhode Island 02912, USA

E-mail: humphrey_maris@brown.edu

Abstract. We have developed an apparatus which can be used to monitor the motion of individual electrons in liquid helium. A sound wave is used to explode an electron bubble for a fraction of a microsecond. While the bubble is expanded, it is illuminated by light from a flash lamp. We describe the details of the experiment and show the results we obtained. The phonon-roton in liquid helium drags the electron bubbles across the experiment cell. In some cases, an electron is seen to follow a snakelike path. Our tentative explanation is that the electron is sliding along a quantized vortex line.

1. Introduction

In this paper we give a brief description of experiments that we have performed in which it is possible to observe the motion of individual electrons in liquid helium [1]. As we will show, the motion of these electrons is governed by the drag on electrons caused by the "phonon wind" and by the interaction of the electrons with quantized vortices.

A highly energetic electron passing through condensed matter will result in the excitation and ionization of atoms along its path. The track of the electron can be determined by observation of the scintillation from the excited atoms, or through the detection of the ionization produced in the material or the energy deposited [2]. For an electron that is moving slowly, these detection methods cannot be applied since the electron does not have enough energy to excite atoms. The determination of the position of an electron by optical means is extremely challenging because of the very small cross-section for photon-electron scattering. For a photon of energy much less than the rest mass of the electron the total scattering cross-section is given by the Thomson cross-section [3]

$$\sigma = \frac{8\pi}{3}\left(\frac{e^2}{m\,c^2}\right)^2 = 6.7\times10^{-25}\ \mathrm{cm}^2 \tag{1}$$

This is for an isolated electron. If the electron is in a liquid or a solid there may be extra scattering because the presence of the electron modifies the medium around it. This modification is particularly pronounced for an electron in liquid helium. An electron strongly repels helium atoms because of the exclusion principle; the 1S levels of the helium atom are occupied and for another electron to be within the volume of the atom the electron has to go to a higher energy state with quantum number n=2. Furthermore, liquid helium is an extremely soft material which has a low surface tension and is easily deformed. As a result, when an electron enters liquid helium it forces open a cavity that is free of helium atoms and becomes trapped in this cavity forming an object usually referred to as an electron bubble. This bubble can move through the liquid and has been studied extensively primarily

[1] To whom any correspondence should be addressed.

through measurements of its mobility [4]. The cavity is approximately spherical and has a radius *R* which minimizes the total energy that is given by the approximate expression

$$E = \frac{h^2}{8mR^2} + 4\pi R^2 \alpha + \frac{4\pi R^3}{3} P \,, \tag{2}$$

where *m* is the mass of the electron, α is the surface tension, and *P* is the applied pressure. The first term in the energy comes from the zero point energy of the electron confined in the spherical cavity, and the second and third terms are the surface and volume energy, respectively. For zero applied pressure, the energy is a minimum for a cavity radius of around 19 Å. The presence of the hole in the liquid (a region of different dielectric constant from that of the liquid) has the consequence that the scattering cross-section σ of light from an electron bubble is larger than the Thomson cross-section, but σ still has the very small value of only $\sim 10^{-23}$ cm^2 for red light.

In order to image the motion of electrons a larger scattering cross-section is needed. One possibility is to use a photon energy that causes the electron to make a transition to an excited state within the bubble. For example, photons of wavelength around 10 μ can excite the electron from the ground state to the 1P state [5]. The cross-section for this process is larger [6], i.e., of the order of 10^{-14} cm^2. The electron can return to the ground state by emitting a photon of wavelength around 30 μ [7]. It might be possible to detect these photons and in this way determine the position of an electron bubble. In the present experiment we have used an alternative approach.

2. Experiment

In this experiment we enhanced the scattering cross-section by increasing the size of the electron bubble. If a negative pressure is applied to the bubble, the radius that minimizes the energy increases. At a critical pressure of [8, 9]

$$P_c = -\frac{16}{5}\left(\frac{2\pi m}{5h^2}\right)^{1/4} \alpha^{5/4} \,, \tag{3}$$

the bubble becomes unstable, i.e., there is no value of the radius at which the energy has a minimum (see figure 1). Based on a value of 0.341 erg cm^{-2} for the surface tension [5], the pressure at which this “explosion” occurs is -1.89 bars at low temperatures. P_c decreases in magnitude as the temperature is raised because the surface tension decreases. Once the pressure becomes negative with respect to P_c, the bubble begins to grow very rapidly and, as we have shown in earlier experiments, can reach a large size [9]. The rate of growth of the bubble can be estimated based on the Rayleigh-Plesset equation [10]

$$\ddot{R} = -\frac{P(t)}{\rho R} - 3\frac{\dot{R}^2}{2R} \,, \tag{4}$$

where ρ is the density of the liquid. In this equation the effect of the surface tension is neglected (surface tension is important only when the bubble is very small) and it is assumed that the work done by the negative pressure when the bubble expands is equal to the rate of increase of the kinetic energy of the liquid surrounding the bubble. Thus, the liquid is taken to be incompressible. If a periodically-oscillating pressure is applied to the bubble, the maximum radius that the bubble reaches depends in a complicated way on the amplitude and frequency of the pressure oscillation, and the negative pressure at which the bubble explodes. For example, if the amplitude is 2 bars, and the frequency is 1.5 MHz, the maximum bubble size is around 8 μ. At this size, the scattering cross section has increased to a value of the order of 10^{-9} cm^2.

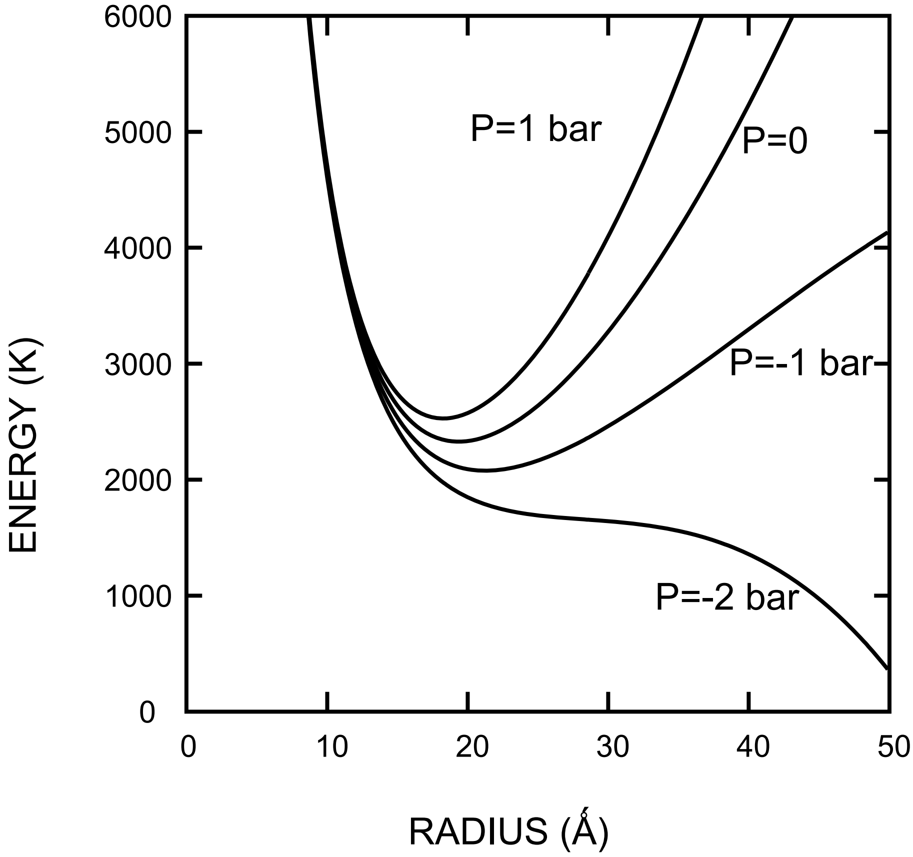

Figure 1. The energy of an electron bubble as a function of its radius for several different pressures in the liquid.

To produce the sound field required in order to explode the electron bubbles, we used a 1.5 MHz lithium niobate ultrasonic transducer with dimensions $1.2 \times 1.2 \times 0.22$ cm. To achieve the required pressure amplitude is very challenging. The amplitude of the pressure wave launched into bulk liquid by a planar transducer is given by the formula

$$\delta P_{He} = \rho c v_{surface} \ , \tag{5}$$

where c is the sound velocity in helium and $v_{surface}$ is the magnitude of the oscillating velocity of the transducer surface. To achieve a pressure swing of 2 bars, it is necessary for $v_{surface}$ to be 600 cm s^{-1}, which corresponds to a strain amplitude of $\sim 10^{-3}$ in the center of the transducer.[1] Because of the very high strain amplitude, several transducers have broken and this remains a major challenge in the operation of the experiment. The transducer was driven with electrical pulses of typical duration 35 μs. Only at the end of the driving pulse is the amplitude of the transducer sufficiently large to give the required pressure swing in the liquid.

The transducer was mounted at the top of the helium cell with the sound pulses propagating down. The cell was cooled by means of a heat link from the bottom of the cell to a continuously-operating 1 K pot, and this enabled measurements to be made down to around 1.3 K. The bubbles were illuminated with light from a flash lamp [11] directed horizontally into the cell through a window and light that was scattered at $90°$ could be viewed through another window. The flash lamp had an output of 0.22 J. The viewing window had a diameter of 1.4 cm. The velocity of sound in liquid helium is

[1] This strain amplitude was incorrectly given as 10^{-4} in our previous paper [1].

approximately 2.4×10^4 cm s^{-1}. As a result, it takes the sound pulse approximately 40 μs to travel down across the part of the helium cell that can be viewed. Hence, electron bubbles in different parts of the cell will explode at different times. To make sure that a bubble would receive a sufficient degree of illumination no matter where it was when it exploded, we used a flash lamp with a pulse duration of approximately 30 μs (full-width at half maximum) but with a very long tail. The timing of the light was set so that the maximum intensity was when the sound pulse was in the middle of the cell.

To detect the light scattered from the bubbles we used a home-style camcorder [12]. In order to collect sufficient light this had to be operated at 4 frames per second in "super-night mode". The acoustic pulses and flash lamp were run at 20 pulses per second, and thus as many as 5 positions of an electron were sometimes recorded by the camcorder on a single frame.

3. Results

In figure 2 we show two examples of images that we have obtained. These are single frames taken by the camcorder on which the position of an electron was recorded four times. The electron is moving down the cell.

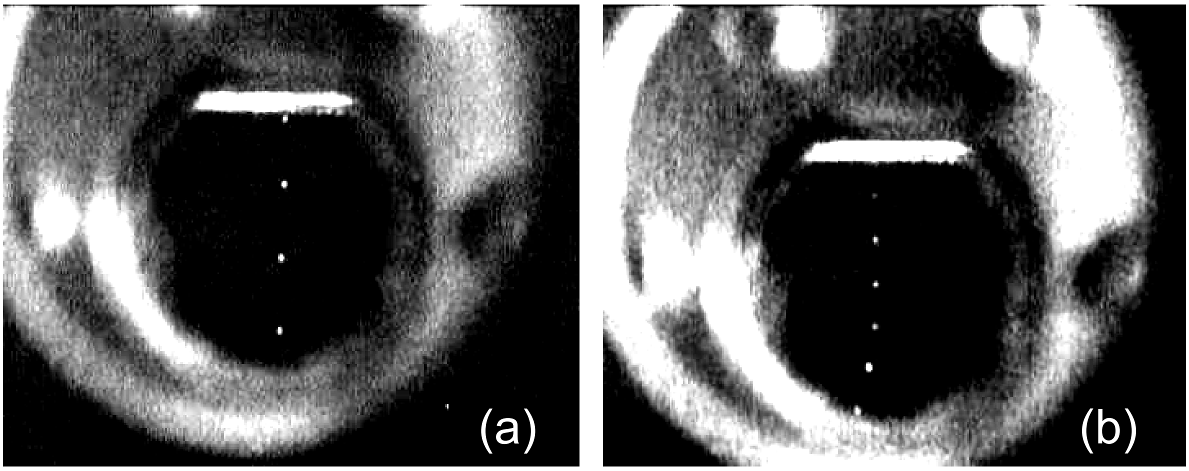

Figure 2. Images of electrons moving down the cell. The temperature is 1.35 K in (a) and 1.91 K in (b). The bright horizontal line at the top of each picture comes from light scattered by the holder of the transducer.

In this first experiment the cell did not contain any source of electrons and so naturally it was important to determine that the objects that are detected are in fact electrons. For example, one could suppose that the images come from the scattering of light by dust particles drifting around in the liquid. We were able to eliminate this possibility by looking to see if scattering occurred when the transducer was not excited. We found that there was no scattering. A second possibility is that the scattering arises more indirectly from dust particles in the liquid. The dust could be too small to give significant light scattering but might still be able to cause heterogeneous nucleation of bubbles in the presence of the sound wave. To test this we made measurements of how the number of times a scattering event was seen varied as a function of the voltage applied to the sound transducer. When the voltage applied to the transducer was above 210 V, it was found that scattering by some object was seen on approximately 1% of the frames recorded by the movie camera. However, if the voltage was reduced to a value below 200 V, no scattering was observed. This sharp threshold is expected if we are seeing bubbles that grow from electron bubbles. For heterogeneous nucleation of bubbles on dust particles, however, one would expect that there would be a different pressure required for each particle and so there should be no sharp threshold.

The majority of the electrons that we have detected travel down the cell along smooth and slightly curved paths. They undergo this motion because of the drag exerted on the electron bubbles by the moving normal fluid. This normal fluid is nothing more than the gas of thermally-excited phonons and rotons and so we can consider that the electrons are drifting with the phonon-roton wind. The wind flows down the cell because the operation of the ultrasonic transducer results in a heat input at the top of the cell and this heat has to cross the cell in order to escape through the cooling heat link at the bottom. The velocity of the wind, i.e., the velocity v_n of the normal fluid, is given by

$$v_n = \frac{\dot{Q}}{ATS}, \tag{6}$$

where A is the cross-sectional area of the cell and S is the entropy per unit volume. The velocity that we observe for the electrons (typically around 5 cm s^{-1}) is consistent with the velocity of the normal fluid as given by this formula when allowance is made for the fact that the cell does not have a simple geometry so the area A is not rigorously defined. The paths of the electrons tend to curve outward away from the center of the cell (see figure 1). This curvature occurs because the heat enters the fluid over a rather small area at the top of the cell whereas it leaves the cell over a larger area at the cell bottom. In future work we hope to use observations of the tracks of electrons to study the velocity field of the normal fluid when the geometry is more complicated, for example, when the normal fluid is flowing around an obstacle in the liquid.

The electron moves with the phonon-roton wind because the effect of other forces acting on it (electrical, gravitational) is very small. The interaction of the electron bubble with the phonons and rotons also gives rise to a diffusive motion. The diffusion coefficient D is related to the mobility μ by the Einstein relation

$$D = \frac{\mu kT}{e}. \tag{7}$$

At 1.5 K, $\mu = 0.245$ cm^2 V^{-1} s^{-1} and so $D = 3.2\times10^{-5}$ cm^2 s^{-1}. The bubbles take approximately one second to drift from the top of the cell and so during this time will diffuse a horizontal distance that is of the order of $\sqrt{Dt}$ ~ 0.006 cm. Thus, the effect of diffusive motion is too small to be seen.

As noted, the cell did not contain any source of electrons and so it is interesting to consider the origin of the electrons that we have seen. The rate at which electrons appeared was approximately 0.025 per second. The majority of these (>90%) were first seen near to the top of the cell and thus appeared to enter at the transducer. However, it is important to note that electrons that entered the liquid at the top of the cell but not near the transducer would not be exposed to the sound field and so would never explode, electrons that enter at the bottom of the cell would immediately be pushed back into the bottom wall by the phonon-roton wind, and electrons entering at a side wall would not be visible through the viewing window. Thus, we consider it reasonable to suppose that electrons are ejected from all of the solid walls but only those coming from the transducer are seen. At present we do not know the mechanism by which electrons are ejected. One possibility is the photoelectric effect. Cosmic ray muons passing through the cell will cause ionization and excitation of helium atoms. This will result in scintillation, primarily giving photons of energy around 16 eV. When these photons strike the walls of the cell, photo-electrons will be emitted into the liquid. These electrons will lose energy by collisions with helium atoms and will, once their velocity has become sufficiently small, become trapped in bubbles. At the top surface of the cell where the phonon-roton wind is blowing away from the wall, the bubbles will be carried away from the wall. It is very hard to estimate the rate of electron production by this process. If the electron bubble is formed near to the wall, it will be pulled back to the wall by the image charge. The drag force on a bubble due to a photon-roton wind of 5 cm s^{-1} at 1.5 K is approximately 3×10^{-11} dynes. This exceeds the image charge force only when the bubble is at a distance of 4.4×10^{-5} cm or more from the wall. Most electrons will form bubbles before they reach this distance and so will be pulled back to the wall. Based on known values of the electron-helium scattering cross-section [13], it should be possible to perform a Monte Carlo calculation to find the fraction of electrons that can escape but as far as we are aware this has not been done [14].

As already mentioned, most of the electrons were first seen when they were near to the top of the cell. Two examples showing tracks of electrons that start within the helium are given in figure 3. It is possible that some fraction of these events are associated with cosmic rays. Along a cosmic track most of the free electrons that are produced by ionization will recombine with positive ions but a small fraction may escape. A second possibility is that the electrons result from the Compton scattering of gamma rays emitted by the natural radioactivity of the material making up the cryostat. We have performed an experiment in which a gamma source was brought up to the outside of the helium dewar. When this was done, a large number of electron tracks could be seen to start in the liquid.

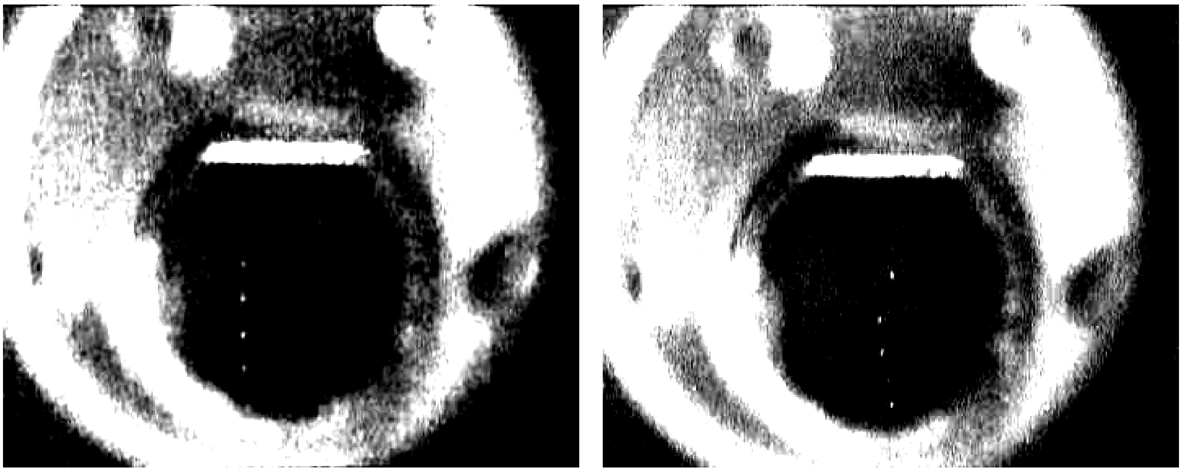

Figure 3. Examples of images in which the electron is first detected somewhere in the interior of the cell.

For some of the electrons that start at the top of the cell a different sort of track is seen as shown in figure 4. The electron moves through the liquid following a path like a snake. These appear to be electrons that have become attached to quantized vortex lines, and are sliding down the line. It is well known that there is an attractive force that can bind an electron to a vortex line [15]. However, this force is very short range, i.e., it is appreciable over a distance of less than 100 Å, and so it is remarkable that the bubble can grow to a radius of several μm and then return to its normal small size and still be attached to the vortex. Observations of the type shown in figure 4 open up the possibility of studies of the geometry and motion of quantized vortex lines.

Finally, we mention that occasionally we record frames on which there are images of several electrons. An example is shown in figure 5. Even though this happens in a relatively small fraction of the time, it appears to occur more often than would be expected based purely on coincidence. Note that in figure 5, although there must be more than one electron present, it is not obvious which of the images are associated with which electron. One possibility is that these events originate when a first electron is excited by Compton scattering and then the lower energy gamma ray that is produced undergoes a second Compton scattering process.

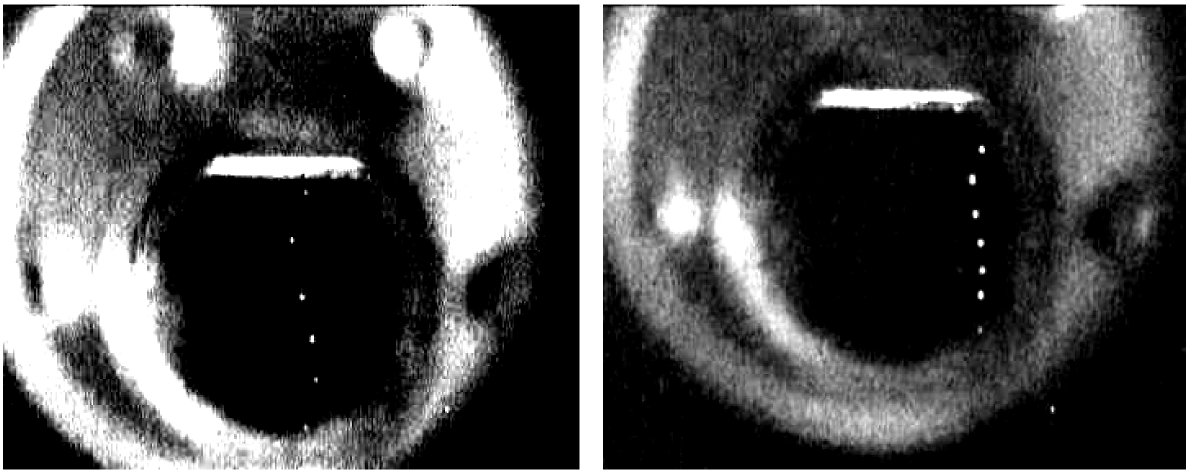

Figure 4. Image of an electron sliding down a vertex line. The temperature is 1.8 K.

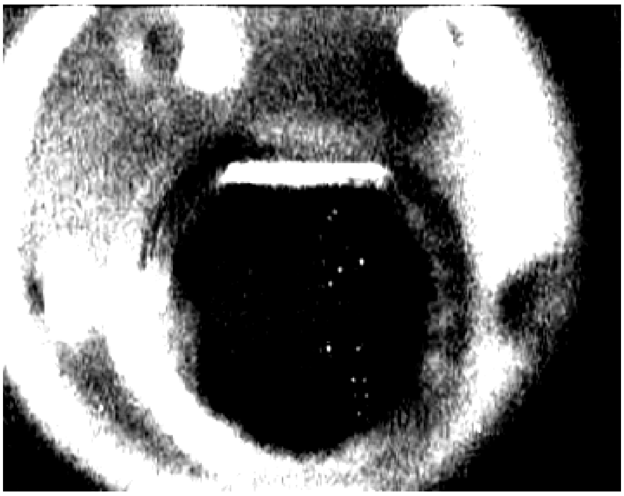

Figure 5. A frame in which more than one electron is present.

Acknowledgements

We thank George Seidel for helpful discussions regarding the interaction of energetic particles with liquid helium. This work was supported in part by the National Science Foundation through grant DMR-0605355.

References

[1] Guo W and Maris H J 2007 *J. Low Temp. Phys.* **148** 199; A section of a movie showing the motion of several electrons is accessible at http://physics.brown.edu/physics/researchpages/cme/bubble/Movie.mpg.

[2] For the development of the bubble chamber and theoretical discussion, see Glaser D A 1952 *Phys. Rev.* **87** 665 and 1953 *Phys. Rev.* **91** 762; Seitz F 1958 *Phys. Fluids* **1** 2; Tenner A G 1962 *Phys. Fluids* **11** 361

[3] See, for example, Heitler W 1954 *The Quantum Theory of Radiation* (New York: Oxford)

[4] The properties of ions in helium have been reviewed by Fetter A L 1976 *The Physics of Liquid and Solid Helium* (chapter 3) ed Benneman K H and Ketterson (New York: Wiley), and Donnelly R J 1967 *Experimental Superfluidity* (chapter 6) (Chicago: University of Chicago Press)
[5] Grimes C C and Adams G 1990 *Phys. Rev. B* **41** 6366 and 1992 *Phys. Rev. B* **45** 2305
[6] Maris H J and Guo W 2004 *J. Low Temp. Phys.* **137** 491
[7] Maris H J 2003 *J. Low Temp. Phys.* **132** 77
[8] Akulichev V A and Boguslavskii Y Y 1972 *Sov. Phys. JETP* **35** 1012
[9] Classen J, Su C –K, Mohazzab M and Maris H J 1998 *Phys. Rev. B* **57** 3000
[10] Strutt J W 1917 *Phil. Mag.* **34** 94
[11] Digital Nova-Strobe from Monarch Industries, Inc
[12] Sony model TRV740 camcorder
[13] Golden D E, Furst J and Mahgerefteh M 1984 *Phys. Rev. A* **30** 1247
[14] Studies of the injection of low energy electrons into helium have been performed by Onn D G, Silver M 1969 *Phys. Rev.* **183** 295 and 1971 *Phys. Rev. A* **3** 1773
[15] See, for example, Donnelly R J 1967 *Experimental Superfluidity* (Chicago: London)