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Experimental Investigation of Mobility Changes of Negative Ions in Superfluid Helium due to Photo-excitation

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Abstract An electron injected into liquid helium forces open a small cavity called an electron bubble. Although one might expect these objects to have a simple structure, experiments have revealed several effects for which there is currently no explanation. In addition to the "normal electron bubble", other negative ions have been detected which have higher mobility. It has also been found that by shining light onto electron bubbles the mobility can be increased, although it is not known by how much. In this paper we report on preliminary measurements of the change in mobility resulting from optical excitation. Mobility measurements are made by the time-of-flight method.

Keywords Superfluid helium · Mobility · Time of flight method · Photo-excited ions · Photo-conductivity

1 Introduction

There have been many studies of both negative and positive ions in liquid helium. Experiments with positive ions have given results which are consistent with the assumption that the ionized helium atom is surrounded by a spherical shell of solid helium resulting from the attraction of polarized helium atoms to the ion [1]. The "normal" negative ion (also known as an electron bubble) consists of an electron inside a bubble of radius about 19 Å; this bubble is essentially free of helium atoms [2]. In addition to these ions, other negative ions, referred to as "fast" and "exotic", have been detected. The fast ion was first seen by Doake and Gribbon [3], and has a mobility about seven times larger than the normal negative ion. Since the mobility of

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an ion in helium is limited by the drag on the ion as it moves through the gas of thermal excitations (rotons and phonons), the higher mobility indicates that the ion must be significantly smaller than the normal electron bubble. In subsequent experiments Ihas and Sanders [4–6] were also able to detect this ion, and in addition discovered twelve more objects which had mobility between that of the fast ion and the normal ion. These ions have also been detected by McClintock and coworkers who were able to demonstrate that above a critical velocity, different for each exotic ion, quantized vortices were nucleated by the moving ions [7–10]. It was found that the fast ion did not nucleate vortices.

The origin and physical nature of the fast and exotic ions is not known. In a time-of-flight mobility experiment a pulse of ions is introduced at one end of a cell. These ions move under the influence of a constant electric field and the charge arriving at a collector electrode is measured as a function of time. In a recent paper we reported on a more detailed study of the fast and exotic ions [11]. To our surprise we found that in addition to sharply-peaked signals corresponding to the ions detected in the earlier experiments, the collector signal contained a component which was a smoothly varying function of time. When the drift field or temperature was varied, this continuous background signal shifted in time in the same way as did the sharp peaks, indicating that the background must arise from negative ions which have a continuous distribution of mobility. Since the mobility is a function of ion size, this result implies that in the experiment there are present ions with a continuous size distribution. As discussed in Ref. [11], it is very difficult to explain this result. If the ions are assumed to be impurities, each impurity ion should have a different and definite size; if they are some type of exotic helium negative ion which has not been discovered before, the ion size would have a discrete value for each different quantum state.

Another mystery concerns photo-conductivity measurements in liquid helium. Northby, Zipfel and Sanders [12–14], and Grimes and Adams [15] found that when light was shone onto liquid helium containing negative ions the current between two electrodes in the liquid was increased. The change occurred only when the photon energy had the correct value to excite the electron from the ground state to an excited state. These experiments were not performed in a way that made it possible to determine how large a change in mobility resulted from the application of the light. In this paper we report preliminary measurements of the change in mobility using the time-of-flight method.

2 Experiment

In the experiments we first produce electron bubbles which are attached to vortices and therefore essentially immobile. We then excite the electrons from the ground 1S state to the 1P state. This excitation enables some fraction of the electrons to escape from the vortices. We then determine the mobility from the time it takes these electrons to move under the influence of a uniform drift field to a collector electrode. The apparatus is shown schematically in Fig. 1. To produce the electrons we have used a section of tungsten wire coated with single-wall carbon nanotubes. This reduces the threshold voltage needed to produce a current. To construct this we used a method

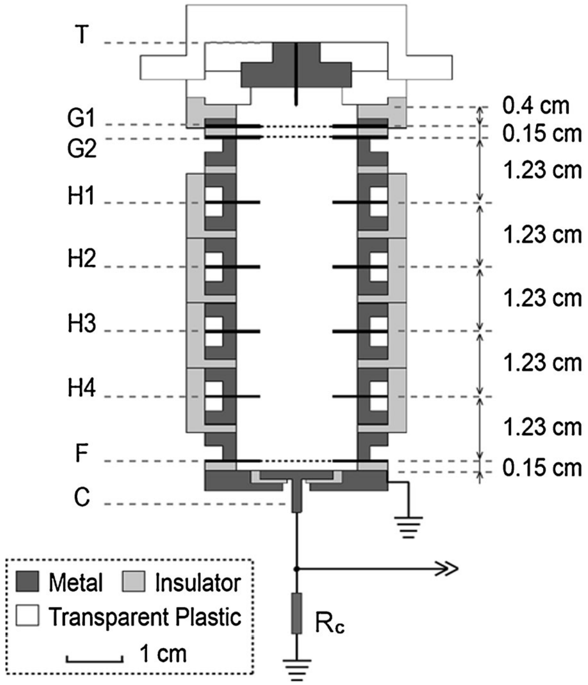

Fig. 1 Schematic diagram of the experimental cell showing the tungsten tip T, gating grids G1 and G2, field homogenizer disks H1–H4, Frisch grid F, and collector electrode C. The current reaching C passes to ground through the 2.4 MΩ load resistor R_c

similar to that described by Kawasaki et al. [16]. The tip was placed at approximately 0.4 cm above the grid G1 (see Fig. 1). When field emission took place, electrons leaving the tip quickly reached the critical velocity for vortex nucleation and became trapped on slowly-moving vortices. A light pulse was applied to the electrons in the region above G1 or below G2. After the electrons passed through these grids they entered the drift region of the cell. They then moved down to the collector in an electric field which was kept uniform by a series of field homogenizer disks (H1–H4). In order to obtain a collector response which accurately reflected the arrival of charge, a Frisch grid was placed in front of the collector.

At zero pressure the photon energy needed to excite an electron bubble from the ground 1S state to the 1P state is 0.11 eV. [15] The energy can be tuned by applying pressure to the liquid; the energy increases by approximately 0.01 eV per bar of pressure. As a light source, we have used a CO_2 laser [17] with a photon energy of 0.1167 eV. Thus the maximum absorption occurs at around 1 bar, but since the full line-width at half maximum is approximately 0.015 eV, there is appreciable absorption even at zero pressure. The laser beam had a diameter of 0.35 cm and entered the cell through a rectangular window which was 0.2 cm high and 0.78 cm wide. When applied below G2 the top of this window was about 0.2 cm below G2. Typically, pulse durations of 1 ms were used. Most of the laser power exited the cell through a window of the same dimensions on the opposite side of the cell. We do not have a way of making an accurate estimate of the laser intensity inside the cell. Negative ions arriving at the collector gave a current passing to ground through the 2.4 MΩ load resistor. The resulting voltage across the load resistor was amplified by 5000 and then averaged over 2000 traces.

Measurements were made as a function of temperature, pressure, the drift field, and laser power. Grimes and Adams [15] noted that photoconductivity was seen only at temperatures below 1.7 K and so we have worked in the temperature range 1 K to 1.4 K. The voltage differences between the tip and G1, and the field between G1 and G2 were also varied. The results obtained had a surprisingly complex dependence on these parameters and here we present only a sample of the data.

In Fig. 2a we show data obtained at 1.04 K with a pressure of 1.45 bars. The laser is pulsed for 1 ms at time zero in the figure with a power into the cell of roughly 0.3 W. The laser is directed below G2. The voltage on G1 is 5 V positive with respect to G2 thus preventing free electrons from passing. However, some electrons attached to vortices can still pass through. The drift field is 46.4 $\mathrm{V\,cm^{-1}}$. At a voltage difference ΔV_{tip} of 550 between the tip and G1 no signal is seen. At 600 V and at 650 V a signal N with arrival time matching the arrival time expected for a normal negative ion is detected. At 650 V there is a small shoulder on the early time side of the normal ion signal. When ΔV_{tip} is increased to 700 V this shoulder turns into a very strong signal A with a mobility larger than that of the normal ion by a factor of 1.07. There are also other peaks B (relative mobility 1.16), and C (relative mobility 1.36) at still earlier times which are not so clearly resolved. At 750 V the N and A signals are greatly decreased, but the C signal is still clearly seen. Results for 1.25 K are shown in Fig. 2b. For these data the drift field was 95.2 $\mathrm{V\,cm^{-1}}$. Again, when the voltage difference between the tip and G1 is increased to above 700 V, the N and A signals become very small.

Figure 3 shows the results obtained at 1.25 K when the laser power is varied from about 0.2 W to 0.5 W while holding all other parameters fixed. The pressure was 1.45 bars, the drift field was 95.2 $\mathrm{V\ cm^{-1}}$, the laser pulse width was 1 ms, and the grid voltages were the same as previously in Fig. 2b. The voltage difference between the tip and G1 was 700 V. At least four, and maybe five, signals arriving before the normal negative ion can be seen.

We have measured the mobility of these objects as a function of temperature and the results are shown in Fig. 4. The temperature dependence was found to be similar to that of the normal negative ion. The peak positions were obtained by fitting each peak with a Gaussian function. The signals at the different temperatures selected for the fitting were similar to the data shown in Fig. 2a at 700 V, and the data shown in Fig. 2b at 650 V.

3 Discussion

At this point we do not understand the origin of the signals resulting from laser illumination. We are assuming that the signals we see result from electrons knocked off vortices by the light in some way. If this is correct, then we can consider two possibilities.

In the description of the results just given it has been implicitly assumed that the detected signals come from some type of negative ion produced in the laser path at the top of the cell. These ions would have to travel the whole length of the cell in order to reach the collector. However, one can consider the possibility that the ions

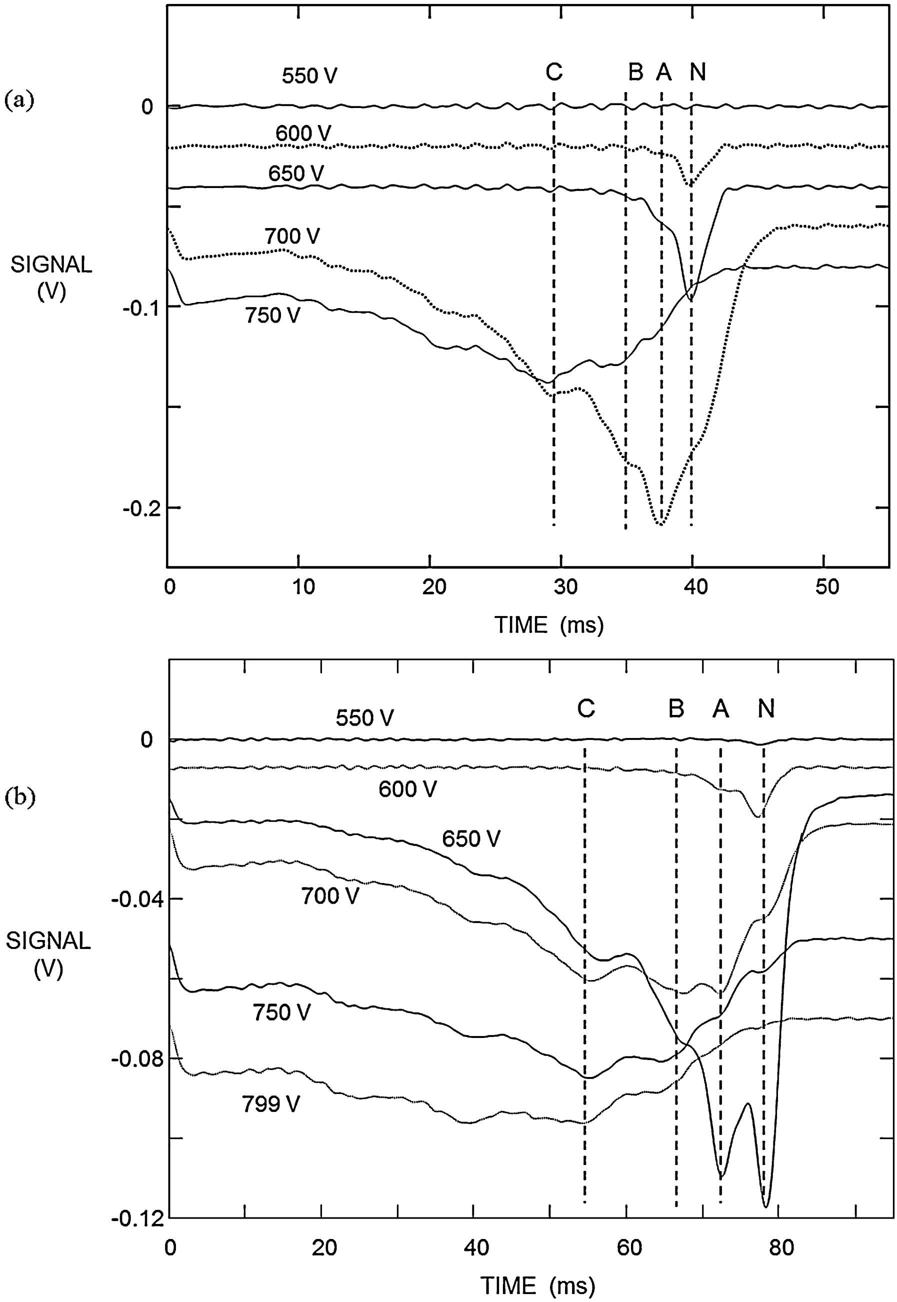

Fig. 2 Collector signal as a function of time. A pulse from the CO_2 laser is applied at time zero. The different curves are labeled by the difference in voltage between the tip and the grid G1. The temperature is (**a**) 1.04 K and (**b**) 1.25 K. Other experimental parameters are listed in the text

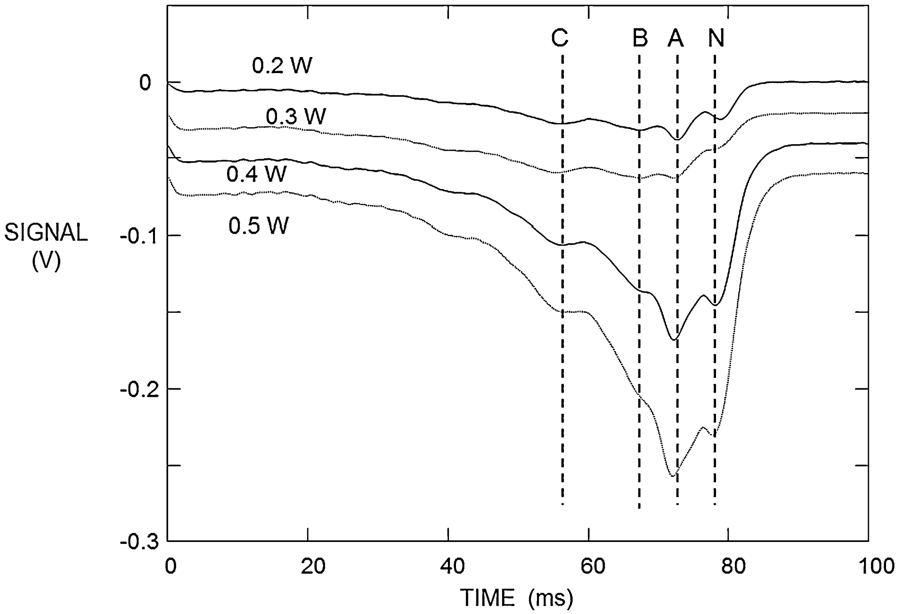

Fig. 3 Collector signal as a function of time. A pulse from the CO_2 laser is applied at time zero. The different curves are labeled by the laser power entering the cell. The temperature is 1.25 K. The voltage difference between the tip and G1 is 700 V. Other experimental parameters are listed in the text

originate some distance below G2 and are simply normal negative ions which arrive early because they travel a shorter distance. For this explanation to be correct, there would need to be regions in the cell where there is a high density of vortices with trapped electrons. The electrons on these vortices could be knocked off by laser light which was scattered down the axis of the cell; certainly some of the laser light may miss the exit window and then be scattered in a broad range of directions. However, some difficulties with this idea are:

(1) The intensity of light should be much stronger in the laser path where the signal from the N ion originates than anywhere in the region below. Thus, the signal from the N ion should always be significantly stronger than the others; this is not consistent with the data shown in Figs. 2a and 2b. One could perhaps explain this by assuming that a fraction of the N ions are re-captured by the vortices on their way through the drift region.
(2) From the arrival time of the signal one can calculate where the regions with high vortex density would have to be. One finds that these regions do not coincide in an obvious way with any structures within the cell, such as the position of the homogenizer disks shown in Fig. 1.
(3) The ratio of the arrival time of the unknown objects to the arrival time of the normal electron bubbles does not change significantly when the temperature is varied over the range from 1 K to 1.3 K. Thus, the regions of high vortex density would have to remain in the same location in the cell over this temperature range.

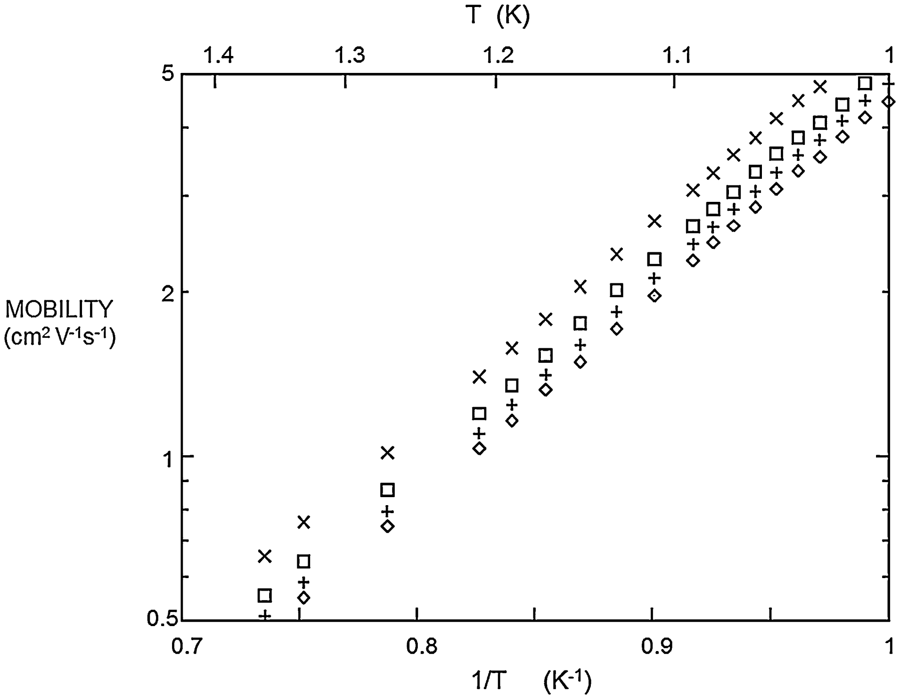

Fig. 4 Mobility as a function of temperature for ions N, A, B and C

(4) The peaks in the signal due to the unknown objects are narrow and typically have a width in time (full-width at half maximum) of only 4 to 6 % of the arrival time of the normal negative ion. This means that each region of high vortex density has to have an extent which measures no more than 3 or 4 mm along the vertical axis of the cell.

To determine if this is the explanation and such structures exist we are currently modifying the cell so that we can apply different fields to the upper and lower part of the cell. Clearly, if the ions come from the lower part of the cell they will be unaffected by changes in the field in the top part of the cell.

The other possibility is that the ions are produced at the top and that they are new objects produced by light. In a previous paper [18], it was proposed that when an electron bubble is excited to the 1P state it may break into two bubbles each containing a part of the wave function of the electron. If the bubble breaks into two, one or both of the smaller bubbles produced might escape from the vortex. However, in that paper it was proposed that the bubbles would have equal size and that the mobility might increase by a factor of about $2^{1/2}$. This would not explain the mobility of the objects seen in the current experiments, but it is possible that after photoexcitation a bubble breaks up in a completely different way when it is attached to a vortex.

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