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Studies of Fast Negative Ions in Superfluid Helium

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Abstract The normal negative ion in liquid helium consists of an electron confined in a bubble of radius approximately 19 Å. These bubbles have been studied in many experiments. Time-of-flight mobility measurements have revealed that there are other types of negative ion of higher mobility and unknown structure. In this note we report on a study of the fastest of these and discuss the conditions under which it can be observed.

I. Introduction

The energy of an electron in bulk liquid helium is about 1 eV higher than it is in vacuum. As a result, an electron injected into liquid helium forces open a spherical cavity with radius R of approximately 19 Å [1]. This cavity contains essentially no helium atoms. These so-called "normal" negative ions have been studied in many experiments. Their size has been confirmed by measurements of the energy of the photons required to excite the electron to higher energy quantum states [2]. The size can also be studied through ion mobility measurements. When the ion moves through the liquid it collides with phonons and rotons, and this results in a drag force which, because the mean free path of these excitations is larger than the diameter of the ion, is proportional to R^2. As a result the mobility μ should be proportional to R^{-2}. In several of the mobility experiments, ions have been detected [3,4,5,6,7] which have a larger mobility than the normal negative ion and thus presumably have a smaller radius. These have become known as the exotic ions and the fast ion. The physical nature of these objects is not known. Until now, we have managed to reproduce the fast ion and some of the exotic ions in our experiments. In this note, we will report only on a study of the fast ion, i.e., the ion with the highest mobility observed so far.

In our experiment we measure the mobility by a time-of-flight method as shown schematically in figure 1. The experimental cell contains liquid with helium vapor above it. To generate ions, a large negative voltage is applied to start an electrical discharge between a sharp tip S and a perforated plate P. This results in electrons entering the liquid. The liquid surface is normally below the level of the plate P. Grid G2 is normally held at a potential negative with respect to G1 and thus blocks electrons from entering the lower part of the cell. By applying a negative gate pulse to G1 and P, the gate can be opened and a pulse of ions introduced into the drift region below G2. The ions then move down the cell as a result of a drift field that is kept uniform by the homogenizer disks H1-4. They then pass through the Frisch grid F to the collector C. The length of the drift region is 6.15 cm, the spacing between G1 and G2 is 0.15 cm, and each gold-plated nickel grid has 28 wires per cm. The collector is connected to ground through a 2 MΩ resistor. Through a measurement of the collector voltage the ion current arriving at the collector can be measured. To improve signal to noise typically 5,000 to 20,000 traces were averaged.

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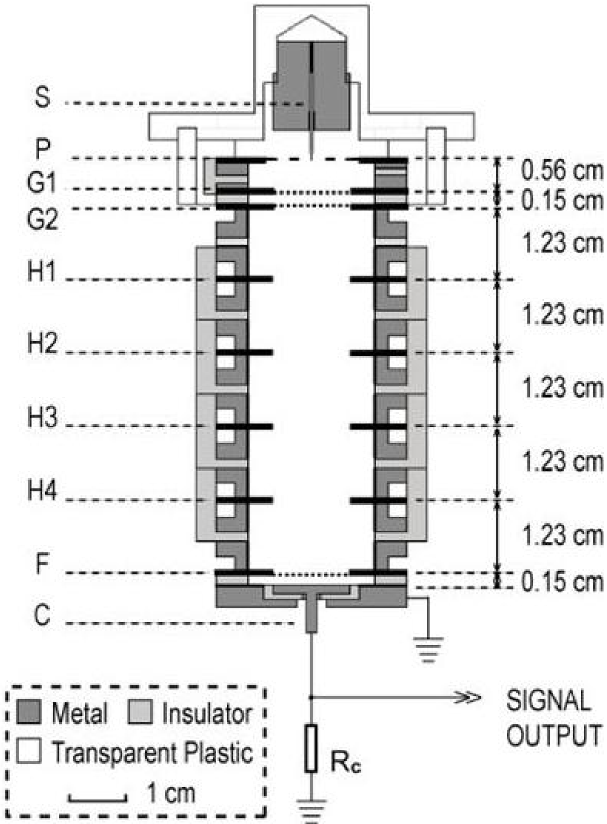

Figure 1. Cross-section through the mobility cell.

Experimental Results and Analysis

Previous work by Ihas and Sanders [4,5,6] and McClintock *et al.*[7] has found that the geometry of the perforated plate has a large effect on the size of the signal coming from the fast ion and the exotic ions. However, the reason for this variation is not known. In our experiment the perforated plate had a 6 mm diameter hole at its center and six 3 mm holes arranged in a circle around the center hole. The end of the tip S was in the plane of the plate. As the current flowing into the tip increased, the color of the discharge changed from pale yellow to pink to purplish white. With the configuration of the plate that we have used, we can easily detect the fast ions as well as the normal ions. A sample trace showing the collector current as a function of time is shown as the solid curve in figure 2. These data were taken at a temperature of 1.03 K with the helium level at 0.5 mm below P, the current flowing into the tip being 93 μA, a drift field of 98 V cm^{-1}, and a gate pulse of width 0.4 ms. From these data we find that each pulse contains 1.3×10^4 fast ions and 8.2×10^5 normal ions, a ratio of 0.016. For a constant current into the tip and constant voltages applied to all the remaining electrodes in the cell, the numbers of both fast and normal ions decreases as the temperature goes up, but the rate of decrease for the fast ions is much greater than that of normal ions.

Results for the drift velocity as a function of electric field at 1.00 K are shown in figure 3. The mobility is independent of field for small fields, but for the fast ion decreases significantly when the drift field reaches 100 V cm^{-1}. In figure 4 we show the mobility as a function of temperature for a fixed drift field of 98 V cm^{-1}. The data are fit very well by

$$\mu = A\exp\left(\Delta / kT\right), \qquad (1)$$

where A is a constant and $\Delta = 8.68$ K for fast ions, and 8.2 K for normal ions. This temperature dependence is to be expected if the mobility of the ions is limited by collisions with rotons. These values of Δ compare with the values of 9.4 K and 8.6 K found by Ihas [5]. The difference between our results and those of Ihas may be a result of the measurements being made at different field strengths.

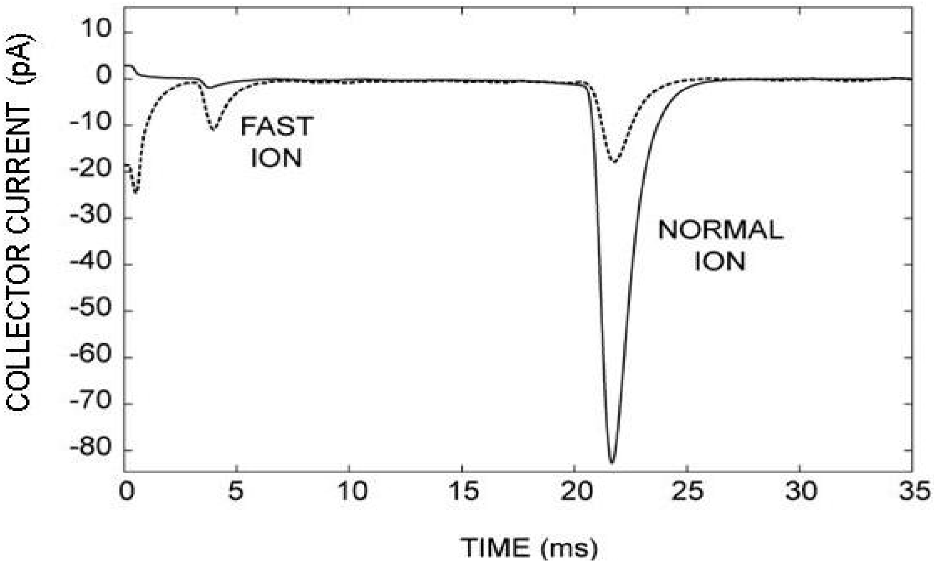

Figure 2. Current arriving at the collector as a function of time. The solid curve shows results obtained with a discharge in the vapor. The dashed curve is with the tip S in the liquid as described in the text.

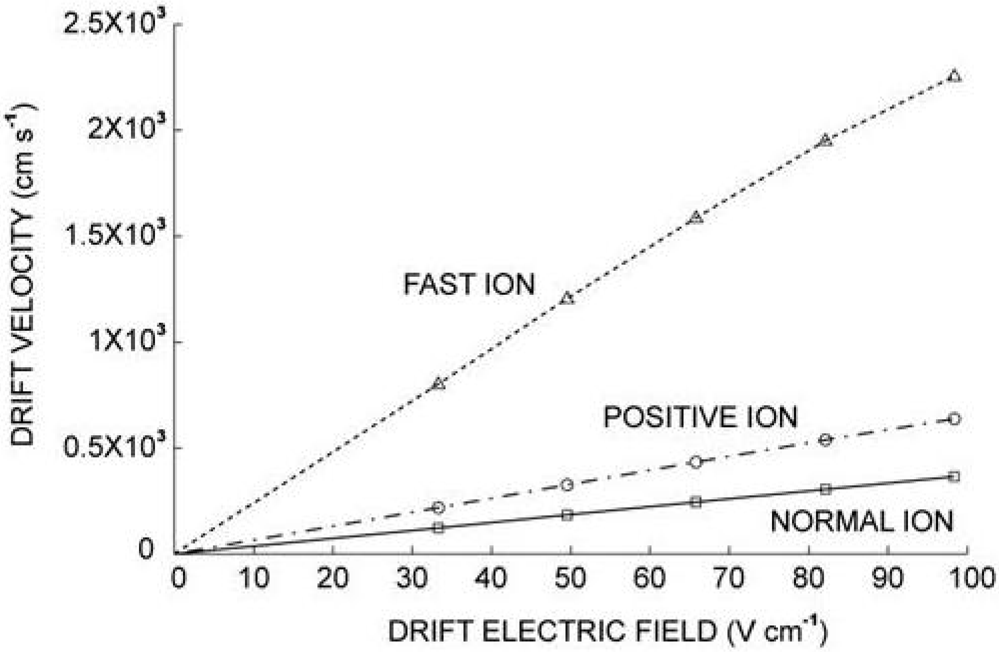

Figure 3. Drift velocity of fast and normal negative ions, and positive ions as a function of the drift field.

By reversing the sign of all of the voltages in the cell we have been able to obtain the results for positive ions that are shown in figures 3 and 4. For these ions we find $\Delta = 8.6$ K. We have seen no sign of any positive ions other than the He^+ ion that has been seen in many previous experiments [8].

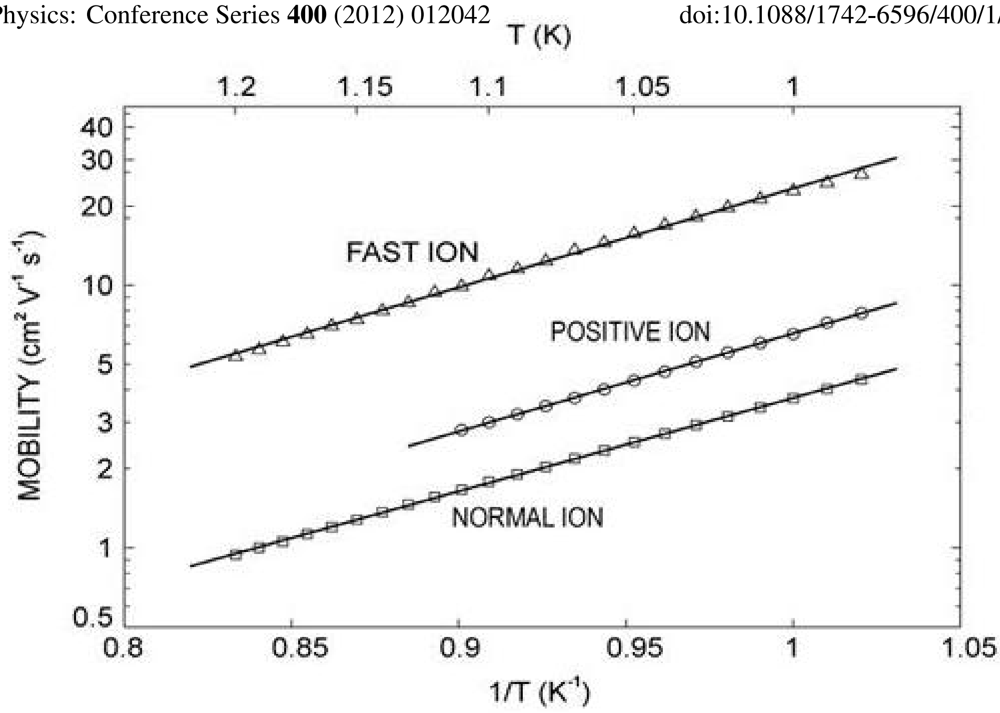

Figure 4. Mobility of the fast, positive and normal negative ions as a function of temperature.

We had also planned to generate ions by field emission from the tip directly into the liquid and see whether fast ions could be produced in this way. However, after adding extra liquid into the cell until the liquid surface was several mms above the tip, we found that before any field emission from the tip could be seen, we saw sparks in the liquid between the metal cylinder holding the tip (see figure 1) and the perforated plate. When this occurred we obtained fast ion peaks of a size comparable to the normal ion signal; an example is shown by the dotted line in figure 2. This trace was taken at a temperature of 1.03 K with a drift field of 98 V cm^{-1}, a gate pulse of duration 0.6 ms, but with a current flowing into the tip much less than the previous case. The number of fast ions per pulse is 8.2×10^4 compared to 1.8×10^5 normal ions, giving a ratio of 0.45 which is much larger than the ratio with the tip in the vapor.

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