Study of Exotic Ions in Superfluid Helium-4 Using a Carbon Nanotube Source

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Abstract. We have extended our measurements of the properties of exotic negatively-charged ions in superfluid helium-4. We measured the ion mobility using the time-of-of-flight method at temperatures in the range between 1.03 and 1.16 K. Ions were generated by an electrical discharge produced by applying a voltage to sharp tips in the helium vapor above the liquid surface. Previous studies by Ihas and Sanders, Eden and McClintock, and by our group used tungsten tips and were able to detect at least twelve exotic ions in addition to the normal electron bubble. In the present work we have experimented with tips each consisting of a stainless steel wire coated with carbon nanotubes. We have found that with these tips the strength of the exotic ion signal is substantially increased making it possible to detect several ions which previously could not be seen. The present data combined with the results of the previous studies indicate that there are at least eighteen exotic ions with different mobility.

Introduction

Studies of ion mobility in superfluid helium-4 have revealed the existence of a number of negatively charged objects in addition to the well-studied normal electron bubble (NEB). Doake and Gribbon [1] produced ions in the liquid using an α source, and discovered an ion now called the "fast ion" which has a mobility about six times larger than an NEB. Ihas and Sanders [2] and Eden and McClintock [3] generated ions by applying a voltage to a sharp tip in the vapor above the liquid to produce an electrical discharge. Ions were then drawn from the vapor into the liquid. These experiments demonstrated the existence of at least 13 so-called "exotic ions" with mobility lying between the mobility of the fast ion and the NEB. In addition, it has recently been found that as well as the ions with 13 different and discrete values of mobility, there is also a large component in the measured signal which comes from ions which have appear to have a continuous distribution of mobility [4].

Despite much effort, an understanding of the structure of these objects is still lacking:

1) One can propose that the ions are negative impurity ions. This seems unlikely because liquid helium does not usually contain any significant concentration of impurities. However, it is possible that in the electrical discharge atoms from the discharge tip are introduced into the vapor. Even if this were to happen, it seems unlikely that there could be 13 different impurities present in the vapor in roughly comparable amounts. Also each impurity species should produce a negative ion of a definite size and mobility. Thus it appears impossible to explain the continuous background in terms of impurities.

2) A second possibility is that the exotic ions are helium ions. Helium ions have been studied in a number of experiments [5] but these have a lifetime much less than the time needed to pass through

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the mobility cell. In addition, helium ions cannot provide an explanation of all 13 different exotic ions or the continuous background.
3) Finally, it has been proposed that the exotic ions and the fast ion could be electron bubbles containing only a fraction of the wave function of an electron [6]. These bubbles could be smaller than an NEB and, as a result, have a higher mobility. The fission theory might be able to explain the existence of the continuous mobility distribution.

To investigate further it is of value to vary the experimental conditions in the mobility measurements as much as possible. In this paper we have changed the way the discharge in the vapor is produced by replacing the tungsten tips (W) used in previous experiments with carbon nanotube tips (CNT). As a result of this change, we have been able to discover several exotic ions not detected before.

2. Experiment

The mobility measurements were made with the cell as shown in Fig. 1. A discharge was formed between the tips mounted on the tip holder T and a plate P containing an array of holes. The level of liquid in the cell was between P and the grid G1. This grid was held with a dc voltage positive with respect to the dc voltage on a second grid G2; these voltages prevented any negatively charged objects entering the lower part of the cell. Application of a negative voltage pulse to G1 allowed a pulse of

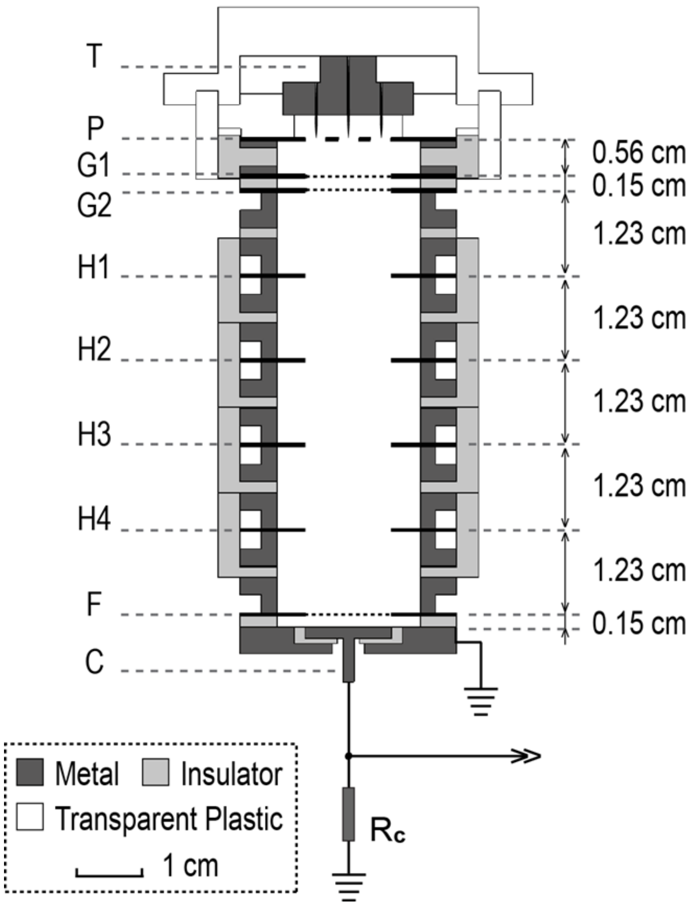

Fig. 1. Schematic diagram of the mobility cell. The function of the different components is described in the text.

negative ions to enter the drift field region below G2. The field in this drift region was made uniform by appropriate voltages applied to the field homogenizer disks H1-4. After passing through the Frisch grid F, the ions reached the collector C.

The current arriving at C passed to ground through a 2.46 MΩ load resistor R_c. The voltage at the collector was amplified and the signal averaged over 5000 traces. Measurements were made as a function of the voltages applied to produce the discharge, the temperature and the drift field.

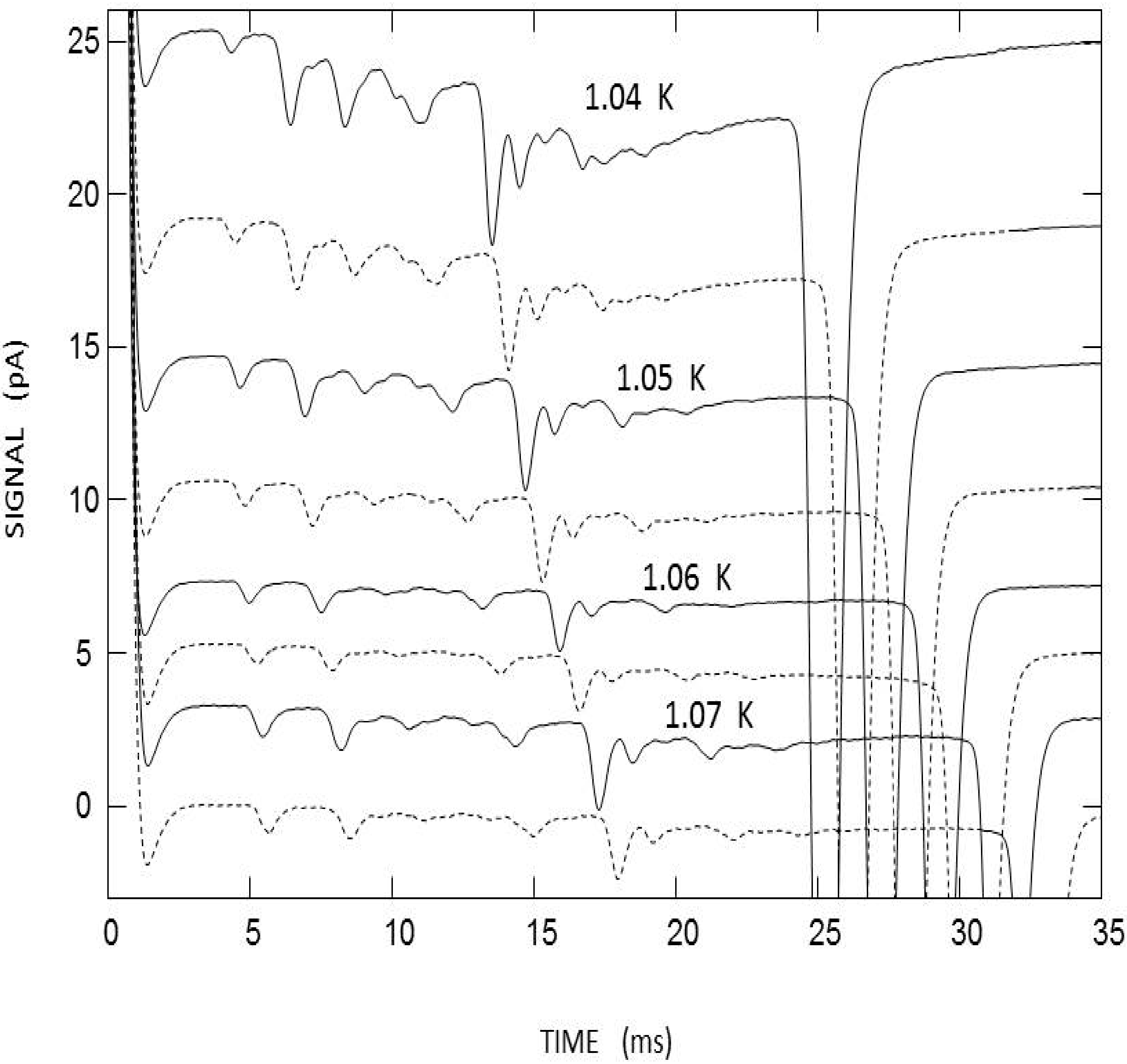

Fig. 2. Current arriving at the collector as a function of time at a series of temperatures spaced by 50 mK. The different data sets are offset for clarity. The peak at early time is the result of electronic pickup and overshoot.

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To prepare CNT tips [7] we first placed one or two drops of acetone containing single-wall carbon nanotubes on a glass slide. After the drops spread and dried out, a piece of soft stainless steel capillary (0.012" OD) was coated with a thin layer of silver epoxy. This was then rolled on the slide before the epoxy dried in order to glue the CNTs onto it. The epoxy was then dried out.

Representative data obtained with the CNT tips at a series of temperatures between 1.04 K and 1.075 K are shown in Fig. 2. These data were taken with -510 V on G1, -520 V on G2 and 15.7 V on the Frisch grid F. The voltages on the tips and on the plate were adjusted slightly to optimize the discharge at each temperature. Typical values were -930 V on the tips and -530 V on the plate. We were surprised to find that the signals with the CNT were considerably stronger than with the tungsten tips.

In Fig. 3 we show in more detail the signal at 1.045 K. Fourteen different ions are detected in addition to the fast ion (arrival time 4.5 ms) and the normal electron bubbles at 26 ms.

We were interested to see if the exotic ions seen with the CNT tips were the same ions that had been seen previously with tungsten tips. It is not so simple to make a definite determination because the strength of the signal coming from a given ion varies considerably with the condition of the plasma, and this is influenced by the properties of the tips. In addition, because the CNT signal is stronger than

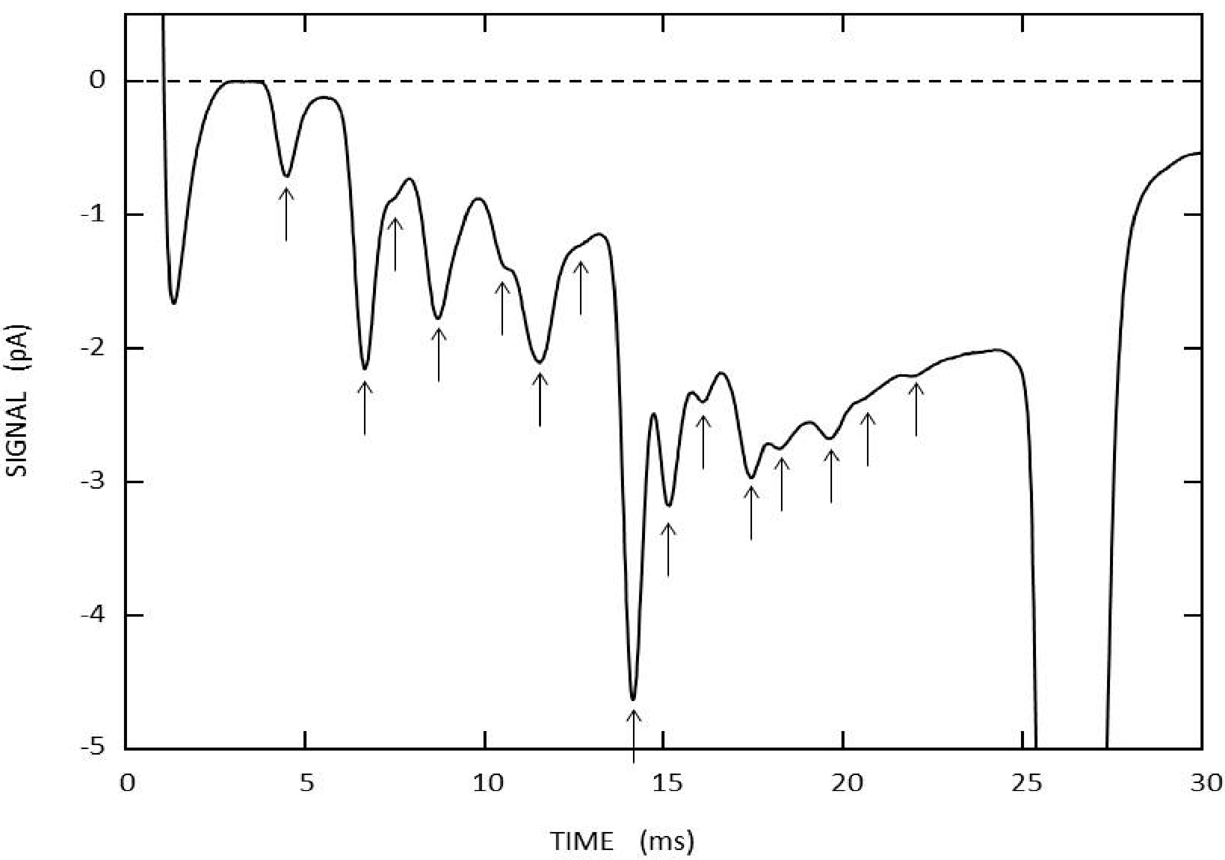

Fig. 3. Signal detected in an ion mobility experiment at 1.045 K. The voltages applied to different parts of the cell are given in the text. The normal electron bubbles arrive at 26 ms. Each arrow indicates the arrival of a particular exotic ion. The peak at 1.3 ms results from overload of the amplifier due to the electromagnetic pickup of the pulse applied to the gate grid.

the tungsten tip signal, it may not be possible to detect some of the ions seen with the CNT when the tungsten tips are used. In Fig. 4 we show a comparison of two data sets both taken at a temperature close to 1.04 K. For the CNT data there was a voltage of -974 V on the tips, -530 V on the plate, -510 V on G1, and -520 V on G2. For the tungsten data the voltage on the tips was -775 V, -550 V on the plate, -510 V on G1, and -520 V on G2. The time axis has been scaled so that the normal electron bubbles arrive at unit time, and the signal axis has been scaled and offset to make it easier to compare the two data sets. One can see from the figure that there are at least six ions that are clearly present regardless of which type of tip is used. This means that these ions cannot have a structure which incorporates the material of the tip. As far as the other ions which appear with either but not both of the sources, it seems most likely that their appearance for only one type of tip is related to the different condition of the plasma. One can see from Fig. 3 that several of the ions which do appear clearly on both traces have a large difference in their amplitude in the two traces. Combining the exotic ions which are seen with either or both the CNT and W we find that there are at least 18 different ions.

In previous work [4] we were able to show that when a fit was made to each peak coming from an exotic ion and this fit used to remove the peak, a continuous background signal was revealed. This background took on two distinct forms depending on the temperature and the voltages applied to produce the plasma. Background type #1 had a sharp cut-off at approximately half the arrival time of the normal electron bubbles. Background type #2 increased smoothly with arrival time and it was not

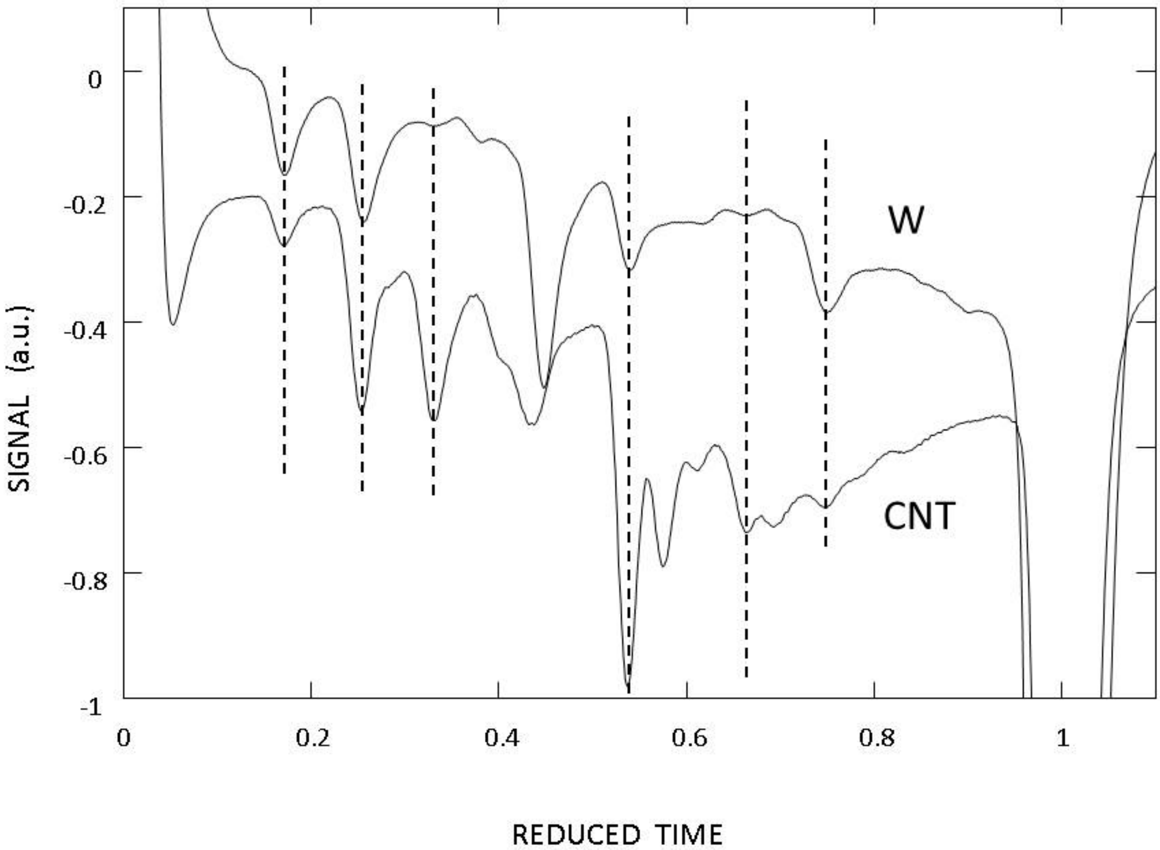

Fig. 4. Comparison of signals obtained at 1.04 K using carbon nanotube (CNT) and tungsten (W) tips. The vertical dashed lines indicate the ions which are clearly present when either type of tip s used.

clear whether there was a cut-off. We have not performed this peak subtraction procedure with the CNT data since it is made difficult by the presence of more ion peaks than were present with the tungsten tips. However, looking at the general form of the data as shown in Figs. 2-4 it appears that the type #1 background is again present.

3. Summary

As emphasized in the introduction, there is no accepted theory of the physical nature of the exotic ions. The present experiment has determined that there are at least 18 exotic ions each with a different mobility. Nearly all of the ions seen previously in experiments with tungsten tips are detected with tips of the different material used here. The experiments also confirm the existence of a signal coming from ions with a continuous distribution of mobility as seen previously[4]. These results make it very unlikely that the exotic ions can be explained in terms of impurities or negative helium ions.

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