STUDY OF EXOTIC IONS IN SUPERFLUID HELIUM AND THE POSSIBLE FISSION OF THE ELECTRON WAVE FUNCTION

W. Wei, Z. Xie, L.N Cooper, G.M. Seidel, and H.J. Maris

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

An electron in liquid helium forces open a cavity referred to as an electron bubble. These objects have been studied in many past experiments. It has been discovered that under certain conditions other negatively charged objects can be produced but the nature of these "exotic ions" is not understood. We have made a series of experiments to measure the mobility of these objects, and have detected at least 18 ions with different mobility. We also find strong evidence that in addition to these objects there are ions present which have a continuous distribution of mobility. We then describe experiments in which we attempt to produce exotic ions by optically exciting an electron bubble to a higher energy quantum state. To within the sensitivity of the experiment, we have not been able to detect any exotic ions produced as a result of this process. We discuss three possible explanations for the exotic ions, namely impurities, negative helium ions, and fission of the electron wave function. Each of these explanations has difficulties but as far as we can see, of the three, fission is the only plausible explanation of the results which have been obtained.

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I. INTRODUCTION

An electron injected into liquid helium forces open a cavity within which there are essentially no helium atoms; this is referred to as an electron bubble. The idea that electrons in helium form a bubble state was first proposed by Ferrell [1]. The bubble is formed because there is a repulsive interaction between an electron and helium atoms (the energy needed to insert an electron into uniform liquid helium [2,3] is 1 eV), and because the surface energy of the interface between liquid and vacuum is very low [4] (0.375 erg cm^{-2}). The radius *R* of this bubble can be estimated with reasonable accuracy from a simple model. The energy E of the bubble is taken to be the sum of the zero-point energy of the electron confined within a sphere of radius *R*, the surface energy, and the volume energy if a pressure *P* is applied. Thus

$$E = \frac{h^2}{8mR^2} + 4\pi R^2 \alpha + \frac{4\pi}{3} R^3 P \qquad (1)$$

Here *m* is the mass of the electron, and α is the surface tension of the liquid. In the derivation of Eq. 1, the penetration of the electron wave function into the liquid is neglected, it is assumed that the surface energy can be taken to be the product of the surface area and the surface tension, and the energy associated with the polarization of the liquid by the electric field of the electron is ignored. From Eq. 1 one finds that when the pressure is zero the equilibrium radius is

$$R_0 = \left(\frac{h^2}{32\pi m\alpha} \right)^{1/4}. \qquad (2)$$

Using the experimentally-measured value of the surface tension [4], this gives $R_0 = 18.9$ Å. Much more sophisticated calculations of the structure of the bubble have been performed using density functional theory to describe the liquid-vapor interface and allowing for the penetration of the electron wave function into the bubble wall [5]. The radius of the bubble obtained from these calculations does not differ greatly from the result in Eq. 2.

The theory of the bubble size can be tested through a measurement of the photon energy required to excite the electron from the ground state to an excited state (1P and 2P states) [6,7,8]. The result of this measurement is in excellent agreement with the density functional theory [5]. Other techniques which can provide some information about electron bubbles include measurements of the effective mass [9,10,11], mobility measurements [12,13,14], ultrasonic experiments [15,16,17,18], and studies of processes in which electron bubbles become attached to quantized vortices [19].

Although the results from several of these experiments on electron bubbles appear to be well understood, there are two interesting phenomena which have so far defied explanation. The first is the existence of other negatively charged objects, the so called "fast ion" and the "exotic ions" [20,21,22,23,24,25,26,27]. Experiments have established that there are at least 14 such objects, each with a different mobility which is greater than that of the normal electron bubble (NEB) just discussed. Despite considerable effort, it has not so far been possible to determine the physical nature of these objects. The second difficulty concerns the effect of light on the electron bubbles. Experiments have been performed by Grimes and Adams [6] and by Sanders and coworkers [28,29,30,31] in which electrons were introduced into the liquid (from a sharp tip or radioactive source) and a measurement was made of the current flowing through the liquid to another electrode at a more positive potential. When light of the right wavelength was used to excite the electrons to a higher energy state, the current to the electrode increased. The energy at which photons were absorbed was in good agreement with theory, but the reason for the increase in mobility is unclear.

In a normal electron bubble the wave function of the electron is entirely confined within the bubble. Thus the integral of $|\psi|^2$ over the volume of the bubble is unity. It has been proposed [32] that the exotic ions might be bubbles in which the integral of $|\psi|^2$ is less than unity, implying that the wave function of the electron is distributed over two or more bubbles. This "fission" theory raises fundamental questions about the measurement process in quantum mechanics as will be discussed later in this paper.

In this paper we report on the results from two new experiments to investigate the anomalous behavior of electrons in helium. In section II we summarize the previous work on the exotic ions, describe the new experiments we have performed, and discuss the possible interpretations of the results. In section III we report on experiments we have performed to investigate the effect of light on electron bubbles, and relate these results to the earlier experiments by other workers. Finally, in section IV we summarize the situation and discuss some open questions. Preliminary accounts of some of the experiments which are reported in detail here have already appeared in two conference papers [33,34].

II. EXOTIC IONS

A. Background

In 1969, Doake and Gribbon [20] reported the observation of a negatively-charged ion with mobility approximately six times that of the NEB. Ions were introduced into the liquid by means of an α source (^{210}Po or ^{241}Am). The mobility was measured by the method developed by Cunsolo [35] using a cell with a grid to gate the ions before they enter a drift field region. The ion discovered by Doake and Gribbon, which has become known as the "fast ion", was next seen in another time-of-flight experiment by Ihas and Sanders (IS) [21,22,23]. IS were able to show that the fast ion could be produced not only by an α source, but also by a tritium β source, and by an electrical discharge in the helium vapor above the surface of the liquid. In their first paper [21], IS reported the existence of two additional negative carriers which had a mobility higher than that of the NEB, but less than the mobility of the fast ion. They called these objects "exotic ions". In a subsequent paper, IS reported a further experiment in which they detected 13 exotic ions each with a different and well-defined mobility [22]. In these experiments the ions were generated from a discharge in the vapor above the liquid. These measurements were made only in the temperature range between 0.96 and 1.1 K. The lower limit was set by the refrigeration capability of the cryostat. The upper limit came about because the density of the helium vapor increases rapidly with temperature, and it becomes difficult to produce a stable discharge in the vapor. IS found that the strength of the signal coming from the different ions depended in a complicated way on the level of the upper surface of the liquid helium in the experimental cell, on the voltage used to generate the discharge, and on the geometry of the electrodes. The IS experiments are described in detail in the thesis of Ihas [23]; the experimental cell is similar to the cell used in our experiments which we will describe shortly. In the upper part of Fig. 1 we show an example of the data obtained by IS. The signal is a measure of the current arriving at the collector as a function of the time after ions leave the top of the cell. These data are for a temperature of 1.005 K, a travel distance of 6.5 cm, and a drift field of 31 V cm^{-1}. The fast ion F and the normal electron bubbles NEB are labeled, and the peaks in the signal between F and NEB arise from the exotic ions.

More recently, these ions have been studied by Eden and McClintock (EM) [24,25,26,27]. They also detected as many as 13 ions with different mobility [36]. In addition, they studied the variation of the mobility with field when the drift field was large. They were able to show that, like the normal ion, the exotic ions nucleate vortices when their velocity reaches a critical value v_c. This critical velocity was found to be larger for the exotic ions of higher mobility. For the fast ion no evidence for vortex nucleation was found. The velocity of the fast ion was proportional to the drift field for small fields but for large fields reached a nearly constant value of around 6000 cm s^{-1}.

The mobility of ions is limited by the drag force exerted on the ion resulting from the scattering of thermal excitations; these excitations are primarily rotons at the temperatures of interest. Since this drag should increase with the size of the ion, it follows that the ion size must decrease with increasing mobility; this assumes that all ions are singly-charged. Both IS and EM put forward a number of proposals to explain the exotic ions, but considered all of these to be unsatisfactory. We will discuss these proposals in detail in section IIC.

B. Exotic ion experiments

1. Apparatus

The experiments of IS and EM were performed using an experimental cell directly immersed in the liquid helium bath of a glass dewar. The temperature was lowered by pumping on the main bath of liquid helium. This method has the advantage of simplicity and provides the large cooling power which is needed when the ions are generated using an electrical discharge in the vapor. However, it is difficult to maintain accurate temperature regulation with this setup and, in addition, the experiment has to be interrupted periodically to transfer additional helium to refill the bath. When this is done, the cell may have to be refilled and the amount of liquid inside the cell adjusted to return the surface of the liquid to the desired position. To avoid these problems, we have constructed a more complex system in which we use a continuously running 1 K pot to cool the cell [37]. The pot and the cell are in a vacuum space below the main helium and nitrogen baths. This arrangement makes it possible to have optical access to the cell without having to look through liquid helium and liquid nitrogen. There are four windows on the cell to provide optical access and another set of windows which make it possible to view the helium level in the 1 K pot if needed.

The 1 K pot had a volume of 220 cm^3 and was filled continuously by means of a capillary running from the main bath. To pump on the pot we used an Edwards 1250 Roots pump followed by an Alcatel 2063 H rotary backing pump. To improve the cooling power, a heat exchanger was used to transfer heat from liquid in the fill capillary to the cold gas evaporated from the pot. The top plate of the cell was an oxygen-free copper plate which also served as the bottom plate of the pot. To reduce the effect of the Kapitza resistance and give good heat transfer between the cell and the pot, we cut grooves into both sides of the plate so as to increase the surface area. These grooves covered the entire area and were 0.125” deep and 0.125” wide. Using the value of the Kapitza resistance for the copper to helium interface as measured by Anderson *et al* [38], the temperature difference between the cell and the pot when the temperature is 1 K and the heat flux is 25 mW should be about 4 mK. The system could handle a heat load of 21 mW at 0.965 K and 136 mW at 1.15 K.

Details of the cell geometry were slightly different in different experimental runs but the general features are as shown in Fig. 2. This figure shows just the elements inside the cell which are involved in the measurement of the mobility; it does not include the outer body of the cell, the windows, electrical feed-throughs, and the connection to the 1 K pot. At the top of the cell were a number of tungsten tips (four in most runs) with end diameter of ~1 μm [39], mounted in a hexagonal brass holder. The end of each tip was approximately 0.05 cm above one of the holes in the perforated plate P. This plate P had seven holes of diameter 0.39 cm diameter, one at the center and six on a circle of diameter 0.95 cm. By applying a sufficiently large negative voltage to the tips, typically between 300 and 500 V negative with respect to the voltage on the plate, a discharge in the helium vapor could be produced. The surface level of the liquid helium was normally positioned between the plate and the grid G1. Electrons in the discharge enter into the liquid and then move in a way controlled by the gate grids G1 and G2. The spacing between G1 and G2 was 0.15 cm, and the grids had 28 wires per cm. If the voltage on G1 is positive with respect to the voltage on G2, the electrons from the discharge will be captured by G1 [40]. Application of a negative voltage pulse to G1 (typical duration 0.4 ms) allows a pulse of electrons to pass though the grid region into the lower part of the cell.

The drift region below G2 is designed to provide as uniform an electric field as possible. A resistor chain runs between the gate G2 and ground. Four field homogenizer disks (H1-H4) are connected to appropriate junctions in the chain so as to minimize variations of the electric field in the space between G2 and the Frisch grid F. The length of the drift region is 6.15 cm. In the first experimental runs, the diameter of the grids G1 and G2 and the Frisch grid was 1.27 cm, and the diameter of the hole in each homogenizer plate was this same diameter. This arrangement had the advantage that an electron entering the liquid from anywhere within a large area of the liquid surface could reach the drift region and pass through to the collector. However, it had the disadvantage that some significant fraction of these electrons passed close to the inner perimeter of the homogenizer discs where there were significant variations of the magnitude and direction of the electric field. Such variations result in broadening of the signal pulse coming from the arrival of ions. To avoid this, in later runs we reduced the diameter of the grids G1 and G2 to 0.8 cm. This reduced the signal strength but made the pulses sharper.

Electrons reaching the collector plate C pass to ground through a load resistor $R_c = 2.46\ \text{M}\Omega$. The measured signal is the voltage across this resistor. The function of the Frisch grid F is to give sharp signal pulses. Without the Frisch grid, electrons approaching the collector would give rise to a slowly increasing image charge on the collector. The Frisch grid results in there being only a very small charge induced on the collector until after the electrons pass through this grid. The distance between the Frisch grid and the collector is 0.15 cm and the time for ions to pass from F to C contributes to the width of the signal pulse. The width is also affected by the RC time constant of the detector circuit. The voltage across the load resistor was measured using a Stanford Instruments SR560 amplifier. The effective capacitance was the sum of the input capacitance of the amplifier (25 pF), the capacitance of the collector plate to ground and the cable capacitance. To keep the total capacitance as small as possible we reduced the capacitance of the cable to the amplifier by bringing the cable out through the tail of the cryostat. This resulted in a total capacitance of 90 pF and an RC time constant of 220 μs. It is straightforward to apply a correction to the measured signal to remove the effects of the finite RC time constant. However, other factors in the experiment, specifically the spatial variation of the drift field, the spacing between the Frisch grid and the collector, the spacing between G1 and G2, and the duration of the pulse applied to G1, had a comparable or larger effect on the pulse width. Consequently, it was not worthwhile to apply a correction to allow for the RC time constant. The gate grid G1 was normally pulsed 10 times per second and in order to achieve a reasonable signal to noise ratio, we typically averaged 5,000 to 20,000 traces. The signal to noise was such that we could usually detect the arrival of ion pulses with a total charge of the order of 500 e.

Thermometry is a challenge in this experiment because the mobility μ varies very rapidly with temperature, and $d\ln\mu / d\ln T$ is approximately -9 at 1 K. The thermometry is based on a germanium thermometer calibrated by Lake Shore Cryotronics

[41]. At 1 K the calibration is specified to be good to ± 0.004 K. This thermometer has replaced the thermometer used for the data already presented in refs. 33 and 37, and we have applied a temperature correction of a few mK to the data repeated from those references.

2. Mobility of exotic ions

Regardless of the conditions of the plasma, it was always possible to detect a strong signal from normal electron bubbles. When allowance was made for experimental uncertainty (primarily temperature errors), the measured mobility of the NEB was in agreement with values in the literature [42]. Signals from the exotic ions were readily detected; these signals were typically between 10 and 100 times smaller than the NEB signal. The amplitude of the signals from the different ions varied in a complicated way with the experimental parameters (see below), and under different conditions different exotic ions were detected. The lower part of Fig. 1 shows data obtained under conditions such that 11 ions could be seen in addition to the fast ion. We have assigned the ions numbers based on increasing transit time with 1 being the first ion after the fast ion. In the data plotted in Fig. 1 there is also a small signal which is only slightly above the noise level and which arrives slightly before ion #4. These data were taken at a temperature of 0.991 K with the tip voltage $V_T = -791$ V, plate voltage $V_P = -550$ V, grid voltages $V_{G1} = -502$ V and $V_{G2} = -520$ V.

To compare our results with those of Ihas and Sanders we calculated the ratio of the mobility of each ion to that of the NEB, and then compared this set of ratios with the same ratios calculated from the IS data. We used this method because it reduced the effect of temperature errors in both our data and that of IS. Based on this comparison it is clear that nearly all of the ions we see have also been seen by IS. This can also be seen simply by comparing signal traces as is done in Fig. 1. In this figure the time axes of the two plots have been scaled so that the positions of the normal electron bubble on each plot match. One can see that while the relative amplitudes of the signal from the different ions vary by a large amount between the two data sets, the arrival times match very well.

Small deviations from matching could result from the difference in temperature since the temperature-dependence of the mobility is slightly different for each different ion.

It is not possible to compare the mobility results with the work of Eden and McClintock [24,25,26,27] since in their experiments they have primarily focused on measurements at high fields where the mobility depends significantly on the field.

In Fig. 3 we plot the mobility of three of the exotic ions, plus the fast ion F and the NEB as a function of temperature.

3. Effect on ion signals of changes in experimental parameters

In the experiment there are a considerable number of parameters which can be varied. These include the voltages on the tips, the voltages on the grids G1, G2, the plate P and the Frisch grid F, and the amplitude and duration of the gating pulse applied to G1. We have also made several variations in the number of tips, the arrangement of the holes in the plate P, and the level of the liquid surface. Even when the voltages, temperature and liquid level are held constant, the tip current changes with time. We presume this is because the tips become less sharp with use. The appearance of the plasma in the helium vapor changed very rapidly with temperature within the temperature range of the experiment. This is not surprising since the equilibrium number density of helium atoms changes from 1.1×10^{18} cm^{-3} at 1 K to 5.9×10^{18} cm^{-3} at 1.2 K. We had hoped to gain some insight into the nature of the exotic ions by looking at how the relative amplitudes of the signals from different ions varied with change in the different parameters but were unsuccessful. We discovered that the variations were extremely complex. For example, it often occurred that a variation of parameter A would give one type of change in the set of amplitudes when another parameter B had the value B1, but if B was changed to a value B2, the same variation in A might lead to completely different results.

There were also situations in which a large change in a parameter would have little effect, but then at a critical value a major change in the signal pattern would occur [43]. As an example, we show in Fig. 4 data obtained at 1.00 K. The voltage on the plate P and on the grid G2 was held at -520 V, giving a drift field of 82.1 V cm^{-1}. The dc potential on G1 was held at a value 15 to 20 V positive with respect to G2, and to open the gate a negative pulse of amplitude 30 V and duration 0.4 ms was applied. The figure shows the effect of varying the current from the tip. For currents up to 28.5 µA no exotic ions are detected. At 29.1 µA exotic ion #4 appears and at 30 µA ion #10 can be clearly seen.

There was also a large change resulting from variation of the voltage difference between G1 and G2, but this particular change could be understood at least qualitatively. In Fig. 5 we show an example. The temperature was 0.991 K and the helium surface was 2.5 mm below P. The drift field was 82.1 V cm^{-1}, the voltage on P was -550 V, G2 was -520 V, and F was -15 V. The dc voltage on G1 was changed in equal steps from -493 to -515 V and the negative polarity gate pulse applied to G1 to open the gate had magnitude 30 V and a duration of 0.4 ms. Thus, when the gate was open, the voltage difference ΔV driving negative ions through the gate region varied from 3 V to 25 V. Changes in ΔV result in changes in the effective duration of the gate pulse since if ΔV is small, some ions may not be able to pass through G2 during the time that the gating pulse is applied. Because the mobility of the normal ion is smaller than the mobility of the fast and exotic ions, a larger ΔV is needed to obtain the full signal for this ion. Thus, as ΔV is increased the ratio of the normal ion signal to that of the other ions increases.

We have managed to detect some of the exotic ions up to 1.16 K but could not see them above this temperature.

On reviewing the earlier papers by Ihas and Sanders [21,22,23] and Eden and coworkers [25,26,27], we noticed a surprising difference in the configuration of the electrodes for the plasma. Eden *et* al. had the tip at a potential more negative than the plate, i.e., the same arrangement as we have used in the experimental set up described so far. This seems like a reasonable approach since with this polarity electrons are driven down towards the liquid. However, Ihas and Sanders had the tip grounded and the perforated plate between -200 and -300 V, i.e., the tip was the anode and the plate was the cathode. We have performed some experiments with this polarity and have succeeded in seeing the same set of exotic ions as with the voltages the other way around. We show an example of data obtained in Fig. 6. These data were taken at 1 K with a drift field of 82.1 V cm^{-1}, and with different voltages on the tip and plate as listed in the caption.

In addition, we have changed the polarity of <u>all</u> of the electrodes, thereby changing the sign of the drift field. When this is done, and the voltages are such as to produce a plasma in the vapor, we saw a signal at the collector coming from helium positive ions, the so-called "snowballs". The measured mobility agreed with literature values [42], and no other positively-charged ions could be detected. Ihas and Sanders found this same result in their work.

4. Study of the continuous background

Examination of the signal traces shows that in addition to the peaks due to arrival of the different exotic ions, there is a background signal which varies continuously with time. This background signal is, in fact, evident in the data of Ihas and Sanders [22,23] included in Fig. 1, although IS did not comment on it. As we will discuss below, the existence of this background provides a very severe test of any theory of the origin of the exotic ions. To see more clearly the form of this background, it is necessary to find some way to remove the peaks. This cannot be done in a completely rigorous way since we do not have a quantitative theory of the shape of the peaks. As already mentioned in section II B1, there are a number of factors which influence the shape of the peaks and the shape of each peak is not necessarily the same. For example, it is likely that part of the width of the peak comes about because some of the ions follow a path which takes them near to the edge of the homogenizer disks where the drift field is not uniform. Different species of exotic ions may originate from ions traveling at different distances from the cell axis and therefore may be more or less affected by the field inhomogeneity.

Despite these difficulties we have tried to remove the peaks coming from the individual exotic ions. We have assumed a functional form for the pulse shape involving some number of parameters, subtracted the pulse from the data, and then adjusted these parameters until the pulse is no longer apparent. As a pulse shape $f(t)$ we have chosen

[44] an exponential starting at time t_s and having a decay constant t_d convoluted with a Gaussian with width parameter t_w, i.e.,

$$f(t) = \int_{-\infty}^{\infty} g(t-t')\,h(t')\,dt' \tag{3}$$

with

$$g(t-t') = \frac{1}{t_w\sqrt{\pi}} \exp[-(t-t')^2 / t_w{}^2] \tag{4}$$

and

$$\begin{aligned} h(t') &= 0 & t' < t_s \\ &= A\exp\left[-(t'-t_s)/t_d\right] & t' > t_s \end{aligned} \tag{5}$$

This gives

$$f(t) = \frac{A}{2}\exp\left(\frac{t_w{}^2}{4t_d^2} - \frac{t-t_s}{t_d}\right)\left[1-\mathrm{Erf}\left(\frac{t_w}{2t_d} - \frac{t-t_s}{t_w}\right)\right], \tag{6}$$

where A sets the amplitude. The result of subtracting peaks using this procedure is shown in Fig. 7.

Of course, this procedure is somewhat subjective since it is based entirely on judging by eye when a pulse has been removed. However, a different choice of the peak fit function gives an almost identical result for the background [33]. One can see that the data of IS shown in Fig. 1 also provide clear evidence of a background of similar form to that shown in Fig. 7. In both the IS experiment and in ours, the background begins at about half of the transit time of the normal ions.

Surprisingly, we have found that under certain conditions the sharp peaks coming from the individual exotic ions are absent and yet the background is still present. An example of this is shown by the dashed curves in Fig. 8. The temperature was 1.025 K, the voltage on the plate was kept at about 40 V negative with respect to G1, and the drift field was increased from 34.7 V cm^{-1} to 99.7 V cm^{-1} in equal steps. These data provide important information about the origin of the background. One possibility is that the background signal comes from ions which have a continuous distribution of mobility. If this is indeed the case then the time τ_b at which the background signal begins should vary inversely with the applied drift field E_d. In Fig. 8 these times are indicated by the vertical arrows. From these times we can calculate an ion velocity v_{ion} equal to L/τ_b, where L is the length of the drift region. In Fig. 9 we plot v_{ion} as a function of E_d. The velocity is clearly proportional to the drift field, thus indicating that the background does indeed come from ions.

As a further test we have looked at how the time τ_b varies with temperature. We find that at constant field, τ_b varies in the same way as does the arrival time of the discrete exotic ions which have an arrival time close to τ_b.

The background is dependent on the characteristics of the discharge. Under some conditions the background switches to a different form which we call type #2. Data showing this type of background are shown by the solid lines in Fig. 8. The background contribution to the signal extends from the time of arrival of the normal electron bubble τ_{NEB} back to about half of this time. This background is evident for each of the five traces with different drift field. The transition between type #1 and type #2 depends on the condition of the plasma as determined by the temperature and voltages on the tip, plate P and the grid G1. The transition can occur over a very small change in the tip current. Observation of the discharge shows that when background #1 is present the discharge is flickering.

Because background #2 is smoothly varying with time, it is possible that it is always present but is masked by background #1 which appears only if the tip current is sufficiently large. Also since background #2 does not have a sharp cut-off at some time, we cannot make a quantitative statement about how it varies with field. However, it is clear from Fig. 8 that the background #2 does shift to earlier times when the drift field is increased.

As a further test, we have looked to see if there is a background present when we change the polarity so as to detect only positive ions. We find that there is a small background appearing with a shape roughly similar to the type #2 background. However, this appears only much closer to the arrival time of the normal ion. It seems likely that this signal arises because as the ions approach the end of the drift region some of the field lines from the ions penetrate through the Frisch grid and induce a charge on the collector.

5. Measurements with carbon nanotube tips

After completing the experiments just described using tungsten tips, we made a few measurements with single-wall carbon nanotubes (CNT) tips [45]. The purpose was to see if a change in the tip material would change the properties of the generated ions. One or two drops of acetone containing CNT were placed on a glass slide. When the drops had spread out and dried, a section of stainless steel capillary (outside diameter 0.013”) was coated with a thin layer of silver. This capillary was rolled on the glass slide to pick up the nanotubes and then allowed to dry out. An example of data taken with the CNT tips is shown as the solid curve in Fig. 10a. These data were taken at 1.04 K with a voltage of -974 V on the tips, -530 V on the plate, -510 V on G1, -520 V on G2. We were surprised to find that the signals with the CNT were considerably stronger than with the tungsten tips. We could identify several of the peaks shown in Fig. 10a with ions already detected in the experiments using tungsten tips. In Fig. 10a these peaks have been marked with the same numbering scheme as used in the lower part of Fig. 1. The observation of ions with the same mobility means that the exotic ions cannot be objects composed of the material of the tip.

In addition to the ions seen with the tungsten tips it was possible to observe a number of ions which had not been detected using tungsten; these ions are not numbered in the figure. These new ions may have been detected simply because the ion signals were stronger. Also, as already noted in section IIB3, changes in the condition of the plasma have a large effect on the relative magnitudes of the different ions, and so it is perhaps not surprising that changing the tip makes it easy to see some ions and harder to see others.

We then followed the same procedure as described previously to see if the data contained a background signal. We removed the contributions from each of the ion peaks in sequence starting with the earliest. Removal of the first ten ions left no significant residual signal in the time range where the peaks were located. However, after removal of peak #11 a background was revealed. Note that peak #11 here refers to the eleventh peak which could be detected, not the eleventh peak based on the numbering scheme used in Fig. 1. This peak #11 was the peak labeled as #7 in Fig. 1. The dashed line in Fig. 10a shows the result of removing the first twelve peaks. The background which is revealed appears to have the same general shape as that found using the tungsten tips as shown in Fig. 7. In addition, from the CNT data the ratio of the time τ_b at which the background begins to the arrival time τ_{NEB} of the normal ion signal is close to the same ratio found with the tungsten tips. Figure 10b shows the signals coming from each of the ions which were removed. These are again labelled as in the lower part of Fig. 1.

We have not tried to remove the contribution to the signal from the ions arriving after the start of the continuous background. There appear to be at least six such ions and so the CNT experiment indicates that there are at least 18 ions in addition to the normal electron bubble.

With the CNT tips we did not observe a signal showing background of type #2, but this may be simply because we did not make an extensive investigation of the effect of varying the electrode voltages.

6. Light from the plasma

We have measured the spectrum of the light emitted from the discharge under a few different conditions. Measurements could only be made in the visible range. We have been able to identify all of the lines which are above the noise level with known lines from helium atoms or helium dimers.

7. Estimate of the size of the ions

The radius of the normal electron bubble as calculated from Eq. 2 using the experimentally-measured surface tension is 18.9 Å [46]. The mobility is limited by scattering of rotons from the moving bubbles. In the temperature range of the experiment the roton mean free path is large compared to the size of the ion and so rarefied gas dynamics should apply. One would then expect that the drag on a moving ion should be proportional to the roton number density and to the square of the ion radius. Thus, within this picture the mobility μ should vary approximately as

$$\mu \propto \exp\left(\Delta / kT\right) / R^2, \tag{7}$$

where Δ is the roton energy gap of 8.6 K. We have fit the data for the temperature-dependence of the mobility for each of the ions to Eq. 7 but replacing Δ in Eq. 7 by an adjustable parameter $\Delta*$. The results are shown in table 1. This table is based only on the measurements with tungsten tips because we have not used the CNT tips to make a detailed study of the temperature-dependence of the arrival times of the different ions. Ihas[23] followed the same procedure, but used a different numbering scheme; we have included his results with this scheme in the table. We note the following

a) The values of $\Delta*$ that we have obtained are systematically smaller than the values found by Ihas. This is probably because of a difference in the thermometry in the two experiments.

b) Ihas and Sanders [22] mention that they detected 13 exotic ions in addition to the fast ion, but Ihas [23] reported $\Delta*$ for only 11. Presumably, this is because some ions could only be detected over a narrow temperature range.

c) For ions #2, 3, 5, 9 and 11 (our numbering) the signal to noise in our data is not good enough for us to obtain a reliable value for $\Delta*$

d) We have not been able to detect a signal corresponding to the ion numbered by IS as #2.

e) We have detected ion #9 not found by IS. In addition, when we remove ion #4 by the method described above, another ion becomes evident. This ion has a mobility 2.5 times the mobility μ_{NEB} of the NEB. We have not included this ion in the table.

In addition, we list the ratio of the mobility of each ion to the mobility of the NEB. The comparison is made at 0.991 K. From this ratio we have estimated the radius using Eq. 7.

It is interesting to consider how reliable these estimates of the radius may be.[47] For ions in a gas the mobility is affected by the mass of the ion; as the mass decreases the mobility goes up [48]. For ions in superfluid helium, the situation is not so simple because of the complexities of the roton dispersion relation and because when a roton collides with the ion, the ion recoils through the liquid [49]. A theoretical study has been made by Barrera and Baym [50] and by Bowley [51]. As far as experiment is concerned, the most direct investigation of the effect of mass on the mobility is the work of Glaberson and Johnson [52]. They studied the mobility of positive ions of the isotopes ^{40}Ca and ^{48}Ca. They found that an ion formed from a ^{40}Ca isotope had a mobility 1.1 % higher than that of the ^{48}Ca isotope. The effective mass $m*$ of these ions consists of the mass m_1 of the calcium atom, the mass m_2 of the solid helium snowball surrounding the atom, and the hydrodynamic mass m_3 arising from the flow of the liquid helium around the ion. For these two calcium isotopes the values of m_2 and m_3 should be the same. For a helium positive ion the effective mass, i.e., $m_1 + m_2 + m_3$, has been measured to be $44m_4$ [9] (m_4 is the mass of one helium atom), so $m_2 + m_3 = 43m_4$. Glaberson and Johnson found that the mobility of the Ca ions was about 11 % higher than the mobility of the helium positive ion indicating[53] that the radius is about 6 % smaller than for helium, so $m_2 + m_3$ for Ca should be $36m_4$. This gives the result that the effective mass for the two Ca isotopes should be $46m_4$ and $48m_4$. Thus, it appears that, at least in this range of effective mass, a 4.2 % change in mass gives a 1.1 % change in mobility, i.e.,

$$d \ln \mu / d \ln m^* = -0.26. \quad (8)$$

For electron bubbles the effective mass is $m^* = 2\pi R^3 \rho / 3$ and so the variation of the mobility with radius (including the effect of the variation of both the drag force and the mass variation) is given by

$$d \ln \mu / d \ln R = -2.78. \quad (9)$$

Thus the results of Glaberson and Johnson suggest that the variation of mobility with radius is considerable larger than would be expected based on Eq. 7 which gives $d \ln \mu / d \ln R = -2$. If we assume Eq. 9 holds for all values of R, we would have $\mu \propto R^{-2.78}$ and this gives the values of R included in the last column of table 1. We note that while this discussion shows that the effect of the ion mass may make a significant change in the relationship between mobility and radius, it is possible that the mass effect is different for positive and negative ions.

Another indication of the ion size comes from the measurements of Eden and McClintock [24,25,26]. For several of the exotic ions, they have measured the critical velocity v_c at which the ions nucleate and become attached to quantized vortices. They found that v_c increased monotonically as the mobility μ of the ions increased. Since μ should increase with decreasing radius, their results imply that v_c increases with decreasing radius. Williams *et al* [54] have pointed out that this variation of v_c with radius is in the direction expected theoretically [55]. Although the theory of the dependence of v_c on radius is probably not sufficiently developed to enable a measurement of v_c to provide an accurate estimate of the radius, the result that v_c is found to increase monotonically with μ is significant. For example, consider the possibility that the exotic ions have a higher mobility simply because they have a charge of $-2e$. Then those exotic ions which have a mobility only slightly greater than μ_{NEB} would have to have a radius larger than the radius of NEB and should therefore have v_c less than the critical velocity for a NEB. This would be in disagreement with the experiments of Eden and McClintock.

C. Interpretation

1. General considerations

Any theory of the exotic ions has to explain the following principal experimental results:

a) There is a large number N of negatively charged ions (in addition to the normal electron bubble) each with a different mobility. In what follows we will take N to be 18, although the number may in fact be larger.

b) There is a contribution to the signal which comes from ions which have a continuous distribution of mobility. The form of this background changes is dependent on the characteristics of the electrical discharge in the vapor.

c) The same ions are seen in experiments in different labs.

d) The lifetime of the ions is comparable to or larger than the transit time through the mobility cell. In the experiments that we have performed, the transit time is typically between 10 and 100 ms.

e) While the ions have been named “exotic”, their total contribution to the signal is not, in fact, small. The integral of the signal from the exotic ions (including the continuous background) can be as large as 90 % of the integral over the peak coming from the NEB.

2. Impurities

Impurity atoms could possibly get into the liquid helium as the result of sputtering of material from the cell walls by the plasma in the vapor. These impurities could be ejected from the walls as negative ions, could form negative ions while in the plasma or after entering the liquid, or could come from the tip itself. The size of a bubble formed by a negative ion will depend on the electron affinity. As a simple model one can treat the impurity as providing an attractive potential well of depth V_0 and radius a for the extra electron. It is then straightforward to calculate the electron affinity ϕ in terms of V_0 and a. One can next consider the state of the electron when it is confined in a bubble of radius R. The potential is now

$$\begin{aligned} V(r) &= -V_0 \qquad && r < a \\ &= 0 && a < r < R \\ &= \infty && R < r \end{aligned} \qquad (10)$$

The energy E_{el} is the solution of the equations

$$\sqrt{\frac{-E_{el}}{E_{el}+V_0}}\tan\left[\sqrt{\frac{2m(E_{el}+V_0)}{\hbar^2}}a\right] = -\tanh\left[\sqrt{\frac{-2mE_{el}}{\hbar^2}}\left(R-a\right)\right] \qquad E_{el} < 0 \qquad (11)$$

$$\sqrt{\frac{E_{el}}{E_{el}+V_0}}\tan\left[\sqrt{\frac{2m(E_{el}+V_0)}{\hbar^2}}a\right]=-\tan\left[\sqrt{\frac{2mE_{el}}{\hbar^2}}\left(R-a\right)\right] \qquad E_{el}>0 \qquad (12)$$

We solve these equations for E_{el}, insert E_{el} into Eq. 1 in place of $h^2/8mR^2$, and then vary R to find the value which minimizes the total energy of the bubble. Results for the radius as a function of V_0 are shown in Fig. 11. The electron affinity (the electron energy in the limit of large R) is also plotted. These results are for $a=2$ Å. A different choice of a (e.g., 2.5 Å) gives results for the bubble radius which as a function of the electron affinity are almost the same. Note that to have the bubble radius above 14 Å one needs an impurity which provides an attractive potential ($V_0>0$) but which is not strong enough for there to be a negative ion in vacuum.

However, the following considerations appear to make any impurity theory implausible:

1) In order for impurities to be the explanation for the 18 ions with discrete mobilities, it would be necessary for there to be at least 18 different impurities present with electron affinity in the required range. These impurities would have to be present in comparable amounts. There are a number of materials in the cell which are exposed to the plasma (stainless steel, tungsten, brass, polycarbonate, nylon, and teflon), but it seems unlikely that these contain the elements that are needed. The cell has ZnSe windows but these are far removed from the region where the plasma discharge is intense.

2) The ratio of the signal from the exotic ions to the signal from the normal electron bubble is typically between 0.1 and 0.01. Thus, the number of impurity negative ions would have to be surprisingly large. Measurement of the spectrum of light emitted from the plasma shows no indication of emission from impurities.

3) Even at 1 K, the density of the helium vapor is sufficiently high to limit the mean free path of helium atoms in the vapor to less than 1 mm. Thus, the number of helium atoms with enough energy to cause sputtering must be very small [56].

4) Each impurity ion should have a different and specific size and mobility. Therefore impurities cannot be the explanation of continuous background seen in the time-of-flight experiments.

5) The fast ion has been seen in experiments in which ions were introduced using an α [20] or β-source [22,23]. These sources would not introduce any impurities into the liquid.

3. Helium ions

Under the conditions of the experiment the liquid can be expected to contain some number of helium atoms in the metastable 2^3S state, neutral dimer molecules, and two distinct types of helium negative ion, He^- and He_2^-. Dimers formed in the vapor are likely to accumulate on the liquid surface and may interact with electrons which are also trapped there. We discuss the two different ions in turn.

A helium atom in isolation has a metastable 2^3S state with a lifetime of 7,870 secs. An atom in this state can bind another electron in the 2P state to produce a He^- ion with total angular momentum J of $1/2$, $3/2$ or $5/2$. There have been a number of experimental and theoretical studies of these ions. In 1967 Brehm *et al* [57] performed a laser photo-detachment experiment and measured the binding energy of the last electron to be 80 ± 3 meV. More recently, Kristensen *et al* [58] have made a more precise determination and obtained a binding energy of 77.516 ± 0.006 meV for the $J = 5/2$ state in excellent agreement with the theoretical value.[59] The energy difference between the different states has been measured [60] with results $E_{J=1/2} - E_{J=3/2} = 36$ μeV and $E_{J=3/2} - E_{J=5/2} = 3.4$ μeV.

Because of the low binding energy of the last electron, these ions should form bubbles with a radius which is somewhere between the radius of the smallest and the largest of the exotic ions. This raises the possibility that one of the exotic ions is in fact He^-. However, the lifetime of He^- appears to be too short. The lifetime of the $J = 5/2$ state measured by Blau *et al* [61] is 345 ± 90 μs, while the lifetime of the $J = 3/2$ and $J = 1/2$ states is 11 μs. These lifetimes are much less than the time it takes ions to pass through the length of our mobility cell (typically 10 to 100 ms). Ihas and Sanders[21] noted that the lifetimes just cited are for ions in free space and raised the possibility that the lifetime of the ions might be increased in liquid helium. We think that this would indeed happen if in the decay process $\mathrm{He}^- \rightarrow \mathrm{He} + \mathrm{e}$ the energy of the emitted electron were below 1 eV since this would make it impossible for the electron to enter the liquid [2]. However, in the $\mathrm{He}^- \rightarrow \mathrm{He} + \mathrm{e}$ process the energy of the electron is 19.7 eV, and so it seems unlikely the liquid will increase the lifetime [62].

The negative helium dimer He_2^- was first reported by Bae *et al.*[63] The He_2^- was formed by double charge exchange from Cs^- in cesium vapor. The binding energy of the electron has been measured by Kvale *et al* [64] with result 0.175 eV. This binding energy would result in an ion in the liquid with a radius comparable to the radius of the exotic ions, and thus He_2^- could be one of the exotic ions. However, as for He^-, the lifetime appears to be too short. Bae *et al*. [63] measured the decay of a beam of He_2^- and found evidence of a component A with lifetime around $\tau_A \sim 10$ μs and another component B with lifetime around $\tau_B \sim 100$ μs. Kvale *et a.l* [64] identified component A as coming from the decay of He_2^- which had been produced in its first vibrational excited state $(\nu = 1)$ going to a final state consisting of a neutral helium dimer with $\nu = 0$ and an electron of energy 11.5 meV. This process should be strongly suppressed when the He_2^- is in liquid helium. Component B was identified as coming from the decay of He_2^- into two ground state helium atoms plus an electron of energy 15.8 eV. The lifetime for this process was later measured precisely using a heavy-ion storage ring giving the result for $\nu = 0$ molecules $\tau_B = 135$ μs [65]. The time τ_B should not be substantially changed when the He_2^- is in the liquid. While the presence of the liquid should suppress the A process for He_2^- molecules in the $\nu = 1$ state, it seems likely that these molecules can still decay by the B process, presumably with a time that differs only slightly from 135 μs.

If there is, in fact, an increase in the lifetime of He^- or He_2^-, this could provide an explanation of one of the ions. It would not provide an explanation of the existence of as many as 18 negative ions and the continuous background.

4. Production of exotic ions by fission of the electron wave function

Fission of the electron wave function was first proposed [32] in order to explain the existence of the exotic ions, and also to explain the results of photoconductivity experiments which had been performed by Grimes and Adams [6], and by Northby, Zipfel and Sanders [28,29,30,31]. In a normal electron bubble all of the wave function of an electron is contained within one bubble; the bubble does not collapse because when the radius decreases the energy of the electron has to go up. However, one can ask what happens if the system (electron plus helium) is prepared in a state such that part of the wave function is in one bubble and another part of the wave function is in another bubble which is at a distance away sufficient to prevent any tunneling between the two bubbles. Thus, fission here refers to fission of the wave function. Assuming that this initial condition can in fact be created, one can then ask what happens to these bubbles? One view, of course, would be that the liquid helium makes a measurement and determines which bubble contains the electron. The bubble in which the electron is found would then become a normal electron bubble and the other bubble (containing no electron) would collapse. Thus the measurement amounts to an irreversible event which makes a permanent change in the system. But is this in fact what happens, and if it does happen, how long is it before the collapse occurs? Or are the bubbles which contain only a part of the wave function stable objects? As we discuss below, if the bubbles are stable this could provide an explanation of the origin of the exotic ions. In ref. 32, it was proposed that for a bubble containing a fraction f of the integral of $|\psi|^2$ Eq. 1 should be modified to

$$E = \frac{f\,h^2}{8mR^2} + 4\pi R^2 \alpha + \frac{4\pi}{3} R^3 P \ , \qquad (13)$$

and so the bubble radius which gives minimum energy is the solution of

$$\frac{dE}{dR} = -\frac{f\,h^2}{4mR^3} + 8\pi R\alpha + 4\pi R^2 P = 0 \tag{14}$$

For $P = 0$, gives a radius

$$R_0 = \left(\frac{f\,h^2}{32\pi m\alpha}\right)^{1/4}. \tag{15}$$

The expression for the energy is consistent with the usual formula for the pressure P_{quant} exerted on a hard wall by a wave function, i.e.,

$$P_{quant} = \frac{\hbar^2}{2m}\left|\nabla\psi\right|^2. \tag{16}$$

For pressure balance

$$P_{quant} = \frac{2\alpha}{R} + P \tag{17}$$

The wave function of the ground state in a spherical bubble is

$$\psi = \sqrt{\frac{f}{2\pi R}}\,\frac{\sin\left(\pi r / R\right)}{r} \tag{18}$$

which gives

$$P_{quant} = \frac{h^2}{16\pi mR^5}. \tag{19}$$

The pressure balance condition then becomes

$$\frac{f\,h^2}{16\pi mR^5} = \frac{2\alpha}{R} + P, \tag{20}$$

which is equivalent to Eq. 14.

We now consider two possible ways in which the initial condition described above may arise.

The first concerns the entry of an electron into the liquid. The plasma in the vapor above the liquid contains electrons with a broad energy distribution. For electrons moving through a gas in a uniform field E the distribution in energy $n(\varepsilon)$ is given by [66]

$$n(\varepsilon)\,\delta\,\varepsilon = \frac{2n_e}{\Gamma(3/4)}\frac{\varepsilon^{1/2}}{\varepsilon_0^{3/2}}\exp\left(-\varepsilon^2/\varepsilon_0^2\right)\,\delta\,\varepsilon\,, \tag{21}$$

where

$$\varepsilon_0 = \lambda eE\sqrt{\frac{M}{3m}}\,. \tag{22}$$

In these equations n_e is the number density of the electrons, M is the mass of the atoms, and λ is the electron mean free path (taken as a constant). This formula applies when the field is sufficiently strong that the typical energy of an electron ($\sim\varepsilon_0$) is large compared to kT; this is the situation that we have in the experiment. The formula does not take account of processes in which an electron excites a helium atom out of the ground state or causes ionization, i.e., Eq. 21 is based on elastic scattering. The electron-helium elastic scattering cross-section for electrons at low energies [67] is $\sim 5\times10^{-16}$ cm^2. For the data shown in Fig. 8, the voltage difference between the plate and G1 was 40 V, giving a field at the liquid surface of 70 V cm^{-1}. The height ϕ of the barrier an electron has to overcome in order to enter the liquid is 1 eV [2]. Electrons with energy below ϕ will not be able to enter the liquid and may become trapped in states just above the surface. The presence of these electrons will reduce the field in the region above the surface and lower the effective value of ε_0. On the other hand, the passage of field lines from the tips through the holes in the plate will increase the field at the liquid surface. If we take the field to be 70 V cm^{-1}, the value of ε_0 is 6.1 eV at 1 K and 2.8 eV at 1.1 K.

A wave packet for an electron with energy slightly above the barrier will be partially transmitted into the liquid. One can then ask how these electrons form electron bubbles. One possibility is that interaction with the helium constitutes a measurement, the electron is either found to be in the helium or is found not to be, and so a normal electron bubble is always produced. However, another possibility is that bubbles are formed directly and a bubble is produced in which the integral f of $|\psi|^2$ over the volume of the bubble is less than 1. Since there is a continuous distribution of values of f, this process would give a continuous distribution of ion mobility and could provide an explanation of the background seen in the mobility experiments.

We take the profile of the potential barrier to be of the form

$$V(z) = \frac{\phi}{1+\exp(-z/a)} \tag{23}$$

where the midpoint of the barrier is at $z=0$ and the liquid is in the region with $z>0$. There have been several theoretical and experimental estimates [68] of the width of the interface; the distance between the positions at which the liquid density goes from 10% and 90% points of its full value is found to be about 7 Å. To get this width we need to set $a=1.59$ Å in Eq. 23; we are taking $V(z)$ to be proportional to $\rho(z)$. Then the transmission coefficient for electrons of energy greater than ϕ is given by [69]

$$Tr = 1 - \frac{\sinh^2\left[\pi\left(k_z - k_z'\right)a\right]}{\sinh^2\left[\pi\left(k_z + k_z'\right)a\right]}, \tag{24}$$

where k_z and k_z' are the components of the wave vector in the direction normal to the surface above and below the surface, respectively. In Fig. 12 we show the transmission as a function of the energy and the direction θ of the incident electrons.

For a given field above the liquid surface, and using the energy distribution given by Eq. 13, it is straightforward to calculate the distribution of the values of f for the electrons entering into the liquid $(f = Tr)$. To convert this distribution to a distribution of mobility we use Eq. 15 to relate f to the radius of the bubble. Then based on Eq. 7 the transit time through the cell should be decreased by a factor of $\sqrt{f}$ relative to the normal ion. This is based on taking the charge to be $-e$. This is discussed in ref. 32.

In Fig. 13 we show the calculated distribution of transit times with the time axis scaled so that the normal electron bubble arrives at $t'=1$. The distribution is normalized so that the integral using this time scale is unity. The figure includes the five data sets which exhibit the #2 background already shown in Fig. 8; these have been scaled and normalized in the same way. In the simulations the value of ε_0 has been chosen to be 2 eV in order to give a good fit to the data; this corresponds to a field across the vapor-liquid interface of 19 V cm^{-1}. Note that because of the normalization scheme the choice of ε_0 is required to give a fit to two characteristics of the data, namely 1) the amplitude of the background relative to the amplitude of the normal ion signal, and 2) the time range over which the background extends. While this calculation gives a remarkably good fit to the #2 background, it does not explain the type #1 background or explain why there are two types of background.

The second mechanism we consider concerns the evolution of the wave function of the electron. How does a (presumably) irregular and complex wave function of the electron evolve after the electron enters the liquid? Does it always collect so as to form a single electron bubble? If it doesn't, what bubbles are formed and how much of the integral of $|\psi|^2$ is found in each? Unfortunately, at present there is very little theoretical guidance on this question. Ideally one would like to perform a series of computer simulations for a wide range of initial wave functions and determine the structures that result, but this has not been done. In earlier work [32], it was pointed out that there is a feedback mechanism which tends to drive a breaking bubble towards a state in which the wave function is divided in a specific way. The argument was presented for the particular case of the evolution of a bubble optically excited from the 1S to the 1P state, but it is more general.

Consider a one-dimensional model of a bubble with the wave function in the second excited state (Fig.14a). We arbitrarily take the length of the “bubble” to be 60 Å. Suppose now that the bubble is approaching fission and a neck is formed between two parts of the bubble at a distance of approximately 20 Å from the origin. Note that a neck between two parts of the bubble is most likely to appear near to a node in the wave function. This is because at a node the probability of finding the electron goes to zero and so there is no outward pressure exerted by the electron preventing the bubble wall moving inward as a result of surface tension or an externally applied pressure. The formation of the neck results in a potential barrier which changes the wave function as shown in Fig. 14b. In the simple model calculation presented here we take the height of the barrier to be fixed at 0.5 eV, the width W of the barrier is 10 Å, and the widths of the wells are $L_1 = 15.8$ and

$L_2 = 34.2$. Since the width L_2 of the right hand well is approximately twice the width L_1 of the left well, the energy of the $n = 2$ state in the right hand well is close to the energy of the $n = 1$ state in the left well and, with the barrier height as chosen, the rate of tunneling through the barrier is sufficiently large that there is comparable probability of finding the particle on either side of the barrier. However, if L_1 is decreased by 1 Å while holding L_2 and W constant (Fig.14c), the energy of the $n = 1$ state in the left well becomes significantly larger than the energy of the $n = 2$ state in the right well, and most of the wave function moves into the left well. The increase in the probability of finding the electron on the left means that the pressure exerted by the electron on the boundaries of the left well will increase and the pressure in the right well will decrease, thus driving the system back towards a configuration in which $L_2 = 2L_1$. As the neck between the bubbles narrows, the height of the barrier increases, and the effectiveness of this feedback mechanism increases, i.e., the wave function becomes more sensitive to small differences between L_2 and $2L_1$ [70].

The mechanism just described tends to drive a bubble to break up into two smaller bubbles A and B such that bubble A has an eigenstate with the same eigenvalue as one of the eigenstates in bubble B. As a result each bubble contains a specific fraction of the integral of $|\psi|^2$. Thus this could be a way in which the exotic ions are produced.

As a specific example, consider the possible fission of a bubble into a bubble containing an electron in a 1S state in a bubble of radius R_1 with $\int |\psi|^2 \, dV = f$ and another bubble containing an electron in a nS state in a bubble of radius R_n with $\int |\psi|^2 \, dV = 1 - f$. Consider the very simplest model for the bubble in which the penetration of the wave function into the liquid is ignored, the energy of the interface is the product of the surface area with the surface tension, etc. In order for the two energy eigenvalues in the two bubbles to be the same we need

$$\frac{h^2}{8mR_1^2} = \frac{n^2 h^2}{8mR_n^2}, \tag{25}$$

so $R_n = nR_1$. But for mechanical equilibrium at the moment the bubble splits (see Eq. 15 for pressure zero)

$$R_1 = \left(\frac{f\,h^2}{32\pi m\alpha} \right)^{1/4} \qquad R_n = \left(\frac{(1-f)\,n^2 h^2}{32\pi m\alpha} \right)^{1/4} . \tag{26}$$

where f is the fraction in the 1S bubble. Equations 25 and 26 give $f = 1/(1+n^2)$. The nS bubble would quickly relax back to a wave function of the 1S form either radiatively or non-radiatively.[17] Then the final radii of the two bubbles would be

$$R_1 = \left[\frac{h^2}{32\pi m\alpha\left(1+n^2\right)} \right]^{1/4} \qquad R_n = \left[\frac{n^2 h^2}{32\pi m\alpha\left(1+n^2\right)} \right]^{1/4} . \tag{27}$$

Based on the simplest formula for the mobility (Eq. 7), this process would result in ions with transit times through the cell which are less than the transit time of normal electron bubbles by factors of $1/\sqrt{1+n^2}$ and $n/\sqrt{1+n^2}$. It is straightforward to consider the more general case of states which do not have S symmetry.

One can ask how many different exotic ions can be formed in this way. If we consider just divisions into the 5 low lying states 1S, 2S, 1P, 2P and 1D there could be $5\times(5-1)+1=21$ ions of different size and mobility. This number is comparable to the number of exotic ions which have been detected.

Although the feedback mechanism just described does drive a bubble towards breaking up into bubbles with particular sizes, it has not been established that the mechanism is strong enough to accomplish this. For example, it could be true that the discrete sizes are produced only for certain forms of the initial wave function ψ, and that a continuous distribution of bubble sizes results from other forms of ψ which do not lead to breakup into specific fractions. This could possibly explain the observed continuous distribution of mobility but does not provide an immediate explanation of why the type #1 background has a cutoff at a particular time.

It does not appear possible to estimate the mobility of these objects sufficiently accurately to make a comparison with experiment. The relation between f and the bubble size is uncertain and, as already mentioned, it is possible that the mobility is not strictly proportional to R^{-2}. In addition, to determine the values of f requires an accurate calculation of the energy of the different quantum states; the simple model along the lines of Eq. 1 is probably not sufficient.

There is one further point to mention regarding the arrival times of ions based on the fission model. Suppose, as an example, that ions are produced which have mobility μ_A and μ_B with $\mu_A > \mu_B$. Let the drift field be E_d and length of the drift region be d. We have assumed in the above discussion that the arrival times registered in the experiment will be

$$t_A = \frac{d}{\mu_A E_d} \qquad t_B = \frac{d}{\mu_B E_d} . \tag{28}$$

But one could argue that the collector plate should be regarded as a detector which determines whether a bubble does or does not contain an electron. Then if bubble A is found to contain an electron a signal is recorded at time t_A. But if A is found to not contain an electron when the bubble arrives at time t_A, bubble B will now contain all of the wave function and will become a normal bubble with mobility μ_{NEB}. Then the arrival time of B will be

$$t_B = \frac{d}{E_d}\left(\frac{\mu_{NEB} + \mu_A - \mu_B}{\mu_A \mu_{NEB}}\right) \tag{29}$$

III OPTICAL EXCITATION

A. Background

There have been several previous experiments to study the effect of light on the motion of ions through liquid helium. Northby and Sanders (NS) [30,31] performed an experiment designed to detect the ejection of electrons from electron bubbles as a result of photo-excitation. They used a ^{210}Po α-source to ionize helium atoms in the liquid. A dc field was applied to draw the resulting negative ions (electron bubbles) towards a grid G1. After passing through this grid the electrons moved through the liquid towards a second grid G2 to which was applied a square-wave voltage of amplitude ΔV_2 and frequency f. The voltage amplitude and the frequency were adjusted so that for normal electron bubbles the time to pass from one grid to the next was slightly larger than one half of the period. Under this condition no electron bubbles should be able to reach a collector plate positioned beyond G2. The idea of the experiment was that if an electron was ejected from the bubble by light, this electron would be able to reach the collector. It was found that when light was shone onto the electrons while they were in transit in the space between G1 and G2, a current did indeed reach the collector. This photo-induced current was measured with light of photon energy from 0.7 to about 3 eV. A peak current was found at 1.21 eV and this was assumed to be the result of photo-ejection.

Zipfel and Sanders (ZS) [28,29] made measurements similar to those of NS, and varied the pressure up to 15 bars. The photoconductivity peak detected by NS was found to shift to higher photon energies as the pressure increased. In addition, a second peak was found at a lower photon energy E_{ZS}. At zero pressure this peak was at approximately 0.5 eV. In order to understand the origin of the photoconductivity, Miyakawa and Dexter [71] performed calculations of the optical absorption of an electron bubble, and concluded that the peak at E_{ZS} was due to excitation of electrons from the 1S ground state to the 2P state. Miyakawa and Dexter also calculated the photon energy required for the 1S→1P transition and found that at zero pressure this should correspond to a wavelength of around 12 µm. This transition was detected by Grimes and Adams [6], again through a measurement of photoconductivity. This transition was later seen by Grimes and Adams [7] and by Parshin and Pereversev [8] by direct measurements of optical absorption.

Although these experiments established the electron transitions responsible for the peaks in the photoconductivity, it was not clear what caused the change in conductivity when light was absorbed. We focus the discussion on the 1S to 1P transition. When the state of the electron is changed from 1S to 1P, the change in the electron wave function results in a large change in the equilibrium shape of the bubble. The bubble resembles a peanut; the length of the bubble along the z-axis increases, and the bubble develops a waist [32]. According to the Franck-Condon principle, one should consider that when light is absorbed, the electronic transition occurs first and the bubble shape then begins to evolve. At high temperatures, i.e., above 1.7 K, the helium has a large density of rotons which damp the motion of the bubble wall and, as a result, the shape of the bubble relaxes smoothly from the initial spherical shape to the new equilibrium form where the outward pressure exerted by the electron balances the surface tension and the pressure in the liquid. However, if the optical excitation takes place at low temperatures, the damping is small and the bubble shape overshoots past the equilibrium shape [32]. Computer simulations predict that if the pressure in the liquid is above a critical value of around 1 bar, the shape of the bubble will evolve in a way such that the bubble breaks into two [72,73]. Below 1 bar the bubble does overshoot the equilibrium shape, but after oscillations have died out, does reach this shape. Unfortunately, to perform these simulations within a reasonable amount of computer time, it has been necessary to make a number of simplifications and so the application to experiment is somewhat uncertain. In the simulations the bubble shape has been taken to have axial symmetry and even parity throughout the time evolution. In fact, because of thermal fluctuations a bubble containing an electron in the 1S ground state before optical excitation will not be perfectly spherical, and it is not clear how such a deviation from spherical symmetry in the initial state will affect the evolution of the shape at later times. Also the scattering of rotons from the bubble wall during the evolution may have an important effect. The feedback mechanism described in the previous section will tend to drive the evolution towards a state in which the bubble divides into two equal parts but it is not clear how efficient this mechanism is. Elser [74] has presented an argument that the feedback mechanism does not lead to fission. As far as we can see, to settle this question it would be necessary to carry out more detailed computer simulations than have so far been performed, i.e., the simulations would not have to restricted by assumptions about symmetry.

One other possibility is that the signal detected in the photoconductivity experiments (again focusing on the 1S to 1P transition) comes from electron bubbles which are trapped on quantized vortices. In the experiments of Northby, Zipfel and Sanders, for example, electron bubbles might be trapped in the region between G1 and G2. If a bubble can escape from the vortex when the electron is excited from the 1S to the 1P state, then it will have time to reach G2 and contribute to the measured signal. Miyakawa and Dexter [71] proposed that when light was absorbed by the bubble, it will vibrate, and the vibrational energy would be converted into heat. This heating could enable it to escape from a vortex, and provide an increase in current. A variation of this mechanism was suggested by Elser [75]. He proposed that after photoexcitation to the 1P state the bubble would break into two smaller bubbles with the electron trapped in one of these; the other small bubble would then collapse. It was argued that this would increase the amount of heat dissipated. Since the breakup would be more likely as the pressure increases, this interpretation could explain the observation by Grimes and Adams [6] that in their experiment no photoconductivity was observed below about 1 bar.

This mechanism requires there to be some number of electron bubbles which are attached to vortices. In the Grimes and Adams experiment, electrons were introduced by field emission from sharp metal tips. Since the electric field near the tips was very large, it is certainly reasonable to assume that a large number of vortices were present. In the Northby, Zipfel and Sanders experiments, the number of vortices should be much lower. The voltages applied to the grids were too small for vortex nucleation by the ions moving through the liquid at the temperatures of the experiment ($T \geq 1.3$ K). Also in the ZS experiment measurements were made up to a pressure of 16 bars. At pressures above about 10 bars, a normal electron bubble moving under the influence of an electric field, loses energy by roton production and does not produce vortices. However, in these experiments vortices could be produced by heat currents in the cell, and there certainly could also be a significant number of remnant vortices [76].

A further possibility is that after photoexcitation the electron bubble undergoes fission into two or more pieces each containing part of the wave function. If these bubbles have higher mobility, this could explain the experiments in which the transitions 1S→1P and 1S→2P were studied [28,29,30,31]. This fission process is more likely to occur when the pressure is increased.

B. Experiments and discussion

In the experiments described in the previous section, an increase in mobility is observed but no information has been obtained about the magnitude of the change, and it is unclear which of the mechanisms listed above apply. To investigate, we have performed a series of time-of-flight experiments to study the effect of light on electron bubbles. We use a CO_2 laser to excite the electrons from the ground 1S state to the 1P state. The results of some initial experiments have been reported previously in a conference paper [34].

In the experiments of Grimes and Adams [6] a photoconductivity signal was observed only when the pressure was 1 bar or higher. Consequently, to investigate the effect observed by Grimes and Adams we could not introduce electrons into the liquid from a discharge in the vapor. A second consideration is that the energy difference E_{1S1P} between 1S and 1P changes according to the pressure applied to the liquid. The photon energy of the CO_2 laser in our lab is 0.1167 eV and matches E_{1S1P} at a pressure of approximately 1 bar. The absorption line has a full width at half maximum of about 0.02 eV [7] and so the absorption of CO_2 light will be significant over a range of pressure. We made most of our measurements between 1 and 1.5 bars.

In a first series of experiments [34] we used as a source a tungsten wire coated with carbon nanotubes prepared by the method described by Kawasaki *et al* [45]. The tip of the wire was positioned in the liquid 4 mm right above G1, and the plate P shown in Fig. 2 was removed. By applying a sufficient voltage difference between the tip and G1 (typically in the range 500 to 800 V), electrons could be driven into the liquid. Because of the large electric field, we expected that these electrons would become trapped on quantized vortices and give a large density of essentially immobile electrons in the region below the tip. In these experiments either a constant voltage was applied to the tip or the voltage was pulsed. We applied pulses from the CO_2 laser to the regions above G1 or just below G2 and measured the signal at the collector coming from electron bubbles which were able to escape from the vortices as a result of optical excitation. Measurements were made as a function of the voltages on the tip and the grids, the laser power, and the temperature. The duration of the CO_2 pulse was typically 1 ms. If the tip was pulsed, then the time between the application of the pulse on the tip and the laser pulse could also be varied.

An example of data obtained with this setup at 1.05 K is shown in Fig. 15; other data have been presented in ref. 34. The data shown are for voltages of -220 and -200 Volts on G1 and G2, respectively. The curves are labelled by the voltage difference between the tip and G1. The laser pulse energy was approximately 8 mJ. The main feature seen in the data is a peak at around 66 ms. The arrival time of this peak is in reasonable agreement with expectations based on the mobility of normal electron bubbles. The data show pulses arriving at 19 and 32 ms as well as a small shift forward and change in shape of the pulse coming from the normal electrons when the voltage on the tip is increased.

The data also show a periodic oscillation in the signal which starts at the time at which the normal electrons arrive. We found that this oscillation is present to a greater or lesser degree in all of the experiments in which the pulsed laser is used. It appears that the oscillation is connected with the excitation by the laser pulse of one or more second sound modes in the cell. Given the complicated geometry of the cell it is not possible to calculate the frequency of these modes. By examining the data in experiments of this type in more detail, one finds that there are other oscillations with higher frequencies. To test the idea that second sound is involved, we measured the period of the oscillation at a series of temperatures, and confirmed that the period did indeed vary with temperature in the same way as the inverse of the second sound velocity. Although this strongly supports the suggestion that second sound is involved, the actual mechanism that results in an oscillation in the signal is not clear. A second sound oscillation will give a periodic displacement to the electron distribution in the cell, and the motion of the normal fluid could also drag the Frisch grid back and forth relative to the collector and induce a time-dependent charge on the collector. However, it is not clear how these two effects can explain the data. The oscillations appear only after the main signal from the electrons arrives, whereas second sound generated at the top of the cell which reach the bottom of the cell a few ms after the application of the laser pulse [77].

In our earlier conference paper two possible interpretations of these results were considered [34]. One possibility was that the peaks in the signal at times before the arrival of the normal electrons came from electrons which, as a result of photo-excitation, escaped from vortices a part of the way down the cell and then formed normal electron bubbles. These electrons would travel a shorter distance to reach the collector than electrons coming from the region directly illuminated and could therefore provide an explanation of the early pulses. For this to provide an explanation of the observation of pulses rather than just provide a smoothly-varying background signal, the electrons which escaped would have to come from small regions in the cell where there was a high density of vortices [78]. A difficulty with this theory is that although given the geometry of the cell there is certainly some scattered CO_2 light, the light intensity in the region directly illuminated must be considerably larger than the intensity throughout the rest of the cell. A second problem concerns the location of the proposed vortex tangles. One might expect that they would be located at special places in the cell, for example, at the position of the homogenizer disks. However, in this initial work we found that the position did not seem to match any features of the cell geometry.

The other possibility was that the signal does come from electrons attached to vortices in the illuminated region at the top of the cell, and that they are new objects of higher mobility produced by light as a result of fission. A difficulty with this interpretation was that if the bubble attached to a vortex broke into two equal parts, one would expect that this would result in a single fast pulse, whereas one can see from Fig. 15 that there are two early pulses. Other data shows as many as five fast pulses.

To resolve these questions we have more recently performed a series of experiments under as wide a range of conditions as possible. In addition to using a tip as an electron source, we used a radioactive β-source (0.1 or 1 mCi ^{63}Ni). In some of the experiments, we also used a small heater to produce a jet of normal fluid to increase the number of vortices in the region below the source. We have also varied the laser power. The results from these experiments made the vortex tangle interpretation appear more likely. A first result was that although the time of arrival of the extra pulses was usually unchanged when the voltage on the tip was varied, it sometimes changed by a large amount. The arrival times were different when a radioactive source was used. Such changes would not be expected if the pulses resulted from fission. A second result in favour of the vortex tangle interpretation comes from mobility measurements as a function of temperature. We measured the arrival time of each of the extra pulses and calculated the mobility assuming that these pulses come from electrons generated by the laser at the top of the cell. An example of results for the mobility obtained in this way was included as figure 4 of ref. 34. These data extended over the temperature range from 1 K to about 1.35 K. We fitted such data to the same form as in Eq. 7, i.e.,

$$\mu \propto \exp\left(\Delta^*/kT\right), \tag{30}$$

and determined Δ^* for each ion. The value of Δ^* found for the normal ion was 8.45 K, and for the other three ions the values were 8.53, 8.56, and 8.49 K. Thus the difference in the value of Δ^* for the different ions is roughly 1%. But if the ions were the result of fission one would expect that the value of Δ^* would be different for each pulse just as it is for the different exotic ions. As can be seen from table 1, for different exotic ions the energy Δ^* varies between 8.12 K and 9.23 K. This variation is 14 %, much larger than the 1 % measured.

In an attempt to find out the initial position of the ions released by the laser we modified the experimental cell so that the ions would experience two different drift fields as they move down the cell. We removed the tips, the grid G1 and the plate P, placed a ^{63}Ni source at the position of G1, and also added a grid at the position of the homogenizer plate H1. With this arrangement we could vary independently the fields in the regions above and below H1. Provided that the ions originate above H1, a measurement of the arrival time as a function of the fields can be used to determine both their starting position and their mobility. To see this, suppose that the ions start a distance z above H1 and let the distance from H1 to the collector be $z_2 = 5.07$ cm. Then the transit time is

$$t = \frac{z}{\mu E_1} + \frac{z_2}{\mu E_2} \tag{31}$$

A graph of t as a function of $1/E_1$ has a slope $s = z/\mu$ and an intercept $t_0 = z_2/\mu E_2$. From the slope and the intercept we can find

$$z = \frac{z_2 s}{E_2 t_0} \qquad \mu = \frac{z_2}{E_2 t_0}. \tag{32}$$

If the ions originate below H1 the transit time will not depend on E_1 and the position and mobility cannot both be determined. However, if it is assumed that the objects are normal electron bubbles, then the mobility is known and the position can be found.

A data set obtained with this new geometry is shown in Fig. 16. These data were taken at 1.28 K with a field of 61 V cm^{-1} below H1, and with a series of different fields above H1 as indicated on the figure. The signal shows large oscillations coming from second sound, and two pulses marked by arrows on the figure. The time of arrival of these two pulses P1 and P2 can be estimated more accurately by applying a simple algorithm to remove the second sound oscillations. Analysis of the arrival time of P2 using Eqs. 31 and 32 determines that the ions come from the region at the top of the cell in which the laser is directly applied. The mobility is found to be 0.747 cm^2 V^{-1}s^{-1}.

It is clear from the figure that the arrival time of P1 does not vary significantly with the field E_1 and so these ions must originate below H1 or, at most, a very small distance above. If we assume that these objects are normal electron bubbles with the mobility as given above, we can calculate from where they originate. This comes out to be within 1 mm of the grid at H1. It is natural to assume that the ions come from electrons bound to a high density of vortices trapped on to the grid. Trapping of electrons on vortices at a grid has previously been noted by Doake and Gribbon [79].

We can summarize these results by saying that in these experiments with the CO_2 laser we have not detected any signal which definitely indicates an ion with higher mobility than the normal electron bubble. If such objects are produced by the light their number would probably have to be at least 20 times less than the number of normal electrons produced.

Unfortunately, our experiment is limited by the wavelength of the CO_2 laser. Because we need the transition energy to match the photon energy from the CO_2 laser, we are only able to perform experiments up to 1.5 bars. In the experiments of Grimes and Adams it was found that the photoconductivity effect for the 1S-1P transition "weakens rapidly as P decreases below 3 atm, and is lost in the noise for $P <\approx 0.9$ atm." Thus, our measurements can only probe a pressure range very close to the lowest pressure at which they observed an effect. It would therefore be of interest to repeat the experiment with a shorter wavelength laser so that measurements could be made at higher pressures.

IV. SUMMARY AND OPEN QUESTIONS

We can summarize the main experimental results of this paper as follows.

1) We have been able to generate and detect a series of exotic ions with mobility in the range up to as much as six times the mobility μ_{NEB} of the normal electron bubble.

2) We have observed not only those ions seen previously by Ihas and Sanders, and Doake and Gribbon, but also about six more ions.

3) We have shown that there is a background signal arising from ions which have a continuous distribution of mobility. The background takes on two distinct forms depending on the condition of the plasma.

4) Background #1 exhibits a sharp cutoff at a maximum mobility of about twice the mobility of the normal ion.

5) Background #2 decreases monotonically with increasing mobility. It is not clear if this background has a cutoff.

6) Experiments have been performed in which a CO_2 laser has been used to excite electron bubbles trapped on vortex lines from the 1S to the 1P state. The excitation enabled electrons to escape from the vortices. We were unable to detect the production of

any bubbles of higher mobility, but could only investigate a very narrow pressure range close to the lowest pressure at which a photoconductivity effect had been observed.

We have discussed three possible explanations of these results:

1) The exotic ions are impurity ions. This hypothesis appears to be ruled out because:
a) The liquid helium is unlikely to contain a significant number of impurities.
b) There are not a sufficient number of elements with electron affinity in the range needed to produce the ions of the size observed.
c) Each impurity ion will have a definite size and mobility. Consequently impurities cannot explain the continuous background seen in the data.

2) The exotic ions are helium negative ions or helium dimer ions. Difficulties with this idea are:
a) Although the existence of these ions is well established by other experiments, the lifetime is much less than the transit time of the exotic ions through the experimental cell.
b) This proposal cannot explain the existence of 18 exotic ions with different size.
c) This theory is inconsistent with the existence of a continuous background.

3) The ions are bubbles which contain different fractions of the integral f of $|\psi|^2$ (fission theory).
a) Through the feedback mechanism discussed in section IIC4, this theory provides a mechanism by which a number of ions with different discrete size (and mobility) can be produced. The number of such ions is comparable to the number of exotic ions which have so far been detected.
b) Since f can potentially take on a continuous range of values, the theory has the potential to explain the existence of a continuous distribution of ion size and transit times.
c) It provides a simple explanation of the type #2 background based on the partial transmission of electrons across the barrier at the surface of the liquid helium. The calculated background is in good agreement with experiment; only one fitting parameter is used for this and the value of this parameter is reasonable.

c) Missing from the theory is an explanation of the origin of background #1, and a quantitative calculation of the ways in which the wave function divides to give the different exotic ions.

One can see that while there are serious difficulties with an interpretation based on impurities or helium ions, the fission theory does have the potential to explain the key experimental results. We review briefly the three key assumptions in the fission approach.

1) The helium is treated as a classical system while, of course, the electron is treated quantum mechanically. The electron exerts a pressure on the wall which is

$$P_{el} = \frac{\hbar^2}{2m} |\nabla \psi|^2 , \tag{33}$$

and balancing the pressures then gives the equilibrium radius as

$$R_0 = \left(\frac{f\, h^2}{32\pi m\alpha} \right)^{1/4} . \tag{34}$$

2) If the wave function of an electron entering the liquid is divided between two or more bubbles, it must still be true that only one electron is detected at the collector. The work done by the drift field E_d is therefore $e\,E_d\,d$ where d is the length of the drift region. This work must equal the amount of energy dissipated in the liquid. We take this dissipation to arise solely from the motion of the bubble in which the electron is found. Then the viscous drag force on this bubble must be eE_d. For this reason the effective charge of an exotic ion bubble is assumed to be the charge on an electron [32].

3) It is assumed that the bubbles containing a fraction of $|\psi|^2$ are stable objects, at least on the time scale for passage through the cell. This amounts the assumption that interaction with the helium does not amount to a measurement and cause an irreversible change in the wave function.

To test the fission theory one needs to find a way to measure some properties of the exotic ions in addition to the mobility. As we have discussed in section IIB7, a measurement of the mobility provides only an approximate value for the size of the ion, and does not provide useful information about the structure. Measurements of the optical absorption by the exotic ions would provide valuable information. Because of the low number density of the ions it is probably going to be difficult to measure this directly, i.e., by measuring the attenuation of a beam of light passing through the cell. However, it may be possible to trap exotic ions on quantized vortices and then find the wavelength of light required to excite the ions and cause their release. By comparison of the result of the measurement with a density functional calculation of the energy levels (for an assumed value of f), it would be possible to determine f. Another approach would be to measure the negative pressure at which each exotic ion becomes unstable and explodes [80]. This type of measurement would also make it possible to determine a value of f. Comparison of the values of f found for the same ion by the optical technique and by explosion would provide a critical test of the fission theory [81].

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Ion #, this paper	Energy gap Δ^*, this paper (K)	Ion #, Ihas and Sanders	Energy gap Δ^*, Ihas and Sanders (K)	μ / μ_{NEB}, this paper	Radius based on $\mu \propto R^{-2}$ (Å)	Radius based on $\mu \propto R^{-2.78}$ (Å)
F	8.76	1	9.3	6.42	7.5	9.7
	-	2	9.3			
1	9.23	3	10.1	4.12	9.3	11.4
2	-	4	10.3	3.13	10.7	12.5
3	-	5	11.2	2.72	11.5	13.2
4	9.23	6	10.1	2.32	12.4	14.0
5	-	7	9.6	2.11	13.0	14.4
6	8.98	8	9.5	1.92	13.6	14.9
7	8.86	9	9.6	1.76	14.2	15.4
8	8.52	10	8.5	1.54	15.2	16.2
9	-	-	-	1.39	16.0	16.8
10	8.1	11	8.5	1.33	16.4	17.1
11	-	12	8.6	1.18	17.4	17.8
N	8.12		8.6	1	18.9	18.9

Table 1. Summary of the results for ion mobility. Columns 2 and 4 list the effective roton energy gap found in the current experiment, and in the work of Ihas and Sanders.[23] The ratio of the ion mobility μ to the mobility μ_{NEB} of the normal electron bubble is from measurements at 0.991 K in the current experiment. The estimate of the ion radius in the last two columns is described in the text.

FIGURE CAPTIONS

Fig. 1. The upper plot shows data of Ihas and Sanders[22,23] taken at 1.005 K with a drift field of 30.8 V cm^{-1} and a drift length of 6.5 cm. The lower shows our measurement of the ion signal versus time at 0.991 K with a drift field of 82.1 V cm^{-1} and a drift length of 6.15 cm.

Fig. 2. Cross-section through the experimental cell showing the tungsten tips T, the perforated plate P, gate grids G1 and G2, field homogenizer discs H1-H4, Frisch grid F and ion collector C.

Fig. 3. Mobility of the fast ion F, three of the exotic ions, and the normal electron bubble as a function of temperature. Note that the temperature difference is slightly different for the different ions.

Fig. 4. Detected ion signal as a function of time. The temperature was 1.00 K, the voltage on the plate P and the voltage on the grid G2 was held at -520 V. The curves are labelled by the tip current and other parameters are given in the text. The different curves are offset for clarity.

Fig. 5. Detected ion signal as a function of time. The temperature was 0.991 K, the voltage on G2 was -520 V, and the different curves are labelled by dc voltage difference between G1 and G2. The other parameters used in the experiment are given in the text. The different curves are offset for clarity.

Fig. 6. Detected ion signal as a function of time taken with the reversed voltages as described in the text. The temperature was 1 K and the drift field was 82.1 V cm^{-1}. The tip and plate voltages were (a) -394 V and -530 V, (b) -532 V and -570 V, and (c) -531 V and -670 V, respectively. The different curves are offset for clarity.

Fig. 7. Detected ion signal as a function of time with the peaks due to exotic ions removed by the method described in the text. The data set is the same as shown in the lower part of Fig. 1.

Fig. 8. Detected ion signal as a function of time at 1.025 K. The voltage on the plate was kept at about 5 V negative with respect to G1, and the drift field was increased from 34.7 V cm^{-1} to 99.7 V cm^{-1} in equal steps. The dashed curve shows the background of type #1

and the solid curve is for background #2. The arrows indicate the end point of background #1. The background switches from type #1 to type #2 when the tip current is decreased. The different curves are offset for clarity.

Fig. 9. Velocity of the fastest ions from the background #1 as a function of the drift field E_d. The velocity is obtained from the data shown in Fig. 8. The solid line is a fit to the data assuming that the velocity is proportional to the field.

Fig.10. a) The solid curve shows the detected ion signal at 1.04 K using the carbon nanotube tip with the voltages given in the text .The dashed curve shows the result of removing the contribution to the signal from the first twelve ions using the method described in section IIB4. b) The signals coming from each of the peaks which were removed. In both parts of the figure the peaks are labelled using in the same numbering scheme as is used in the lower part of Fig. 1.

Fig. 11. Bubble radius and electron affinity ϕ as a function of the parameter V_0 based on the calculations described in the text.

Fig.12. Transmission of electrons into the liquid as a function of energy and angle θ from normal incidence. The curves are labelled by the angle of incidence θ in degrees.

Fig.13. The signal of background type #2 scaled in time and normalized as described in the text. The data sets are the same as shown in Fig. 8, and are labelled by the drift field. The simulation is described in the text.

Fig. 14. Schematic of fission. (a) shows the wave function of the 2^{nd} excited state for a particle in an infinite square well.(b) shows the effect of a barrier.(c) shows the effect of reducing the width of the left hand well.

Fig. 15. Results of an experiment at 1.05 K in which a CO_2 laser pulse is used to excite electrons attached to vortices. The different curves are labelled by the voltage difference between the tip and the grid G1. The other parameters are given in the text. The different curves are offset for clarity.

Fig. 16. Results of an experiment in which two parts of the cell contain different drift fields as described in the text. The different curves are labelled by the field in the upper part of the cell in V cm^{-1}.