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# Observation of a New Type of Negative Ion in Superfluid Helium

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**Abstract.** In recent work, we have developed a new technique for the study of the properties of electron bubbles (negative ions) in liquid helium. We use ultrasound to measure the critical negative pressure $P_c$ at which an electron bubble becomes unstable and explodes. The value of $P_c$ is affected, for example, by the quantum state of the electron and is reduced if the bubble is attached to a quantized vortex. In the present experiments, we have discovered a new type of object that appears to be larger than the usual electron bubble. We will consider possible explanations of these observations.

**Keywords:** Electron bubble, Critical negative pressure
**PACS:** 67.40.H, 43.35

## INTRODUCTION

An electron injected into liquid helium forces open a spherical cavity or radius $R$ approximately 19 Å in which there are no helium atoms.[1] The size of this so–called electron bubble is determined by a balance between the outward pressure exerted by the electron, the surface tension $\alpha$, and the pressure $P$ in the liquid. The equilibrium radius is found by minimizing the total energy $E$ given by

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

where $h^2/8mR^2$ is the ground state energy of the electron confined in the bubble ($m$ is the electron mass). A number of different techniques have been used to study electron bubbles including mobility measurements and optical studies.[1,2] These experiments are consistent with the radius found from Eq. 1. However, several groups have detected other negatively charged objects in superfluid helium. These objects include the "fast ion"[3] and the "exotic ions".[4,5] The size of these objects can be estimated from their mobility, and it appears that their radius lies in the range between 10 to 16 Å. This is much larger than the radius for negatively-charged impurity ions, and there are major difficulties with other possible explanations.[4] The purpose of this paper is to report a new experiment in which we detect for the first time another unidentified electron object (UEO). This appears to be an electron bubble that is larger than the normal electron bubble.

## EXPERIMENTAL SETUP

We have constructed an experimental cell which can be used for optical and ultrasonic experiments down to 0.6 K (see Fig. 1). To inject electrons into the helium we use a field emission tungsten tip. In some experiments this tip was replaced by a $^{63}$Ni $\beta$– source with an activity of approximately 5 mCi. The maximum energy of the emitted electrons is 67 keV giving a range in liquid helium of less than 1 mm. After entering the liquid, each electron forms a bubble which then moves through the liquid under the influence of the local electric field. An externally applied field is produced by applying a negative dc voltage to the tungsten tip (or radioactive source) and keeping the lower surface of the ultrasonic transducer at ground potential. In addition, each electron bubble is acted on by the space charge field produced by the other electron bubbles in the liquid. The number density of electrons in the liquid can be modified by changing the externally applied field. The density also changes with temperature because as the temperature is lowered the number of thermal excitations (phonons and rotons) decreases rapidly resulting in a reduction in the drag force on a moving bubble and a large increase in mobility.

We have developed an ultrasonic method that can be used to detect single electron bubbles and to determine some information about their characteristics.[6] If the pressure in the liquid is decreased a bubble becomes larger, and at a critical negative pressure $P_c$, the bubble becomes unstable and begins to grow without limit. If the electron inside the bubble is in the ground state (1S), calculations predict that this pressure should be -1.89 bars. Measurements give results in good agreement with this estimate.[6] For an electron in an excited state, e.g., the 1P state, the outward pressure exerted by the electron is larger and so $P_c$ is smaller.[7] For an electron bubble attached to a quantized vortex, the pressure in the liquid near to the vortex is reduced relative to the ambient pressure due to the Bernoulli effect, and so the magnitude of the critical pressure is reduced relative to the magnitude of $P_c$ for electron bubbles in bulk liquid.[6]

In the experiments reported here, a hemispherical ultrasonic transducer was used to generate sound pulses at a frequency of frequency 1.35 MHz (see Fig. 1). To a good approximation one can assume that the pressure oscillation at the acoustic focus is proportional to the amplitude of the ac voltage $V_{ac}$ driving the transducer. If there is an electron bubble close to the acoustic focus, it will explode as soon as the pressure becomes less than $P_c$, i.e., more negative than $P_c$. After the bubble becomes unstable it grows rapidly. A He-Ne laser beam is sent through the region around the acoustic focus and the light scattered from the bubble is detected through the use of a photo-multiplier tube (PMT in Fig.1). In the experiment, a sequence of a few hundred acoustic pulses is generated and the number of times that an exploding bubble is detected is counted. From the results, the probability $S$ of cavitation per sound pulse is calculated.

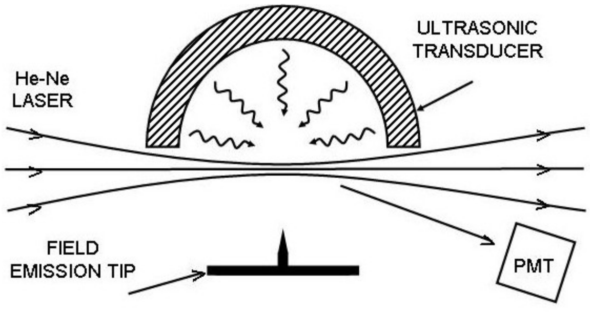


**FIGURE 1**. Schematic diagram of the experiment.

## EXPERIMENTAL RESULTS

At high temperatures (e.g., 2 K) there are no electron bubbles attached to vortices. Consequently, the probability of cavitation is zero until the transducer voltage reaches a critical value $V_{c1}$ such that the negative pressure swing at the focus reaches the critical pressure $P_c$. For this transducer voltage, there has to be an electron bubble precisely at the acoustic focus in order for an explosion to occur. When the voltage is increased above $V_{c1}$ electron bubbles in a region near to the focus can explode and so the cavitation probability increases rapidly. From the variation of $S$ with $V_{ac}$, the number density of the electron bubbles in the liquid can be determined.

At high temperatures, measurements show that there is a single threshold voltage at which cavitation begins to be seen. However, at low temperatures the experiment reveals multiple cavitation thresholds, thus indicating the presence of different types of electron bubbles with different critical pressures. Sample data showing this is in Fig. 2, taken at 0.72 K. Two distinct thresholds can be seen at 18.5 and 20.6 V. The solid curve in this figure is a fit to the data based on the assumption that two distinct objects are present, and suing the same type of analysis as in ref. 7.

To investigate these objects in more detail, we have made measurements of the cavitation probability as a function of voltage, temperature and applied electric field. From these data, it is clear that there are three distinct types of electron bubble present. The number density of each of these objects varies considerably with temperature and electric field and so for most

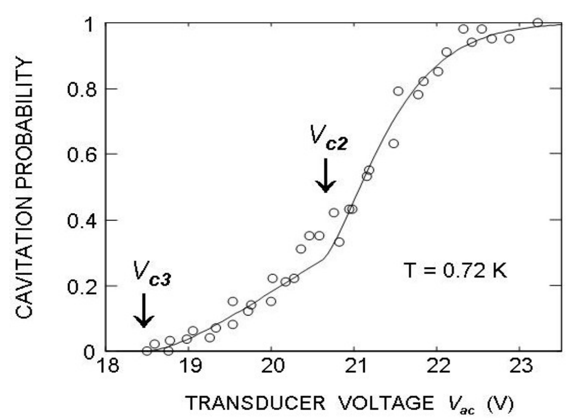


**FIGURE 2**. Probability of cavitation $S$ as a function of the driving voltage $V_{ac}$ applied to the transducer showing the two thresholds at $V_{c2}$ and $V_{c3}$.

combinations of temperature and fields the thresholds for only one or two of the objects can be seen. The pressure at which each of these objects explodes is shown as a function of temperature in Fig. 3. We are confident that we have correctly identified two of these objects, but we do not know the nature of third object.

The first object #1 exploding at $P_{c1}$ is the "normal" electron bubble in bulk liquid. This identification is based on the result that it was the only object seen when the radioactive source was used to inject electrons, the temperature was high ($T \geq 1.1$ K), and a small electric field (<100 V cm$^{-1}$) was applied to direct the electrons towards the transducer. Under these conditions, the electron bubbles should move through the liquid too slowly to produce vortices. When the temperature is lowered, the mobility of the electron bubbles increases and the number density of the type #1 objects decreases rapidly. For $T \leq 1.1$ K, the number density became too low for the cavitation threshold to be detected. This variation of the number density with temperature is consistent with object #1 being an electron bubble in bulk liquid.

For larger electric fields and at temperatures below 1.95 K, the second object #2 is seen with threshold at $V_{c2}$. These objects appear to be electron bubbles that are attached to quantized vortices. Evidence in favor of

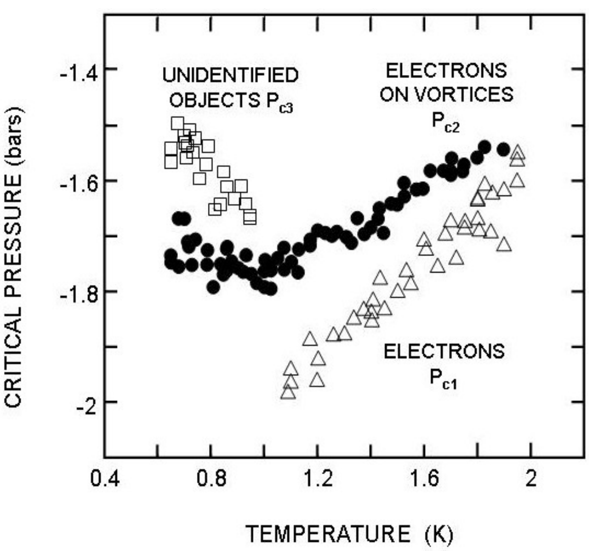


**FIGURE 3.** Measured negative pressure required to explode an electron in liquid helium as a function of temperature. Distinct thresholds are found for electron bubbles moving in bulk liquid $P_{c1}$, bubbles attached to a vortex $P_{c2}$, and for the new unidentified objects $P_{c3}$

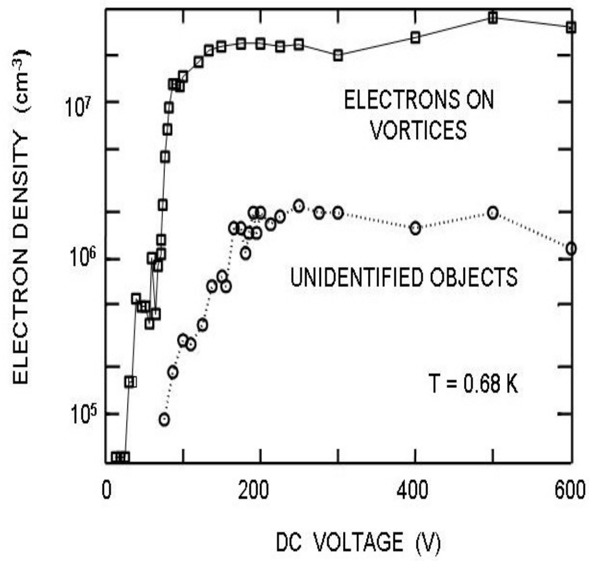


**FIGURE 4.** Measured density of electrons on vortices and unidentified electron objects as a function of the magnitude of the applied dc voltage (negative) that is applied to the radioactive source. These measurements were made at 0.62 K.

this assignment comes from a measurement of the number density of the objects as a function of electric field . When the radioactive source is used to inject electrons, the #2 objects are only seen when the electric field is sufficiently large to give the electron bubbles the critical velocity needed for the nucleation of quantized vortices. When the field emission tip is used instead of the radioactive source, the situation is a little more complicated. Near to the tip, the electric field is very large and vortices will be created even when the electric field in the bulk of the cell is not high enough to give electron bubbles the critical velocity. The vortices created near the tip, together with attached electrons, can travel across the cell losing energy as they go and may be able to reach the acoustic focus.

The new unidentified electron objects #3 (UEO's) appear only when the temperature is below 1 K. They can be detected when electrons are injected from either the tip or the radioactive source. With the radioactive source the UEO's appear only when a sufficiently large electric field is applied. This critical field varies with temperature. Figure 4 shows measurements of the number density of the UEO as a function of the magnitude of the negative voltage applied to the radioactive source. The UEO's first appear at a voltage that is roughly a factor of two larger than the voltage needed to produce electrons on vortices. The density of the UEO's is always at least one order of magnitude less than the density of electrons on vortices.

## DISCUSSION

We have been unable to establish the physical nature of these objects. The observation that they are only seen when the electric field is above a critical value, suggests that they must have some connection with quantized vortices. The bubbles explode at a negative pressure that has a smaller magnitude than the explosion pressure for a normal electron bubble. This means that the objects are probably larger than standard bubbles. The pressure enters into the expression for the total energy as the term $PV$ (see Eq. 1) and so for a larger bubble the effect of an applied negative pressure will be larger, thereby giving a critical pressure for explosion that has a smaller magnitude.

One possibility is that the UEO's are electron bubbles that are moving at high velocity just after having escaped from a vortex line. These bubbles would be accelerated by the electric field, and quickly reach the critical velocity at which a new vortex ring can be nucleated. The electron bubble would then again be trapped. While the bubble is moving at high speed, the pressure at the surface of the bubble will be reduced below the pressure in the bulk liquid due to the Bernoulli effect. As a result, the bubble should explode at a critical pressure of the bulk liquid which is of a smaller magnitude than the magnitude of the critical pressure for a stationary bubble. The critical velocity $v_c$ for vortex nucleation is around $30\ \mathrm{m\ s}^{-1}$, and so the order of magnitude of the Bernoulli pressure is $\rho v_c^2/2 = 0.65$ bars. This is of the right order of magnitude to explain the shift in the critical pressure that we detect. However, since electron bubbles are continually escaping from vortices at a certain rate, if it is these bubbles that are the UEO's we would expect that the probability that cavitation occurs should be proportional to the length of time for which the negative pressure is applied. To look for this effect we measured the cavitation probability $S$ as a function of the number of cycles $N$ in the sound pulse. However, we found no significant variation of $S$ when $N$ was changed, and thus we think that the UEO cannot be fast moving bubbles.

Since the UEO's appear to be related to the presence of vortices it is possible that they are electron bubbles that are attached to two vortex lines or to a single vortex line that has a circulation around it of $2h$. As far as we know, there has been no previous experimental support for the existence of doubly-quantized vortices, although Dalfovo has performed calculations of their energy and structure.[8]


## ACKNOWLEDGMENTS

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