Observation of a New Type of Electron Bubble in Superfluid Helium

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We report on the observation of a new type of electron bubble in superfluid helium-4. This object appears to be larger than the normal electron bubble and is associated with the presence of quantized vortices in the liquid.

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Electrons injected into liquid helium repel helium atoms and form bubbles of radius R approximately 19 Å [1,2]. The size of these bubbles is such as to minimize the total energy of the bubble, i.e., the quantity E given by

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

where the ground state energy of the electron confined in the bubble is $h^2/8mR^2$ (m is the electron mass), $4\pi R^2\alpha$ is the surface energy (α is the surface tension), and $4\pi R^3 P/3$ is the work done in forming the bubble against the applied pressure P. These electron bubbles have been investigated extensively through mobility measurements and optical studies [1–3], and their behavior is well understood. In addition to these bubbles, there have been several observations of other negatively charged objects whose physical nature is still a mystery. These include the so-called "fast ion" [4] and the "exotic ions" [5–7]. Because they have a higher mobility that the normal electron bubbles, these objects are believed to be smaller, probably with radius in the approximate range 10–16 Å [8]. In this Letter we describe a new experiment in which we detect for the first time another object which appears to be an electron bubble that is *larger* than the normal electron bubble.

In the experiments reported here, we use a cell filled with liquid helium with windows for optical observation. Electrons are injected into the liquid helium either from a β source or from a field emission tip. Figure 1 shows the experimental setup when the β source was used. The source was a ^{63}Ni source with an activity of approximately 5 mCi. The range of the most energetic electrons emitted by the source is less than 1 mm. After coming to rest in the liquid, each electron forms a bubble which then diffuses through the liquid and also drifts under the influence of the electric field. The field is the sum of the field that is externally applied and the space charge field arising from the density of electron bubbles in the liquid. The externally applied field is produced by giving a negative dc voltage to the radioactive source while maintaining the inner surface of the transducer at ground potential. By varying the voltage on the radioactive source it is possible to change the number density of the electrons in the helium over some range. The number density is also affected by the mobility of the bubbles which increases rapidly as the temperature is lowered.

To detect the electron bubbles we used an ultrasonic method that has been described previously [9,10]. The method is based on the fact that there is a critical negative pressure P_c at which an electron bubble becomes unstable and explodes, i.e., at this pressure the bubble begins to grow without limit. For an electron bubble with the electron in the ground state, this pressure has been calculated to be -1.89 bar [9] and experimental measurements give results in good agreement with this estimate [8]. Instead of moving freely through bulk liquid, electron bubbles can become attached to quantized vortices [1,2]. The pressure near the vortex is reduced due to the Bernoulli effect and so bubbles that are trapped on vortices explode at an applied negative pressure of smaller magnitude than that required for a bubble away from a vortex [9].

To generate a negative pressure, a hemispherical ultrasonic transducer was used to produce sound pulses of frequency 1.35 MHz (Fig. 1). The outer surface of this transducer was grounded. The amplitude of the pressure oscillation at the acoustic focus was proportional to the amplitude of the ac voltage V_{ac} driving the transducer. When an electron bubble comes sufficiently close to the

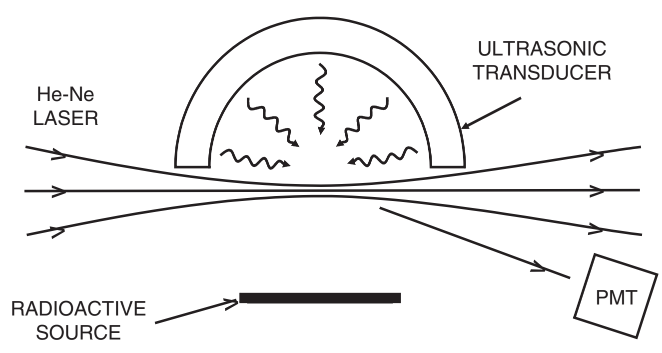

FIG. 1. Schematic diagram of the experiment. The ultrasonic transducer generates sound which results in a large pressure oscillation at the acoustic focus. When an electron bubble explodes, scattered laser light is detected by the photomultiplier tube (PMT).

acoustic focus, it will explode if the pressure at its location becomes negative with respect to P_c. The bubble then rapidly grows in size. In order to detect the bubble, a laser beam is passed through the acoustic focus and some of the light that is scattered by the bubble is detected by means of a photomultiplier. The experiment consists of sending in a series of acoustic pulses (e.g., 200) and measuring the number of sound pulses for which a bubble is detected. This gives the probability S of cavitation per sound pulse.

If the helium contains just one sort of electron bubble, the cavitation probability is zero until V_{ac} is increased to a value sufficient for the negative pressure swing at the focus to exceed P_c. When V_{ac} is increased above this value, the cavitation probability increases rapidly since it becomes possible for bubbles to explode even if they are not precisely at the acoustic focus. From the rate at which S increases with increasing V_{ac}, it is possible to estimate the number density of the bubbles in the liquid. When there are more than one species of bubble present, a plot of S as a function of V_{ac} exhibits multiple cavitation thresholds. An example of this is shown in Fig. 2, which is data taken at 0.85 K. This data shows two thresholds. We have made an extensive series of measurements of this type at different temperatures and with different applied electric fields. The results indicate the existence of three distinct objects, (not all observable at the same time) and the critical pressure at which each of these objects explode is plotted as a function of temperature in Fig. 3.

We have been able to identify two of these objects, but not the third. The identification was achieved as follows: (1) When the radioactive source was used to inject electrons, the temperature was high ($T \geq 1.1$ K), and only a small electric field (roughly 100 $\mathrm{V\,cm^{-1}}$) was applied to direct the electrons towards the transducer, the electrons move through the liquid too slowly to produce vortices. Thus, we expect that the only objects present should be electron bubbles in bulk liquid. Under these conditions, the experiments do indeed indicate a single threshold pressure for cavitation (threshold #1), and we identify this pressure with the explosion of electron bubbles in bulk liquid. As the temperature is lowered, the mobility of the electron bubbles increases causing a rapid decrease in their number density. Below about 1.10 K, the number density became too low for the cavitation threshold to be detected. (2) When a large electric field is applied and the temperature is between 1.1 and 1.7 K, a second threshold is seen (threshold #2, at V_{c2}). We believe that this threshold is associated with the explosion of electron bubbles that are attached to vortices. This interpretation is supported by measurements of the magnitude of the electric field that is needed in order for the threshold to be seen. This field is found to have approximately the magnitude needed to give electron bubbles the critical velocity that is required in order to nucleate and become attached to quantized vortices. When the field emission tip is used instead of the radioactive source, the threshold for electrons on vortices can be detected up to a somewhat higher temperature. We assume that this is because vortices are created in the region near to the tip where the electric field is very large. These vortices, with attached electrons, then travel across the cell losing energy as they go but because if their large initial energy are still able to reach the acoustic focus.

The new unidentified electron objects (UEO's) appear when the temperature is below 1 K and a sufficiently large electric field is applied (threshold #3 at V_{c3}). The variation

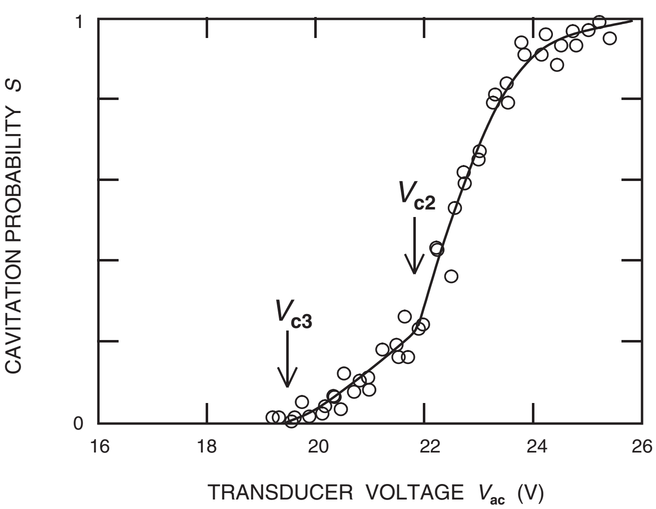

FIG. 2. Probability of cavitation S as a function of the driving voltage V_{ac} applied to the transducer showing the two thresholds at V_{c2} and V_{c3}. These measurements were made at 0.85 K.

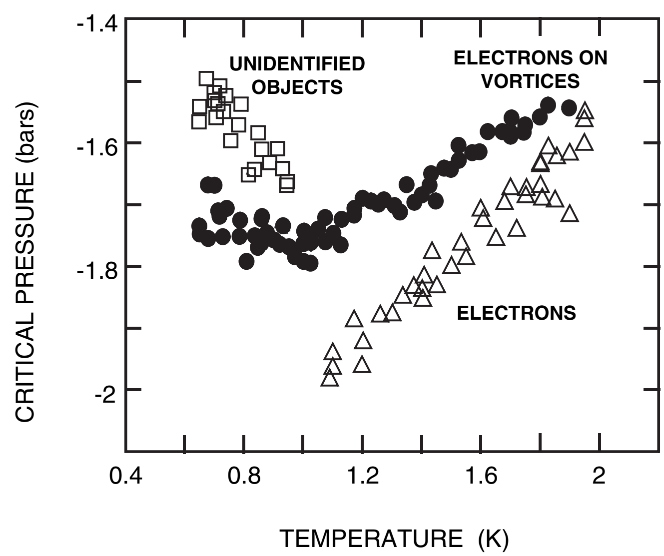

FIG. 3. Measured negative pressure required to explode an electron in liquid helium as a function of temperature. Three distinct thresholds are found for electron bubbles moving freely through the liquid V_{c1}, for bubbles attached to a vortex V_{c2}, and for the new unidentified electron objects V_{c3}.

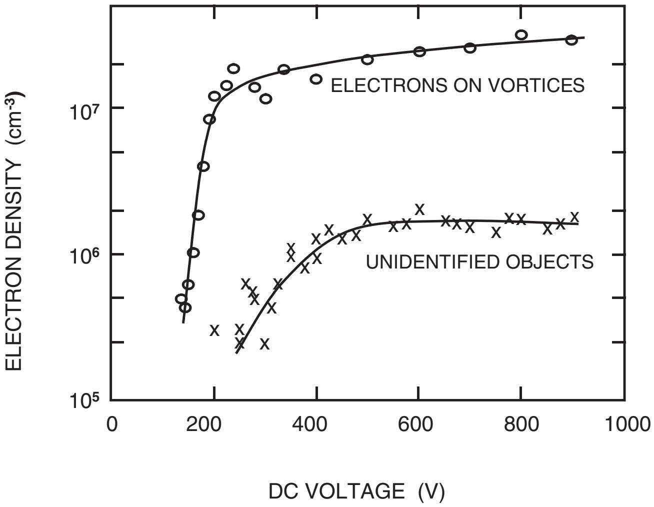

FIG. 4. Measured density of electrons on vortices and unidentified electron objects as a function of the magnitude of the applied dc voltage (negative) that is applied to the radioactive source. These measurements were made at 0.79 K.

of the threshold pressure for UEO's with temperature is included in Fig. 3. The variation of the number density of the UEO with the magnitude of the negative voltage applied to the radioactive source is shown in Fig. 4, along with the number density of the electrons on vortices. It can be seen that the UEO first appear at a voltage that is roughly a factor of 2 larger than the voltage needed to produce the electrons on vortices, and that the density of the objects is always at least 1 order of magnitude less than the density of electrons on vortices.

We do not know what these objects are. It is quite remarkable that the very simple system of an electron coupled to chemically inert helium atoms can support negative ions (i.e., the UEO reported here, the fast ion, and the exotic ions) whose physical nature cannot readily be understood. The fast and exotic ions appear to be objects that are smaller than the normal electron bubble and moving freely through the liquid. On the other hand, the experiments reported here suggest that the UEO must in some way be connected with vortices since they are only observed when the electric field is above a critical value. The fact that they explode at a negative pressure that is smaller in magnitude than for a normal electron bubble suggests that the objects are probably larger than standard bubbles. This comment is based simply on the observation that the pressure enters into the expression for the total energy of a bubble through the term PV and so a larger initial volume means that the effect of a pressure change is greater. As far as we are aware, it is not possible to make this argument more quantitative.

We have considered the possibility that the UEO could be electron bubbles that have just escaped from being trapped on a vortex line. Such bubbles would accelerate under the influence of the electric field, reach the critical velocity and then nucleate a new vortex ring and become trapped on it. During the time that the bubble is moving at high speed, the Bernoulli effect could cause the pressure at the bubble surface to be reduced compared to the pressure in the bulk liquid. This would cause the bubble to explode when the pressure in the bulk liquid was less negative than the pressure required to explode a stationary bubble. The critical velocity v_c for vortex nucleation is around 3×10^3 cm s^{-1}, and so $\frac{1}{2}\rho v_c^2 = 0.65$ bar. Thus, the magnitude of the Bernoulli pressure is in the right general range to explain the experimental results. However, if this were the explanation of the UEO we would expect that the probability of cavitation occurring would be proportional to the length of time for which the negative pressure was applied, since presumably electron bubbles are continually escaping from vortices at a certain rate. We performed an experiment to see if the cavitation probability S did in fact increase for longer sound pulses and found that this did not happen.

Another possibility is that the UEO 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 are aware, there is no prior experimental evidence for such objects, although Dalfovo has considered the theory of a doubly-quantized vortex [11].

In a recent interesting Letter Berloff and Barenghi [12] have shown that collapsing bubbles in a superfluid can result in vortex nucleation. It is conceivable that this mechanism could lead to electron bubbles attached to two vortices or to a doubly quantized vortex.

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