Observation of Exploding Electron Bubbles in Liquid Helium

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Electrons in liquid helium become trapped in bubbles from which the liquid is excluded. By applying a negative pressure to the helium, we are able to make these bubbles explode. The pressure at which this occurs is in reasonable agreement with theoretical expectations. [S0031-9007(96)01031-9]

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When an electron enters liquid helium, it experiences a repulsive potential V_0 of approximately 1 eV [1]. As a consequence it is energetically favorable for the electron to become localized within a spherical volume from which the helium is nearly completely excluded [2]. As a first approximation one can consider that the energy E is the sum of the zero-point energy of the electron, the surface energy of the bubble, and a volume energy proportional to the applied pressure P, i.e.,

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

where R is the bubble radius, m is the electron mass, and α is the surface energy per unit area [3]. At zero pressure the radius at which the energy is a minimum is

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

This radius is 19 Å at $T = 0$ and increases slightly as the temperature goes up. In writing down Eq. (1), it is assumed that the energy of the electron is much less than the barrier height V_0, so that the penetration of the electron into the bubble wall is unimportant. In a more sophisticated theory, several other effects can also be included such as the polarizability of the liquid and the finite width of the liquid-vapor interface [3].

Application of a positive pressure naturally makes the equilibrium size of the bubble decrease. A negative pressure expands the bubble and for a sufficiently large negative pressure P_c the bubble becomes unstable; i.e., the energy is a monotonically decreasing function of the radius. This is indicated in Fig. 1. It is straightforward to show that the pressure P_c is given by

$$P_c = -\frac{16}{5}\left(\frac{2\pi m}{5h^2}\right)^{1/4}\alpha^{5/4}. \tag{3}$$

This critical pressure is approximately -2 bars at $T = 0$ K. If a pressure more negative than P_c is applied to the bubble, it will grow without limit. In this Letter we report the first observations of these explosions [4].

The liquid helium was contained in a low temperature optical cell that was filled with helium from a gas cylinder at room temperature. Electrons were introduced into the liquid by means of a 10 μCi ^{204}Th β source. On entering the liquid the electrons lose energy by ionization while they travel at high velocity and then form bubbles when they reach the end of their range. To produce a transient negative pressure we used a hemispherical piezoelectric transducer (PZT) ultrasonic transducer of inner radius 0.64 cm to generate and focus 560 kHz sound waves into a small volume. The duration of the sound pulses was 29 μs. The β source was located approximately 0.3 cm below the acoustic focus, and on the opposite side of the focus from the transducer. If an electron bubble is in the region of the acoustic focus and the pressure swing is large enough, the bubble will explode and grow in size to the point that it can be observed by light scattering. A He-Ne laser beam was passed through the acoustic focus, and the light that was scattered was detected by means of a photomultiplier tube.

The average density of electrons in the liquid is determined by a balance between the rate at which they are injected by the source and the rate at which they leave the liquid. The rate at which they leave is determined by their drift velocity under the influence of electric fields arising from the space-charge or external sources, and may also be influenced by diffusion, or by currents in the liquid. With the 10 μCi source that we have used, the density of electrons is such that there is not always an electron close to the acoustic focus, i.e., within a small distance compared to the acoustic wavelength. Consequently, even when the pressure swing at the focus exceeds P_c, an explosion does not always occur. The

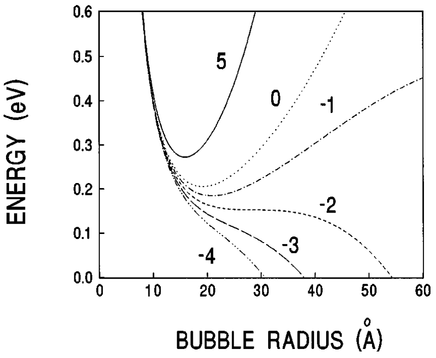

FIG. 1. The energy of an electron bubble in liquid helium at zero temperature as a function of radius. The different curves are labeled by the pressure in bars.

experiment consisted of applying a series of acoustic pulses and measuring the probability S of observation of a large (i.e., exploded) bubble. Results of measurements of this type are shown in Fig. 2, where the acoustic amplitude is measured in terms of the ac driving voltage V_{ac} applied to the transducer. In these measurements the density of the electrons could be changed by a static electric field produced by the application of a dc voltage V_{dc} to the inside surface of the hemispherical transducer, i.e., to the surface adjacent to the acoustic focus.

When a large dc negative voltage is applied ($V_{\mathrm{dc}} = -200$ V), the density of electrons in the vicinity of the acoustics focus is small. In this case the cavitation probability is low until the ac drive voltage is increased to around 200 V. At this point there is a rapid rise in S which results from the homogeneous nucleation of bubbles in the liquid, i.e., the formation of bubbles by homogeneous nucleation independent of the presence of electrons. For smaller negative bias and for positive bias the electron density is increased. One can then see in the data a clear threshold at an ac voltage V_{ac}^{c} of approximately 100 V. At this level of drive to the transducer, the pressure swing is large enough to explode an electron bubble, but only if the bubble is precisely at the acoustic focus. For larger drive voltages the probability S can be written as

$$S = 1 - \exp[-nv(V_{\mathrm{ac}}/V_{\mathrm{ac}}^{c})], \tag{4}$$

where n is the number density of electrons in the liquid and $v(V_{\mathrm{ac}}/V_{\mathrm{ac}}^{c})$ is the volume of the liquid around the acoustic focus in which the maximum negative pressure swing exceeds the value required to explode an electron bubble. From calculations of the variation of the sound field in the vicinity of the acoustic focus [5], one can make a theoretical estimate of the dependence of v on the ratio of V_{ac} to V_{ac}^{c}. The solid curves in Fig. 2 are fits to the experimental data based on Eq. (4) using the electron density n as an adjustable parameter. The agreement is excellent considering the uncertainty in the estimate of $v(V_{\mathrm{ac}})$. The fit values of n range from 825 000 cm^{-3} for $V_{\mathrm{dc}} = +27$ V to 10 400 cm^{-3} for $V_{\mathrm{dc}} = -200$ V.

It is difficult to calculate the magnitude of the pressure swing at the acoustic focus from the piezoelectric and mechanical characteristics of the transducer [6]. To overcome this problem we have made measurements similar to those shown in Fig. 2 as a function of static pressure P_{stat} applied to the liquid. These data give the threshold voltage V_{ac}^{c} required to explode a bubble at the acoustic focus as a function P_{stat}. The derivative $dV_{\mathrm{ac}}^{c}/P_{\mathrm{stat}}$ can then be used as a factor to convert applied voltage to minimum pressure P_{min} at the focus according to

$$P_{\mathrm{min}} = -V_{\mathrm{ac}}^{c}/(dV_{\mathrm{ac}}^{c}/dP_{\mathrm{stat}}). \tag{5}$$

This assumes, of course, that P_{min} is linearly proportional to V_{ac}. This assumption is supported by the observation that over a static pressure range in which V_{ac}^{c} changes by a factor of 2, the relation between V_{ac}^{c} and P_{stat} is reasonably linear [7]. Using this calibration we can then determine absolute values for the pressure required to explode an electron bubble, and the results as a function of temperature are shown in Fig. 3. The solid curve is the theoretical prediction from Eq. (3) using the surface tension as measured by Iino *et al.* [8]. The agreement is reasonable, but suggests that the theory could perhaps be improved through the use of a more accurate calculation of the energetics of the electron bubble allowing for penetration of the electron wave function into the helium, polarizability of the helium, etc. We are currently attempting to make calculations to incorporate these effects.

Finally, we report two other interesting effects which have been observed in these experiments. So far these have only been studied qualitatively. Below the threshold voltage needed to explode an electron bubble, the probability of observation of cavitation is very small (less than

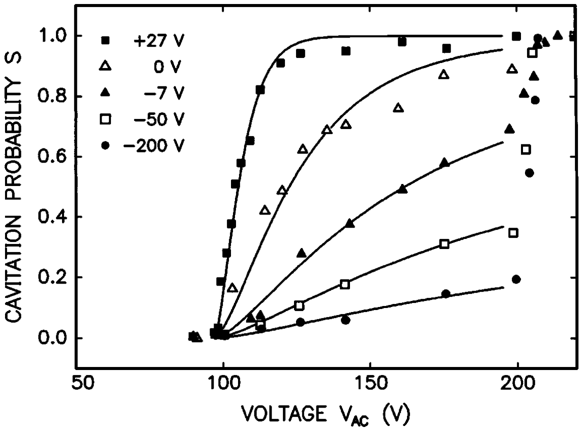

FIG. 2. The probability S of cavitation as a function of the voltage V_{ac} applied to the transducer. The results are for different electron densities in the helium resulting from the application of dc electric fields as described in the text. Solid curves are fits to the data based on Eq. (4).

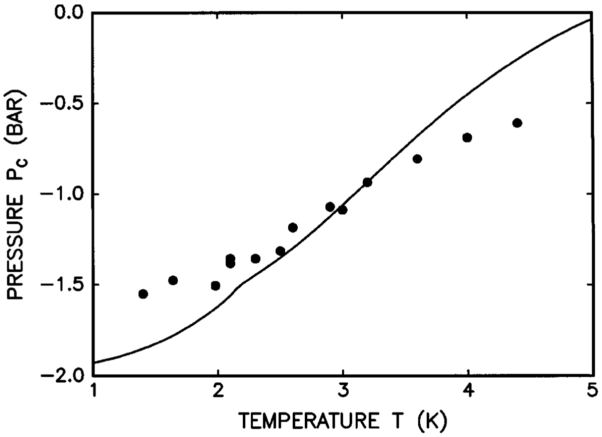

FIG. 3. The pressure P_c at which electron bubbles explode as a function of temperature. The solid curve is calculated from the theoretical result Eq. (3).

2%), but is nonzero. These "rare events" are unaffected by the application of static electric fields. They cease to occur when a small metal plate is placed as an obstacle in the direct line between the source and the acoustic focus. These observations suggest that the rare events arise from high energy electrons which pass through the acoustic focus at the same time that the sound pulse is present. These electrons deposit energy along their track, and this energy can locally raise the temperature of the helium and result in nucleation of bubbles. The rate of these rare events is in rough agreement with what is expected based on this interpretation [9].

A second effect occurs at low temperature. As the temperature is lowered below 1 K, there is a sudden *decrease* in the voltage V_{ac} that is required to produce visible bubbles. In addition, the results become somewhat irreproducible; i.e., the measured values of the probability S depend on the time that has elapsed since the previous acoustic pulse. One interesting possibility is that these effects come about because the electron bubbles are being trapped on quantized vortices. An electron trapped on a vortex should explode at a somewhat smaller negative pressure because of the circulation of the superfluid around the vortex. However, we have not yet made a quantitative estimate of the pressure at which this should occur.

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[5] This calculation was performed along the lines described by H. T. O'Neil, J. Acoust. Soc. Am. **21**, 516 (1949).

[6] The ultrasonic transducer has a number of acoustic modes with frequencies close to the frequency of the fundamental thickness mode. A quantitative calculation of the magnitude of the pressure swing requires that the contribution from all of these modes be included.

[7] The derivative $dV_{\mathrm{ac}}^{c}/P_{\mathrm{stat}}$ was measured at several temperatures within the range of temperatures of the experiment, and was found to be approximately independent of temperature. Consequently, the average value of this quantity was calculated, and this average value used for the conversion of applied voltage to pressure at all temperatures.

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