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Cavitation in Superfluid Helium Possibly Arising from Penning Ionization of Dimers

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We have performed a series of experiments to study cavitation in superfluid helium into which electrons are injected by field-emission from a sharp tip. The injected electrons force open small cavities in the liquid ("electron bubble"). These objects explode at a critical negative pressure P_c, and in previous experiments we have studied the cavitation that results from these explosions. In the present experiments we have detected cavitation events that occur before a negative pressure as large as P_c is reached. We suggest that these events may arise from a process in which two neutral helium dimers interact and an electron is injected into the liquid through Penning ionization.

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When an electron is injected into liquid helium and comes to rest, it forces open a small cavity in the liquid, referred to as an electron bubble. These objects have been studied in a wide range of experiments[1]. Recently, it has been demonstrated that when a negative pressure exceeding a critical value $P_c \approx -1.89$ bars is applied to liquid that contains an electron bubble, the bubble becomes unstable and rapidly grows to a size such that it can be detected optically. In these experiments, a sound wave is generated by an ultrasonic transducer and comes to a focus within a small volume of the liquid[2]. If this volume contains an electron bubble and on the negative pressure swing the pressure becomes more negative than P_c, cavitation will occur. The probability that a sound pulse will lead to cavitation thus increases with increase in the density of electron bubbles and with the volume of the liquid throughout which P_c is exceeded.

In the first experiment of this type, the electrons were injected into the liquid through the use of a β-source. This produced high energy electrons with a continuous spectrum of energies. Electrons came to rest at differ-

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ent locations throughout the liquid and the resulting electron bubbles then slowly drifted toward the cell walls under the influence of the space charge electric field and an externally-applied field. Thus, the bubbles were formed and were later exploded by the sound field. Surprisingly, it was found that even when the pressure swing reached a critical value $P_c^{(a)}$ of $\approx 0.5P_c$, there was still a small but measurable probability of detecting cavitation. These so-called "rare events" arose in the following way. There was a small probability that a high energy electron from the β-source might pass through a region of the liquid at an instant when the pressure was negative. If the high energy electron ionized a helium atom, the secondary electron that was produced would form an electron bubble at a location a short distance away from where the ionization took place. When the bubble was being formed, there was a rapid flow of liquid away from the bubble. The inertia of this flow caused the bubble radius to overshoot its equilibrium value and, as a result, the bubble could continue to grow without limit even if the pressure was positive with respect to P_c.

In the experiments reported here, we have used a tungsten tip to inject electrons into the liquid by field emission. As in the experiment with the β-source, we have found that cavitation can occur before the pressure P_c is reached, but we believe that the reason for this is different from the previous experiment.

The experiment is shown schematically in Fig. 1. A hemispherical PZT transducer was used to generate focused sound waves. The sound frequency was 1.35 MHz with a 1 Hz pulse repetition rate. Cavitation was detected by passing a He-Ne laser beam through the acoustic focus and detecting scattered light with a photomultiplier (PMT). The distance between the field emission tip and the acoustic focus was 2.5 mm. The tip had a threshold voltage for emission in the range -500 to -1000 V and was made by electrochemically etching a 0.275 mm diameter tungsten wire. The inner surface of the transducer was connected to ground through a $10^{11}\ \Omega$ resistor that served to stabilize the tip current. The density of electrons n_e, in the vicinity of the acoustic focus could be controlled by varying the tip current. This current was typically around 1 nA. All measurements were made under saturated vapor pressure, and in the temperature range 1.4–1.9 K. The cavitation probability S was measured by applying 200 acoustic pulses and counting the number of times that cavitation occurred. This was then repeated for different driving voltages V_{tran} on the transducer. Results for acoustic pulses of 14 and 56 cycles are shown in Fig. 2. A sharp rise in the cavitation probability occurred when the pressure swing at the acoustic focus first exceeded $|P_c|$ and electron bubbles began to explode. The voltage V_c required for 56 cycles is less than for 14 cycles because for the longer acoustic pulse there is

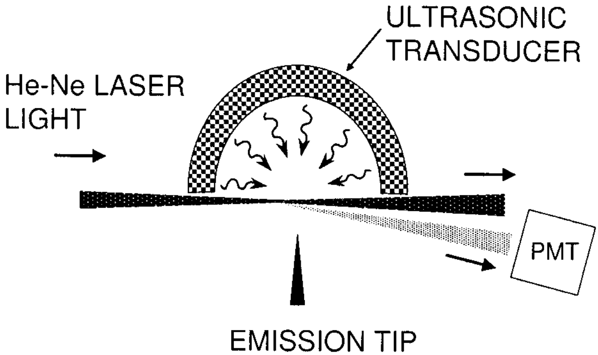

Fig. 1. Schematic diagram of the apparatus used to study cavitation.

more time for the vibrational amplitude of the transducer to build up. This decrease in V_c is affected by the quality factor of the transducer. Below the critical voltage, the probability S was small but continued to be non-zero down to a voltage that was about $0.6V_c$. Thus, there are some new objects or mechanisms that can lead to cavitation as soon as the pressure falls below ${P_c}^{(b)} = 0.6P_c = -1.3$ bars. It can be seen from Fig. 2 that in the voltage range below V_c, S is considerably larger for the 56 cycles pulse than for the 14 cycles pulse (roughly by a factor of 4). This suggests that the cavitation in this voltage range originates from a process that is occurring at a certain rate $\dot{R}$ per unit volume and per unit time in the regions of the liquid where the pressure is less than the critical value ${P_c}^{(b)}$. Accordingly, we have performed a numerical calculation to determine the probability of cavitation as a function of the transducer voltage, for a given value of $\dot{R}$. We first find the pressure in the liquid in the region around the acoustic focus as a function of time and position. From this, we determine the volume $v(t)$ throughout which the pressure is less than ${P_c}^{(b)}$ at time t. The probability of cavitation occurring in this volume in a time increment δt is $\dot{R}v(t)\delta t$. From this, the probability that cavitation occurs at any time during the application of one sound pulse can be found. When the pressure is less than P_c, there is an extra contribution arising from the explosion of ordinary electron bubbles. The results of the calculation are compared to the experimental data in Fig. 2. The adjustable parameters in the fit are $\dot{R}$, the density of ordinary electron bubbles n_e, and the critical pressures P_c and ${P_c}^{(b)}$. The best fit values are $\dot{R} = 1.0 \times 10^{11}$ cm^{-3} s^{-1} with an uncertainty of about 10%, and $n_e = 2.0 \times 10^8$ cm^{-3}.

Consider now the possible origin of the cavitation events. It is reasonable to assume that the events come about from some process that leads to

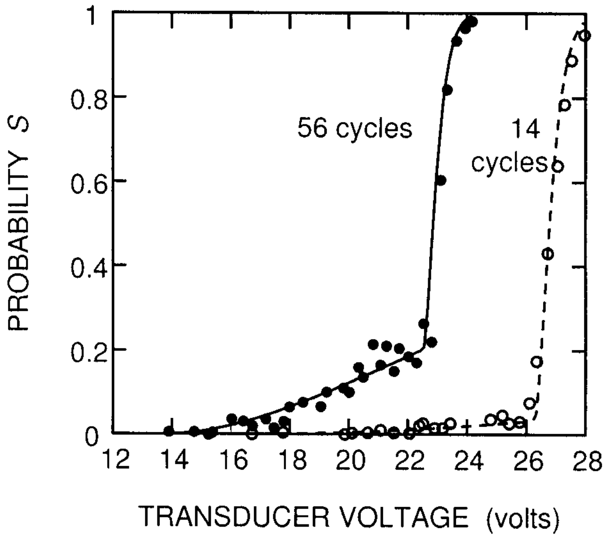

Fig. 2. Probability of cavitation S as a function of transducer voltage V_{tran} when the transducer is driven for 14 (open circles) and 56 cycles (solid circles). The solid and dashed curves are the results of the simulations described in the text.

the injection into liquid helium of electrons that then form electron bubbles, i.e., we suppose that the mechanism is similar to the rare events that are seen with the β-source. However, the tip does not produce high energy electrons that can travel through the helium and cause ionization at the acoustic focus. An emission tip immersed in liquid helium produces in addition to electrons, a large number of neutral dimers[3]. These are diatomic helium molecules He_2^* in an excited state. The singlet molecules undergo radiative decay to the ground state in less than 10^{-8} s, and hence will be found only in the immediate vicinity of the tip. An isolated triplet molecule in the liquid, on the other hand, has a lifetime that is greater than 15 s. It has been shown[4] that triplet dimers in liquid are destroyed in a bimolecular process

$$\frac{dn_d}{dt} = -\alpha {n_d}^2 , \tag{1}$$

where n_d is the density of triplet dimers at the focus and the coefficient α at the temperature of 1.58 K is approximately 5×10^{-10} cm^3 s^{-1}. In this process an electron is injected by the Penning ionization process

$$\begin{aligned} {He_2}^* + {He_2}^* &\rightarrow 3He + He^+ + e^- \\ \text{or} \qquad &\rightarrow 2He + {He_2}^+ + e^- , \end{aligned} \tag{2}$$

where He indicates a helium atom in the ground state. We propose that the cavitation events that we see with threshold $P_c^{(b)}$ arise from the electrons injected into the liquid by this mechanism. In order to have the rate of destruction of dimers to be equal to $\dot{R}$, we need to have $n_d = 1.4 \times 10^{10}\,\mathrm{cm}^{-3}$ in the vicinity of the acoustic focus. It is not easy to decide if this is a reasonable value. Zimmerman *et al.*[3] have estimated that when electrons are injected from a tip, of the order of one neutral dimer is produced for each electron. In our experiment, this would mean that the rate of production of dimers would be of the order of $10^{10}\ \mathrm{s}^{-1}$ but, of course, this number could be affected by the different geometry of the tip, applied voltage, etc. The density of dimers and the rate of destruction will decrease rapidly with distance from the tip. The density of electrons is strongly affected by the electric field geometry in the experimental cell. Hence, the number of dimers and electrons may be quite different at the acoustic focus. However we note that if we consider a sphere of radius equal to the distance of the tip from the focus, the volume of this sphere would be 0.07 cm^3 and so if the rate $\dot{R}$ everywhere within this sphere were constant at the value $10^{11}\ \mathrm{cm}^{-3}\,\mathrm{s}^{-1}$, the rate at which dimers are consumed would be $1.4 \times 10^{10}\,\mathrm{s}^{-1}$, a value not inconsistent with the rate of production.

The dimers will move away from the tip as a result of diffusion but will also be dragged along by the flow of the normal fluid[3]. This flow arises because the electric field gives a force on the electron bubbles, whose motion in turn gives a force on the normal fluid. To make a quantitative calculation of the density of dimers at the focus requires a calculation of the flow pattern of the normal fluid, and this in turn requires more detailed information about the electric field distribution in the cell than is currently available.

Assuming that the cavitation events do indeed arise from Penning ionization of dimers, one can ask why the threshold pressure $P_c^{(b)}$ is somewhat larger in magnitude than the onset pressure $P_c^{(a)}$ for the rare events seen with the β-source. We think that the explanation may be as follows. In both of these processes, an electron is injected into the liquid as a result of ionization and comes to rest at a short distance from a positive ion. The electron begins to form a bubble and, at the same time, is pulled back towards the positive ion with which it soon recombines. In order for cavitation to take place, the bubble must reach a critical size before the electron and the positive ion recombine. The electrons produced by the Penning process have a lower kinetic energy (probably $5 - 10$ eV) than the secondary electrons produced by β-ionization (typically $10 - 30$ eV), and thus travel a shorter distance from the positive ion before coming to rest in the liquid. As a result the time available for a bubble to grow before recombination is less, and so a larger negative pressure may be needed to make a bubble of the critical size.

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