Heterogeneous cavitation in liquid helium 4 near a glass plate

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We have used a focused acoustic wave to study cavitation, i.e. the nucleation of bubbles, in liquid helium 4 near a clean glass plate. From the reflectance of light at the glass/helium interface, we measured the amplitude of the acoustic wave in the focal region and the nucleation pressure. From an analysis of the transmitted light we also measured the nucleation probability. We observed three different regimes with different statistics and threshold pressures in the range 0 to -3 bar, significantly less negative than for homogeneous cavitation.
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1. Introduction

By focusing ultrasound waves far from any wall in an ultrapure liquid such as liquid helium, we have progressed in the understanding of cavitation, a stochastic phenomenon of great technical importance.[1,2] In our previous studies, we studied homogeneous cavitation and one major difficulty was the measurement of the instantaneous pressure at which nucleation takes place. In order to measure it, we have inserted a clean glass plate at the center of the wave emitter, a hemispherical piezoelectric transducer. By doing this we significantly improved our knowledge of the acoustic waves we use, including the non-linear effects which affect their focusing.[4] Moreover, we extended our studies to the nucleation of solid helium.[3] We also shifted from homogeneous nucleation far from any wall to heterogeneous nucleation on a clean wall. Our preliminary results show that heterogeneous cavitation is significantly different from homogeneous nucleation, even on a wall which is perfectly wet by liquid helium.

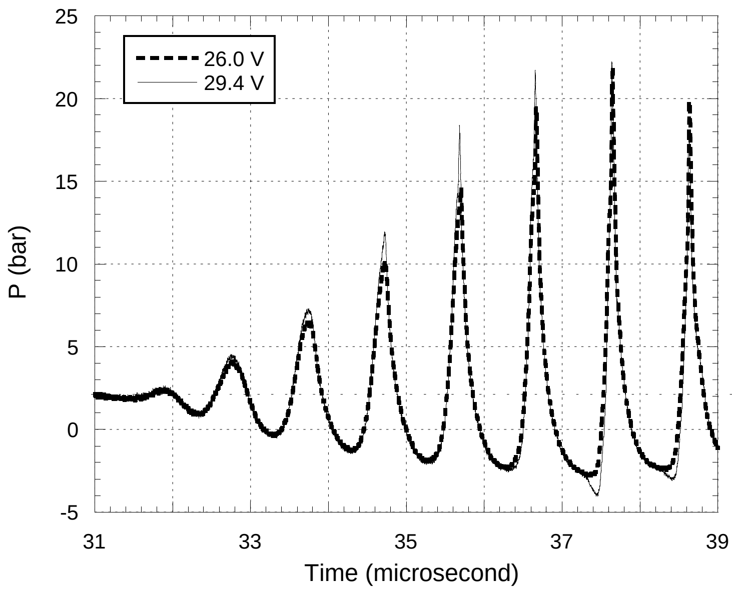

Fig. 1. Two recordings of the sound amplitude. Here, the static pressure in the cell is 2.03 bar and the temperature is 200 mK. The curve corresponding to the highest excitation voltage (29.4 V) shows not only non-linear effects which distort the wave form but also additional signals at the end of negative swings, which are due to the occurence of cavitation.

2. The wave amplitude and the cavitation threshold pressure. A first regime of heterogeneous cavitation.

For the present study, our transducer was excited at resonance (1.019 MHz) with electrical bursts of 6 oscillations. Since the quality factor of the transducer is finite (Q $\approx$ 90 at 2 bars), the amplitude of the emitted wave increases during 6 periods before decreasing slowly to zero. Fig.1 shows two recordings of the wave amplitude at 200 mK with a static pressure P_{stat} = 2.03 bar in the cell. The two curves correspond to two different excitation voltages (26.0 and 29.4 V). These curves are averages on 10 000 bursts which are repeated at 9 Hz. The pressure calibration is obtained as follows.[3,4] We first measure the static pressure in the cell and calculate the static density from the equation of state.[5] We then use the Clausius-Mossoti relation to calculate the index of refraction of liquid helium and we finally obtain the amplitude of the reflection coefficient at the glass/helium interface, in the absence of acoustic wave. Finally, by measuring the ratio of the ac-modulation of the reflected light to its dc-component, we have access to the absolute amplitude of the density oscillation in the acoustic wave (or the pressure by using the equation of state again).

For the lowest voltage (26.0 V), we see evidence for non-linear effects. Indeed, the negative swings are broad with a smaller amplitude than the positive swings which are sharp and about 5 times larger. The negative swings are also asymmetric in time. All these distortions from a sinusoidal shape are functions of the wave amplitude. A good agreement was found with numerical calculations which account for the non-linearity of the equation of state and the formation of shocks in the acoustic focal region.[6] There is no sign of cavitation on this curve, contrary to the one at 29.4 V, which shows an additionnal signal when the pressure reaches its maximum negative value.

The reflected signal is needed to measure the instantaneous density or pressure, but it is not sensitive enough to measure cavitation events one by one. Fortunately, we could also detect the light transmitted through the acoustic focus, which is strongly scattered by bubbles if they nucleate. This transmitted light allowed the detection of single nucleation events. From these two measurements, we had access to both the nucleation pressure threshold and the statistics of nucleation (see Fig.2). In Fig.1, we present curves which are ordinary averages, in order to show the cavitation phenomenon qualitatively. For a precise measurement of the cavitation pressure, we performed selective averages where we eliminated signals either with cavitation or without cavitation. For a 29.4 V excitation, we measured a cavitation probability $\Sigma = 45$ % and a cavitation pressure -2.7 bar.

This cavitation pressure is less negative than what we had found for homogeneous cavitation.[2] In the absence of the glass plate, we had found $-10.4 < \mathrm{P_{cav}} < -8$ bar, in good agreement with the predicted spinodal limit P_{sp} = -9.6 bar where the liquid becomes totally unstable. To find a much less negative cavitation pressure in the presence of a wall is somewhat surprising and interesting. Indeed, at first sight, since liquid helium wets glass perfectly, we expected that bubbles would not nucleate on the glass surface but in the acoustic focal region close to this surface. If this simple picture was correct, we should have found about the same -9 bar as before. As we shall see below, we had to be carefull with the intensity of the laser beam which illuminates the nucleation region, and there are further differences between heterogeneous and homogeneous cavitation.

3. Other regimes of heterogeneous cavitation

Our optical method uses a laser beam which is focused at the glass/helium interface, in the center of the acoustic focal region.[4] Since quantum noise in the reflected beam is a non-negligible source of uncertainty, we had to use a minimum laser amplitude. The laser power is typically 30 to 300 μW at the glass/helium interface. Most of this light is either trans-

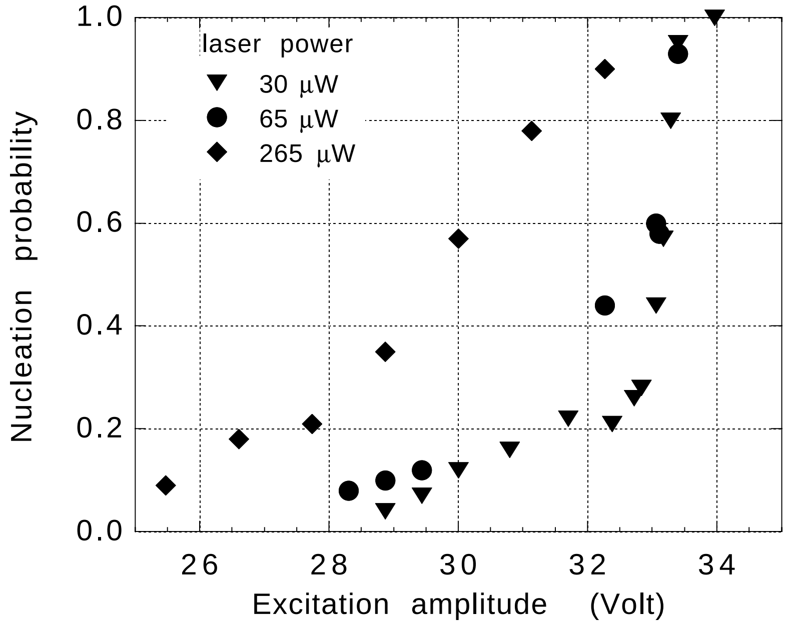

Fig. 2. The probability of cavitation as a function of the voltage applied to the piezoelectric transducer. The three symbols correspond to three different laser intensities at the glass/helium interface.

mitted through the cell, or is reflected back. Moreover, there is a shutter so that the cell is illuminated during 10 ms only, each time a sound pulse is emitted. Even if the light absorption in the cell is rather small, it was important to look for possible thermal effects due to the illumination. Fig.2 shows the cavitation probability as a function of the excitation voltage for three different laser powers. For the highest intensity (open circles), the probability curve is broad and it is shifted down in voltage. This set of data corresponds to the recordings of fig.1. For the lowest intensities (black diamonds and squares), the probability curve still has a broad foot but most of the rest is sharp and independent of the incident light. In the limit of low laser intensity, we found a cavitation probability $\Sigma = 0.5$, i.e. a cavitation threshold at P_{cav} = -3.1 bar, corresponding to an excitation voltage 33.1 V. This is slightly more negative than for the data on fig.1, but still much less negative than observed in the case of homogeneous nucleation (in the absence of glass wall).

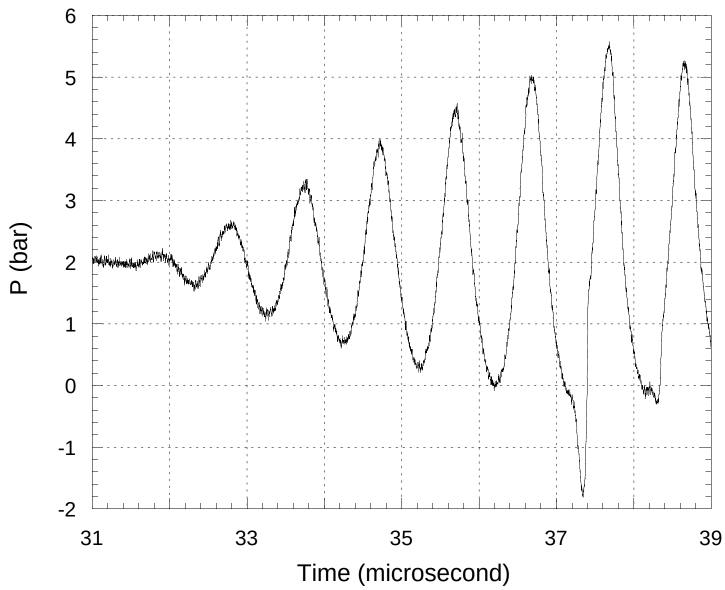

Fig. 3. This recording shows the occurence of cavitation at reduced sound amplitude, near 0 bar. We attribute it to the presence of a defect on the glass wall.

When we studied homogeneous nucleation, we observed sharp probability curves similar to the upper part of the curves at low laser intensity. These preliminary results demonstrate the existence of at least two different cavitation regimes. The first one looks similar to homogeneous nucleation except that it occurs at a less negative pressure, -3 bar instead of -9 . A second one occurs at even smaller excitation and has a broader statistics, which indicates a smaller activation energy with a different dependence on pressure. Since the reflected beam is only sensitive to the immediate vicinity of the glass plate, it is likely that all these cavitation regimes take place on the glass surface. This conclusion is of course supported also by the observation of a cavitation threshold which is different from what was observed in the bulk of liquid helium.[2]

Eventually, we observed a third type of cavitation which occurs only slightly below 0 bar, i.e. very close to the saturated vapor pressure. By tilting the incidence of the laser beam, we could translate the optical focus at the glass surface. Slightly away (20 μm) from the center of the acoustic focal region, we have found that cavitation occurred at 0 bar where the helium density is 0.14513 g/cm^3 (see fig.3). We checked this by changing the static pressure in the cell from +2 to +4.3 bar, where we found threshold densities from 0.14515 to 0.14512 g/cm^3. We believe that the glass plate has a defect there which considerably lowers the nucleation barrier of the bubbles. We do not know the nature of this defect. Moreover, we do not understand which kind of defect can lower the energy barrier for the nucleation of bubbles. Indeed, only bare cesium is known to be slightly favourable to the gas phase, and there is no cesium in our cell, of course. Everything else is perfectly wet by liquid helium. In fact, even for the nucleation which takes place at -3 bar, it is difficult to be sure that there is no defect there either. Our observations lead to a double question: how could a flat glass plate decrease the nucleation barrier? what kind of defect could decrease this barrier even more?

4. Conclusions

We have started a study of heterogeneous cavitation at the interface between a glass plate and liquid helium. We have found at least three different regimes. Although liquid helium perfectly wets glass, cavitation always occurs at a pressure wich is less negative than in the bulk (homogeneous nucleation). Some particular defects are apparently able to suppress the metastability of liquid helium at negative pressure. This may explain why old studies[7] found cavitation a few mbars only below the saturated vapor pressure. Even in the absence of defects, our results indicate that the presence of a clean glass wall shifts the metastability limit of liquid helium from the theoretical spinodal limit at -9.6 bar to -3 bar only. This observation calls for new theoretical ideas.

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