Cavitation in normal liquid helium 3

F. Caupin, P. Roche, S. Marchand and S. Balibar

Laboratoire de Physique Statistique de l'Ecole Normale Supérieure
associé aux Universités Paris 6 et Paris 7 et au CNRS
24 rue Lhomond 75231 Paris Cedex 05, France

We have studied cavitation, i.e. bubble nucleation, by focusing ultrasound burts in normal liquid helium 3 at temperatures down to 40 mK. As in helium 4, cavitation is found to be stochastic, with a cavitation probability 0.5 at a given value of the sound amplitude, which we define as a "cavitation threshold". This threshold is found significantly lower in helium 3 than in helium 4, a result which agrees with theoretical predictions of a spinodal limit at - 3.1 bar in helium 3 instead of - 9.5 bar in helium 4. We also measured the temperature variation of this cavitation threshold; it decreases with temperature as expected for a thermally activated nucleation process. We have not yet found any evidence for a crossover toward cavitation by quantum tunneling below 120 mK as predicted by several authors; if confirmed, it might indicate that the superfluid coherence plays a role in quantum cavitation.

1. INTRODUCTION

Cavitation is the nucleation of bubbles which occurs in a liquid when it is depressed below its saturated vapor pressure. Helium is an ideal liquid to study this phenomenon, because of its extreme purity. Furthermore, in a pure liquid, cavitation is related to the existence of a spinodal limit where the liquid phase is macroscopically unstable, and this spinodal limit has been calculated in helium 4 and in helium 3.[1–3] It has also been predicted [4,5] that cavitation should occur very close to this limit and by quantum tunneling below a certain crossover temperature T^*.

In superfluid helium 4, our previous experiments are consistent with such a crossover and show good agreement with the calculations by Maris.[4] In studying cavitation in normal liquid helium 3, our motivation is double: we want to check that cavitation occurs at much less negative pressures than

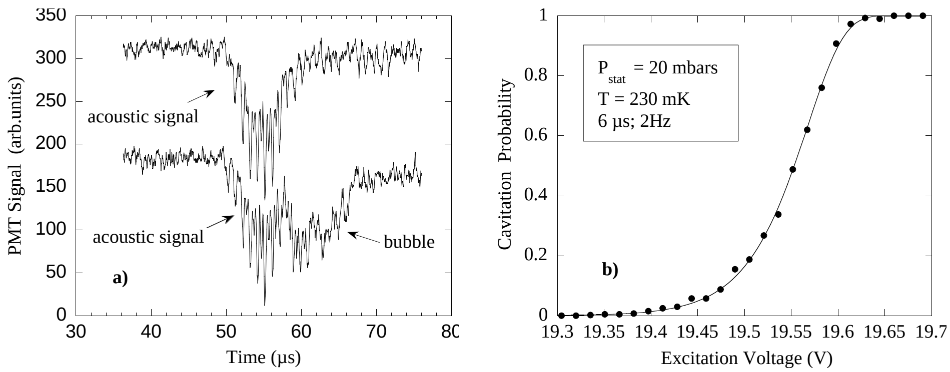

Fig. 1. a) Two recordings of the scattered light detected by the photomultiplier tube. The excitation is the same; only the lower recording shows cavitation. b) Cavitation probability versus excitation voltage at $P_{stat} = 20\,$mbars and $T = 230\,$mK. The solid line is a fit with Eq. (1).

in helium 4, the prediction for the spinodal limit being $-3.1\,$bar instead of -9.5.[1,4] We also want to determine if the superfluid coherence is involved in quantum cavitation or not, a question which is still open.

2. EXPERIMENTAL SETUP

Our setup is similar to the one previously used in helium 4.[6,7] The experimental cell is thermally anchored to the mixing chamber of a dilution refrigerator with optical access. Inside this cell, a hemispherical piezoelectric ceramic is used to produce $6\,\mu$s bursts of 1MHz ultrasound which are focussed in a region of about 100 microns far from any wall (the inner radius of this ceramic is $R = 8\,$mm). A laser beam is also focussed onto the acoustic focus. Light is scattered both by the acoustic wave and by the bubbles, and then detected by a photomultiplier tube. A typical signal is shown on Fig. 1a). In this experiment, there is a mechanical dissipation inside the ceramic. In order to minimize it, we used such short bursts with a repetition rate as low as 0.2 Hz when working at the lowest temperatures; this corresponds to a dissipation of $1\,\mu$W. Despite this mechanical dissipation and some absorption of light from the laser (about $2\,\mu$W in total), experiments could be performed down to $40\,$mK. The effect of the dissipation becomes progressively negligible while increasing temperature, so that we could use a repetition rate up to $2\,$Hz above $200\,$mK.

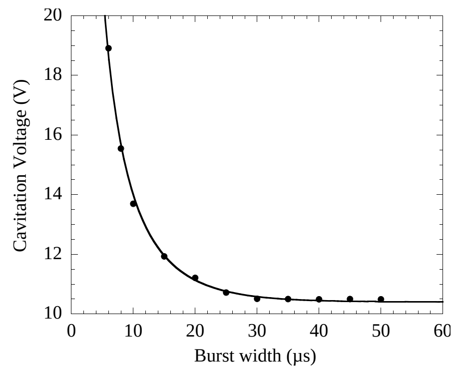

Fig. 2. Cavitation voltage threshold versus burst width at $P_{stat} = 47\,\mathrm{mbars}$ and $T = 492\,\mathrm{mK}$. The full line is a fit which shows a raising time of 7.3 ms.

3. RESULTS

As in helium 4, we found that cavitation is stochastic. We measured the cavitation probability Σ by counting in series of 100 or 400 bursts the number of bursts leading to at least one bubble. When increasing the amplitude of the voltage V applied to the transducer, and consequently the amplitude of the negative pressure swing at the acoustic focus, the probability increases continuously from 0 to 1 as shown on Fig. 1b). Our data are in good agreement with the asymmetric S-shape curve given by the equation:

$$\Sigma = 1 - \exp\left(-\ln 2\, \exp\left(\left(\frac{V}{V_c} - 1\right)\xi\right)\right) \tag{1}$$

This formula is derived from a linear expansion of the activation energy around the cavitation threshold V_c where $\Sigma = 0.5$. The coefficient $\xi = (E/k_B T)(\partial \ln E/\partial \ln V)$ is the inverse width of the curve.[7] The quality of this fit provides a strong evidence that we are really looking at a metastable state with finite lifetime.[7] We have studied the dependence of V_c on the different parameters: drive frequency, burst width and repetition rate, static pressure and static temperature.

At 1015 kHz, the cavitation threshold shows a minimum as function of drive frequency. This minimum is particularly broad if 6 μs bursts are used, which ensures that our measurements are not sensitive to possible drifts in the generator frequency. In such operating conditions, the temperature drift of the ceramic resonance frequency was also negligible. Because of the finite quality factor of the ceramic, the amplitude of its oscillations depends on the burst width τ. We have studied this variation by measuring V_c versus τ

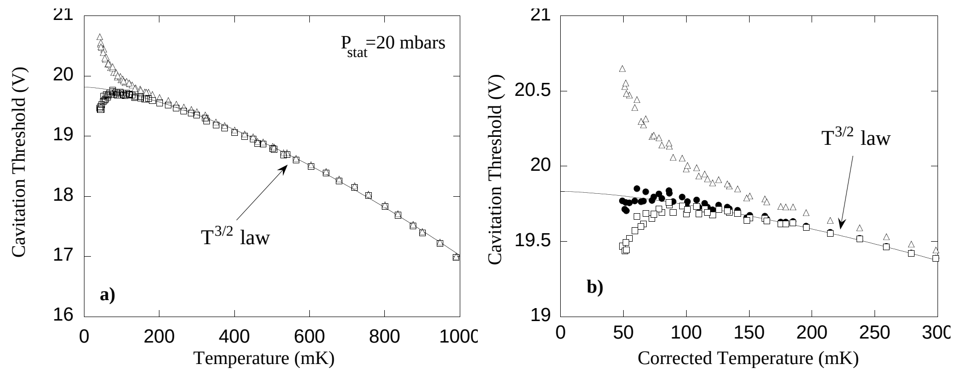

Fig. 3. Cavitation threshold versus temperature at $P = 20\,\mathrm{mbars}$ up to 1 K (a) and below 300 mK (b). The solid line is the $T^{3/2}$-law given in Eq. (3). Triangles correspond to raw data, squares and black circles to corrected data (see text).

as shown on Fig. 2. A good fit is given by the formula :

$$V_c(\tau) = V_c(+\infty)/\left(1 - \exp(-\tau/\tau_0)\right) \quad (2)$$

with a raising time $\tau_0 = 7.3\,\mu\mathrm{s}$.

Three sets of data obtained at $P_{stat} = 20\,\mathrm{mbars}$ are shown on Fig. 3b). The upper one corresponds to raw data. For the lowest one, a correction has been applied because the viscosity of liquid helium 3 diverges at low temperature.[8] Thus, we have to take into account the small attenuation of sound waves which propagate over 8 mm. In the intermediate set, we have included in the correction the small heating effect due to dissipation. We used a value of $2\,\mu\mathrm{W}$ to estimate the temperature difference between the region of the ceramic and our thermometer (a few mK).

4. INTERPRETATION

At high enough temperature, the cavitation threshold V_c decreases with temperature. Qualitatively, this is consistent with the formation of a critical nucleus by thermal activation over an energy barrier ΔE.

As shown on Fig. 3 a), between 150 mK and 1 K we found a good fit for our data with the simple power law:

$$V_c(T) = 19.833\ (1 - 0.14117\ T^{3/2}) \quad (3)$$

with T in K.

At first sight, one could imagine a simple explanation for such a power law. Indeed, the cavitation barrier at the cavitation threshold approximately verifies $E \propto T$ since the attempt frequency varies much more slowly with temperature than the exponential Boltzmann factor in the cavitation probability.[7] Furthermore, the values calculated by Maris[1] for E are well interpolated by $E \propto (P - P_s)^{2/3}$. If one also assumes that the negative pressure swing at the acoustic focus is proportional to the driving voltage V, one finds a 3/2 power law dependence for V_c as in Eq. (3).

However, this explanation is clearly too simple and needs further study. Indeed one expects P_s to vary with T. Furthermore, we also expect the variation of $P(V)$ to be non-linear as one approaches P_s. Our interpretation for the temperature dependence of the cavitation threshold is only qualitative.

Let us now consider the low temperature region and the possible existence of nucleation by quantum tunneling at low temperature. As in helium 4, it would manifest itself by a temperature independent plateau below a certain crossover temperature T^*. This crossover has been predicted to be 120 mK in helium 3 instead of 200 mK in helium 4. On Fig. 3b) the intermediate set of points shows no obvious deviation from the $T^{3/2}$-law; the maximum on corrected data might well be an artefact due to some overestimate of the wave damping in our experiment. Any evidence for quantum cavitation requires that we further check the correction to be applied to the cavitation voltage.

Finally, we can compare the magnitude of the cavitation threshold in helium 3 and in helium 4. In our previous study[7] of liquid helium 4, we used the same ceramic with 70 μs bursts. We thus had to extrapolate the present data to longer width by using Eq. (2). After this and also extrapolating V_c to zero temperature and static pressure, we found $V_{c,4} = 20.87$ V for helium 4 versus $V_{c,3} = 11.02$ V for helium 3, i.e. a ratio 1.9 from helium 4 to helium 3. If we assume that cavitation occurs close to the spinodal limit, it is straightforward to show[7] that in a linear approximation $V_{c,4}/V_{c,3} = (\rho_3/\rho_4)\,(P_{s,4}/P_{s,3}) = (0.0815/0.145) \times (9.5/3.1) = 1.7$, where $\rho_{3,4}$ are the respective liquid densities at zero bar. This result is very close to our experimental value.

Further evidence that the cavitation threshold is about -3 bar in helium 3 can be obtained from an extrapolation of V_c as a function of the static pressure in the cell, assuming again a linear dependence. We have measurements at 20, 40, 80 and 130 mbar; a straight line drawn through the experimental points $V_c(P_{stat})$ crosses the axis $V_c = 0$ at $P_{stat} = -2.7$ bar, the right order of magnitude again (the same method led us to -11.5 bar in helium 4).[7]

5. CONCLUSION

We have studied cavitation in helium 3 at negative pressures in the temperature range 40 mK - 1 K. As in helium 4, we have found that cavitation is stochastic. Our measurements of the cavitation probability agree very well with the hypothesis that the nucleation of bubbles is homogeneous and activated by thermal fluctuations above 100 mK. The compared magnitude of the cavitation threshold also agrees with the prediction that the spinodal pressure in helium 3 is 3 times less negative than in helium 4. As for the prediction that quantum cavitation can occur in normal liquid helium 3 below 120 mK, not only in superfluid helium 4 below 200 mK, our results are too preliminary to decide whether it is confirmed or not. We plan to investigate this further, especially by a direct measurement of the sound wave attenuation in our experiment.

REFERENCES

1. H.J. Maris, *J. Low Temp. Phys.* **94**, 125 (1994).
2. F. Dalfovo *et al.*, *Phys. Rev. B* **52**, 1193 (1995).
3. J. Boronat, J. Casulleras and J. Navarro, *Phys. Rev. B* **50**, 3427 (1994).
4. H.J. Maris, *J. Low Temp. Phys.* **98**, 403 (1995).
5. M. Guilleumas *et al.*, *Proc. of LT21, Czech. J. Phys.* **46**, 389 (1996), Suppl. S1.
6. J.A. Nissen *et al.*, *Phys. Rev. B* **40**, 617 (1989).
7. H. Lambaré *et al.*, *Eur. Phys. J. B* **2**, 381 (1998).
8. M.A. Black, H.E. Hall and K. Thompson, *J. Phys. C* **4**, 129 (1971).