THE LIMITS OF METASTABILITY OF LIQUID HELIUM

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Abstract. We review the present understanding of liquid helium outside its usual stability range. Most theoretical predictions and experiments concern the negative pressure region, where the phenomenon of cavitation has to be considered in relation with the existence of a liquid-gas spinodal limit. New experiments at high pressure also open perspectives in the study of the homogeneous nucleation of solid helium from the overpressurized liquid.

1. Introduction

During the last decade, the phase diagram of liquid helium has been considerably extended. One used to study liquid helium 4 in its stability region only, between its boiling line at low positive pressure and its melting line around 25 bar. Today, not only in their theoretical predictions but also in their experiments, physicists study liquid helium 4 down to about -9 bar and also far above the melting pressure, possibly up to +200 bar. As for its light isotope helium 3, it was only between 0 and about 30 bar, and interesting results have now been obtained down to -3 bar, where an unexpected similarity was found with possible properties of metastable water. In our first section, we briefly summarize the main theoretical predictions concerning the extended phase diagram of liquid helium 4 and 3. We then describe the acoustic technique which allowed recent experiments on metastable liquid helium and new studies of the nucleation of either bubbles in stretched liquid helium or crystals when it is overpressurized. In our last section, we compare predictions with experimental results. We finally conclude with a list of open questions to be studied in the near future.
2. Theory: the extended phase diagram of liquid helium 4

We are interested in the limits of metastability of liquid helium. As shown in Fig.1, this metastability is possible below the saturated vapor pressure, i.e. below the liquid-gas equilibrium line, down to a liquid-gas spinodal (SP) line. It is also possible above the melting line, up to a high pressure instability (HPI) line. The SP line is now rather well established. It corresponds to a divergence of the isothermal compressibility, and H.J. Maris[1] first calculated its location from an extrapolation of the sound velocity at very low temperature. His extrapolation was based on the following form for the equation of state of liquid helium:

\[ P - P_{sp} = \frac{b^2}{27}(\rho - \rho_{sp})^3 \]  \hspace{1cm} (1)
His most recent values are $P_{sp} = -9.6201 \text{ bar}$, $\rho_{sp} = 0.094262 \text{ g/cm}^3$ and $b = 1.4054 \times 10^6 \text{ g}^{-1}\text{cm}^4\text{s}^{-1}$. This form was criticized by Kotschevik[3] but recently confirmed by the Monte Carlo simulations of Bauer et al.[4]. In order to obtain the spinodal limit, Boronat[5] also used Monte Carlo simulations, as for the Barcelona group[10] and Dalfovo[6], they used density functional theories. The results of these various works and a few others are summarized in Fig.2.

As can be seen, all theoretical predictions agree that, at $T = 0$, $P_{sp} = -9.4 \pm 0.3 \text{ bar}$ at $T=0$. The corresponding density is $\rho_{sp} = 0.100 \pm 0.005 \text{ g/cm}^3$.

The temperature variation of the spinodal pressure was calculated by the Barcelona group[9]. Their results agree with the extrapolations by Hall and Maris[8] and the Monte Carlo calculations by Bauer[4]. The spinodal line has to end at the liquid-gas critical point ($P_c = 2.289 \text{ bar}$, $T_c = 5.2 \text{ K}$).

An interesting property of the spinodal line is its slope $dT_{sp}/dT$. It was noticed by Speedy[12] that the sign of this slope is the same as the sign of the isobaric expansion coefficient $a_P = (1/V)(\partial V/\partial T)_P = -(1/V)(\partial S/\partial P)_T$. 

\textit{Figure 2.} Successive theories and calculations lead to a rather well established prediction for the liquid-gas spinodal limit in helium 4. It is a line in the (P-T) plane extending from -9.4 bar at T=0 up to the critical point at +2.289 bar and 5.2K.
As shown in Fig. 1, we now believe that the slope of the spinodal line in helium 4 is positive at all temperatures, meaning that $\alpha_P$ is also always positive near the spinodal line. This is far from obvious since, in the stable region at positive pressure, $\alpha_P$ changes sign twice. There is a line of maximum density (MD) in the phase diagram, but also a line of minimum density; they form a loop and do not reach the spinodal. This was first predicted by Skripov[13] and recently confirmed by the calculations of Edwards, Maris and Caupin[2, 15]. The physical origin of these extremum density lines in helium 4 is important to understand.

Since the work of Landau[14] and subsequent neutron scattering studies, it is known that the elementary excitations in superfluid helium are "phonons" and "rotons". The phonons are quantized sound waves; the rotons are special phonons with large wave-vectors whose density of states diverge near their energy minimum $\Delta$. Landau thought that rotons were kinds of quantized elementary vortices, but it is now generally accepted that they are free atoms dressed by the interaction with their neighbours. Since the roton energy gap $\Delta$ is of order 10 K in the stable region ($0 < P < 25 \text{ bar}$), the thermodynamics of superfluid helium is controlled by rotons above about 1K and by phonons at low temperature.

The pressure dependence of the energy of phonons is the opposite of that of rotons. As $P$ decreases towards the spinodal line, the phonon energy decreases (liquid helium becomes soft at large wavelength). On the contrary, the roton energy increases, and the roton minimum might change into an inflexion point around the spinodal limit[6, 15]. In the stable region, $\partial \Delta / \partial P$ is sufficiently negative for the roton contribution to $\alpha_P$ to overcome the phonon contribution and lead to a positive $\partial S/\partial P$ and a negative $\alpha_P$. As one approaches the spinodal line, the phonon contribution increases and the roton contribution decreases. This leads to a positive expansion coefficient.

Another interesting feature of the phase diagram of helium 4 is the superfluid transition or "lambda" line. Superfluid helium becomes normal when it is invaded by excitations, and one can calculate the lambda line within Landau's "two fluids" model by calculating the "normal density" associated with thermal excitations and determining the temperature at which it equals the full density of liquid helium. It is again the particular pressure dependence of the roton gap which is responsible for the negative slope of the lambda line in the positive pressure region (see Fig. 1). Since the compressibility diverges at the spinodal limit, one could expect the superfluid to be invaded by an avalanche of phonons as one approaches the SP line. Some authors[3, 13] thus predicted that the lambda line bent back and reached the SP line at $T=0$. However, more recently, Skripov[13] considered the possibility that the lambda line meets the SP line at finite temperature. Bauer[4] and Apenko[16] found from their recent simulations
that the lambda line does not bend back so much; it seems to be almost vertical at negative pressure in the phase diagram, reaching the SP line around $T = 2K$. This is now confirmed by the analytic calculations of Caupin[15], and by the numerical calculations of Edwards and Maris[2].

The reason for this is as follows. It is only the static compressibility which diverges at the spinodal limit. As a consequence, only the zero frequency phonons have zero energy there. The phonon branch in the dispersion curve goes from linear above the spinodal limit to quadratic at the spinodal limit[17]. As a result, there is no avalanche of phonons occurring at the spinodal limit. At finite temperature one needs to reach temperatures of order 2 K for the density of excitations to be high and destroy superfluidity.

Other interesting properties of the helium phase diagram are now considered at high pressure, far above the melting line, but they are mostly speculative at present. Some of them date back from the work of Schneider and Enz[18]. In 1971, they considered the possible instability associated with the vanishing of the roton energy gap. Indeed, since the roton gap decreases when the pressure increases, one could imagine that, at some critical pressure $P_{HP1}$, $\Delta = 0$. Since the roton wavevector is finite, of order the inverse of the average distance between nearest neighbours in the liquid, it seems likely that the liquid would spontaneously organize in a periodic state which could be crystalline helium. At that time, one had no precise method to extrapolate $\Delta(P)$, no hope to make measurements up to the necessary pressure either. This has changed recently. Indeed, the density functional theory by Dalfovo et al.[6] allows to calculate the phonon-roton dispersion relation at any pressure, so that Maris and Edwards[15] recently predicted the roton gap to vanish around $P_{HP1} = +200$ bar. Furthermore, as explained in Section 4, it might be possible to overpressurize liquid helium up to such a very high pressure by using fast acoustic pulses. The recent experiments by Chavanon et al.[19] have demonstrated that it is possible to pressurize liquid helium more than 4 bar above the liquid-solid equilibrium line. They were performed in the presence of a clean glass wall and the heterogeneous nucleation of solid helium was easily detected. They opened interesting perspectives for a much larger overpressurization when their glass plate will be removed in order to look for the homogeneous nucleation limit.

In the high pressure region also, the extrapolation of the lambda line is an interesting open problem. Very recent calculations[15] predict that the lambda line meets the HP1 line at $T = 0$. This is first because superfluidity cannot be suppressed at $T = 0$ and high pressure except if the roton energy is zero. Secondly, on the HP1 line, the zero value of $\Delta$ induces an avalanche of rotons at any finite temperature, so that superfluidity is destroyed at finite temperature. However, on the HP1 line, the Landau theory is not
valid and it is not easy to make rigorous predictions\cite{15}. Furthermore, the slope of the lambda line close to $T = 0$ is not known and it has been drawn horizontal arbitrarily on Fig.1. Finally, it seems natural to expect that if the lambda line meets the HPI line at $T = 0$, so do the extremum density lines as well. Basically, all the above predictions at high pressure remain to be checked experimentally. The slope of the HPI line near $T = 0$ is uncertain at present.

3. Theory: the extended phase diagram of liquid helium 3

The case of liquid helium 3 is similar to the one of helium 4, with some important differences. Predictions have been limited to the negative pressure
Figure 4. Chavanee et al.[19] studied metastable liquid helium 4 with an acoustic technique. A large pressure and density oscillation is produced at the center of a hemispherical piezo-electric transducer. This transducer is pressed against a glass plate and light is also focused at the acoustic focus. The local instantaneous density is measured from the amplitude of the light reflected at the interface between glass and liquid helium. The transmitted light is very sensitive to the possible nucleation of either crystals or bubbles at the center. The glass plate is useful to calibrate the transducer but it affects the nucleation. By removing the glass plate and recording the transmitted light, homogeneous nucleation can also be studied.

region and are shown in Fig. 3. The first difference to be noticed is that helium 3 is three times more fragile than helium 4: its spinodal pressure is predicted to be three times less negative. This is due to the larger quantum kinetic energy which makes the molar volume larger and the cohesion forces weaker in helium 3 than in helium 4. Another difference is the existence of one MD line only. The physical origin of this MD line has to do now with the Fermi liquid properties of liquid helium 3 at low temperature. As explained by Landau[14], the entropy of a Fermi liquid is proportionnal to the effective mass of quasi-particles which is an increasing function of pressure. As a result the expansion coefficient is negative at low temperature and changes sign at higher temperature when the Fermi liquid behavior is smeared out by thermal fluctuations. As summarized in Section 5, Caupin et al.[20] found experimental indications for the existence of a minimum in the spinodal line of helium 3. They also found strong theoretical arguments supporting this, as a consequence of the MD line meeting the spinodal line near 0.4 K. The case of helium 3 illustrates a property of spinodal lines which was first proposed by Speedy[12] for water.
4. Experiments on liquid helium at high pressure

In order to describe the acoustic technique which recently allowed to extend experiments far away from the stable region of liquid helium, let us start by describing what Chavanne et al.\cite{Chavanne19} measured at high pressure. As shown in Fig. 4, they used a hemispherical piezo-electric transducer to emit and focus 1 MHz sound waves. At the acoustic focus, they were able to produce a very large acoustic pressure oscillation, up to about ±20 bar despite the small acoustic impedance of liquid helium. In order to measure the instantaneous acoustic intensity at the acoustic focus, i.e. at the center of the transducer, they introduced a glass plate and measured the intensity of the light reflected at the glass/helium interface. Indeed, the reflectivity depends on the refractive index of liquid helium which is a known function of its density and is modulated by the wave.

Fig. 5 shows two pairs of recordings of sound intensity and nucleation events at the acoustic focus. In the lowest part, the “reflexion” traces are averages on 1000 acoustic bursts. The transducer is pulsed during 6 periods, and it has a finite quality factor $Q$ of order 50. This is the reason for the envelope of the detected burst. As the amplitude is increased just above a certain threshold (about 10 Volt in the excitation voltage for this particular experiment), a positive peak is detected, superimposed to the sinusoidal wave. It is due to the nucleation of a small crystal whose density is 10% larger than that of the liquid. One trace corresponds to an excitation just below the nucleation threshold. The other one, which is superimposed on the previous one, corresponds to the threshold where the nucleation probability is 0.5. The reflected light is mainly used for the measurement of the instantaneous density. Since the equation of state of liquid helium is well established, it is easy to convert densities into pressures thanks to a slight extrapolation. In this particular experiment, the solid nucleated when the density reached 0.17543 g.cm$^{-3}$, i.e. 4.3 bar above the melting line at $T=25.3$ bar where the density is 0.17245 g.cm$^{-3}$. By also studying the light transmitted through the acoustic focus, Chavanne et al. showed that the observed nucleation was influenced by the presence of the wall. As shown by the same Fig. 5, the transmitted light is very sensitive to phase changes in the acoustic focal region, so that single events could easily be detected. There is no averaging on the two “transmission” traces in the upper part of this figure. They were recorded for the same excitation and showed that nucleation is stochastic: it occurs with some probability in a certain density region. This good sensitivity allowed the measurement of the nucleation statistics as a function of sound amplitude and temperature. From all these measurements, Chavanne et al. were able to determine the activation energy $E$ and the number of nucleation sites. They found $E/k_B T \approx 10$ along the
nucleation curve, and a number of sites of order one. From this they inferred that, in their experiment, there was one small defect on the glass surface which favored the nucleation by lowering the local energy barrier more than others.

Indeed, if one had homogeneous nucleation, the energy barrier could be estimated as about 3000K from the standard equation

\[ E = \frac{16\pi \gamma^3}{3} \frac{\Delta G^2}{\Delta G} \]  

(2)

where \( \Delta G = (\rho_L/\rho_C - P_L)(P - P_m) \) is the difference in free energy per unit volume between the crystal and the liquid phase \( P_m \) is the equilibrium...
melting pressure and ρC and ρL are the respective densities of the crystal and the liquid). Furthermore, the number of nucleation sites would be of order 10⁷, the size ratio of the acoustic focal region (∼ 10 μm²) to the critical nucleus (∼ 1 nm²). Thanks to the cleanliness of their experiment, Chavanne et al. showed that it is possible to overpressurize liquid helium 100 to 1000 times more than had been previously achieved[21]. After removing their glass plate, they should be able to look for homogeneous nucleation and the possible existence of an instability around + 200 bar, as explained in Section 2. However, as we shall see now, the calibration of such experiments is not easy without a glass plate.

In the case shown in Fig.5 the acoustic intensity is moderate and the wave nearly sinusoidal. However, one can see on Fig.6 that, if the sound amplitude is very large, its shape is distorted by non-linear effects. Indeed, the sound velocity is much smaller for the minima than for the maxima of the wave. We have shown from both measurements and numerical integration of the propagation equations, that the wave minima have to be broader and smaller in amplitude than the maxima. This is due to the curvature of the equation of state, and this effect is enhanced by the focusing[22]. As a consequence, without precise knowledge of the non-linear effects, it

Figure 6. A recording by Chavanne et al.[19] of a large amplitude sound wave showing the existence of non-linear effects. The sinusoidal shape of the wave is distorted in a way consistent with the equation of state of liquid helium. The largest negative swings produce heterogeneous cavitation on the glass plate at -3 bar. The presence of such non-linear effects in the focusing of large amplitude acoustic waves makes the calibration of the density or pressure difficult when the glass plate is removed (see text).
is difficult to relate the magnitude of the positive swings or that of the negative swings to the excitation voltage. In the case shown in Fig.6, cavitition occurs if the density is low enough. In the next sections, we review experimental studies of cavitition. They were done without a glass plate to ensure that the nucleation of bubbles was homogeneous. The calibration of the density or pressure at the nucleation time was difficult.

5. Experiments on liquid helium at negative pressure

In its upper part, Fig.7 presents most of the measurements of the cavitition pressure in helium 4. The early data by Sinha et al.[23] were obtained at positive pressure near the critical point, by heating a bismuth crystal. All the others have been obtained with a acoustic method similar to the one described in the previous section. It was first introduced by Nissen et al.[24]. A hemispherical acoustic transducer focuses a high intensity sound wave and cavitition is detected optically. In the absence of glass plate, the acoustic focus is far from any wall, so that cavitition is homogeneous (it is an intrinsic property of the liquid). Nissen et al.[24] calibrated the amplitude of the focused wave by two methods. They first calculated the displacement of the inner wall of the transducer from the characteristics of its electrical resonance. They also analyzed the light scattering from the density oscillation at the focus. The two methods led to consistent results. The recent experiments by Caupin et al.[7] are shown as vertical bars between an upper bound and a lower bound. Indeed, they also used the characteristics of the electrical resonance of their transducer to calibrate their amplitude, but they noticed that, in the presence of nonlinear effects, this only gives a lower bound for the cavitition pressure. For the upper bound, they studied the cavitition voltage as a function of the static pressure in their experimental cell. The last group of data by Pettersen et al.[26] were not calibrated: the cavitition threshold was given in Volt, not in bar. For this review, we have adjusted them to agree with Nissen, and realized that this gave agreement also with the data by Caupin at low temperature. All the data by Caupin, Pettersen, Nissen and Sinha look consistent with each other. The data by Hall[27] appear to be slightly above all others. They were calibrated from a comparison with the pressure at which “electron bubbles” exploded, which can be calculated[28].

Fig.7 calls for several remarks. One first sees that it is only at low temperature that the results by Caupin discriminate between the standard nucleation theory and the more elaborate calculation done in Barcelona. Only the latter accounts for the existence of a spinodal limit. However, above about 1.5K, nucleation occurs far above the spinodal limit, and the size of the critical nucleus is rather large. Its energy can be calculated as
Figure 7. Cavitation in helium 4 (top) and in helium 3 (bottom). Comparison between experiments and theory. The standard theory models the nucleus as a bubble with a surface energy equal to the macroscopic surface tension. The low temperature measurements by Caupin et al. agree with the more elaborate calculations done in Barcelona [10], with a density functional theory which accounts for the existence of a spinodal line.
that of a bubble with a sharp surface whose energy per unit area is nothing but the macroscopic surface tension. This is the “thin wall” approximation of the “standard theory”. Nissen used the following expression for the nucleation rate per unit volume and per unit time from the work of Blander and Katz[25]:

$$J = N \left( \frac{2\gamma}{\pi m} \right)^{1/2} \exp \left( \frac{-16\pi\gamma^3}{3kT(P_\gamma - P_L)^2} \right),$$

(3)

where $N$ is the particle number density of the liquid, $m$ is the molecular mass, $\gamma$ is the surface tension, $P_{\gamma,L}$ are the respective pressures in the vapor inside and in the liquid outside the nucleating bubble. The quantity $P_{\gamma} - P_L$ is related to the departure from the equilibrium pressure $P_L - P_{\gamma}$ by the relation

$$P_{\gamma} - P_L = (P_{\gamma} - P_L)\delta,$$

(4)

where $\delta = 1 - \rho_{L}/\rho_{\gamma}$. The dashed curve in this figure is obtained with Eq.3. For this, we have written $JV\tau = 1$ and taken the product of the experimental volume $V$ by the experimental time $\tau$ equal to $2 \times 10^{-16}$ cm$^3$s, as in the experiments by Caupin and by Pettersen.

As can be seen from Eq.3, the cavitation pressure depends only logarithmically on the product $V\tau$. If we had chosen $V\tau = 4 \times 10^{-5}$ cm$^3$s as in the experiment by Sinha et al., the “standard theory” curve would have been slightly above, in better agreement with Sinha’s data. This is illustrated in the lower part of Fig.7 which concerns helium 3. In this other case, the two dashed curves respectively correspond to $V\tau = 7.3 \times 10^{-16}$ (the lowest one) and to $4 \times 10^{-5}$ cm$^3$s.

The curve labelled “nucleation line (Barcelona)” results from successive calculations[10] in the years 1992 to 2002. By using a density functional theory, the density profile of the nucleus was adjusted to minimize its energy $E$ at all temperatures and pressures. This functional accounted for the existence of a spinodal limit whose temperature variation was calculated. The nucleation line was obtained from the equation:

$$E = kT \ln (\Gamma_0 V\tau)$$

(5)

The “prefactor” $\Gamma_0$ was taken as a thermal frequency $kT/h$ divided by the typical volume of a critical nucleus (1 nm$^3$). This is not significantly different from the prefactor in Eq.3. As above, we have chosen the product $V\tau = 2 \times 10^{-16}$ cm$^3$s. The Barcelona result is close to a straight line from $T^*$ to the critical point. At the temperature $T^*$ a crossover occurs from a thermally activated nucleation regime to a quantum one where nucleation takes place by quantum tunneling through the energy barrier. The discussion of this quantum regime is beyond the scope of this review article. As explained
Figure 8. A comparison of experiments in helium 3 with the cavitation curve obtained in Barcelona[10]. The various data points correspond to the relative temperature variation of the cavitation threshold in successive experiments done at different static pressures in the experimental cell. A better agreement is found with a similar theory using a modified spinodal line. Indeed, according to extrapolations of the sound measurements by Roach[11], a shallow minimum should exist in the spinodal line. It is consistent with calculations of the expansion coefficient of liquid helium 3, which was found negative at low temperature by Caupin et al.[32].

Elsewhere[29] experimental results confirm the theoretical prediction that $T^*$ is about 0.2 K. A good agreement between theory and experiments is found after a temperature correction is applied to the data, which is due to the adiabatic cooling in the acoustic wave at low temperature[29].

Fig. 7 shows that experiments had to be done at low temperature to test the existence of the spinodal limit and check its location in the phase diagram. Of course, the evidence is clearer below about 1.5K, where the nucleation line of the standard theory crosses the spinodal line. Despite the good agreement found, some disagreement remains in the region from 1.5 to 2.2 K, below the superfluid transition. Despite the large scatter in the experimental data, one sees a cusp in the temperature variation of the cavitation pressure. Furthermore, cavitation seems to occur at a pressure which is more negative than predicted by available theories. It was also noticed by Maris[28] that, in the presence of electron bubbles, the cavitation threshold shows no such cusp. In the latter case, cavitation results from the mechanical instability of already existing seeds (the electron bubbles). There seems to be here an effect which calls for new physical arguments.
possible that the spinodal line also has a cusp where the lambda line meets it? Could it be that the prefactor has some anomaly when the temperature is increased through the lambda line? Could this be a consequence of the presence of quantized vortices in the superfluid? Since such vortices should favor cavitation[30], their existence should probably lead to an increase of the cavitation pressure, instead of the observed decrease. The observed cusp has no clear interpretation yet and obviously requires further studies.

Let us now come to the case of helium 3 (lower part of Fig.7). The high temperature data by Lezak[31] were obtained with the same method and in the same group as those by Sinha et al. for helium 4. They show good agreement with the standard nucleation theory if one takes $4 \times 10^{-5} \text{cm}^3\text{s}$ for the product $V\tau$ (upper dashed curve). As in helium 4, one needs to study cavitation at low enough temperature (below 1K for $V\tau = 7 \times 10^{-16} \text{cm}^3\text{s}$) if one looks for the existence of a spinodal limit. Caupin et al.[32] confirmed that, near $T=0$, the spinodal pressure is around -3 bar in helium 3 instead of -9 bar in helium 4. They carefully studied the temperature variation of the cavitation threshold in the range 0.1 to 0.6 K and noticed that it was found weaker than predicted by the Barcelona theory. As shown in Fig.8, they found a better agreement by using a spinodal line having a shallow minimum at 0.4K. In fact, the existence of such a minimum was also found by extrapolating the sound velocity measurements of Roach et al.[11]. It was further supported by considering the sign of the expansion coefficient in liquid helium 3, which is negative at low enough temperature where the Fermi liquid behavior is well established. Caupin et al.[32] thus concluded that liquid helium 3 shows a minimum in its spinodal line, as had been proposed for water by Speedy[12]. The reason is the same: both liquids expand instead of contracting when cooled down at low temperature, but the physical origin of the anomalous sign of $\alpha_P$ is very different in the two liquids. In the temperature range from 0.6 to 1.4 K, Caupin et al. also measured the cavitation threshold, and the agreement with the Barcelona calculation is not very good. As in helium 4, experiments indicate that cavitation occurs at a pressure which is more negative than predicted by theory. It is possible that the prefactor in the calculation is overestimated but this remaining problem also needs further study.

6. Conclusion: open questions

Liquid helium 4 and liquid helium 3 are model systems. They are extremely pure, and homogeneous cavitation can be studied in experiments using high intensity ultrasound. Furthermore, they are simple liquids and it is possible to calculate some features of their phase diagram rather accurately. During the last decade, all theoretical approaches have converged and the
spindal limits in both liquids are now well established from the theoretical point of view. Experiments at low temperature have confirmed most of the predictions and showed where the spinodal limit have to be considered to interpret cavitation. As noticed in this review, several important questions remain to be answered. Why do experiments show a singularity in the cavitation threshold at the superfluid transition temperature? Moreover, did cavitation studies measure the location of the superfluid transition in the metastable parts of the phase diagram of helium 4? Is there an instability line for the liquid-solid transition at high pressure? Is it around +200 bar as recently suggested, and could it be checked in some future experiments? Eventually, what is the superfluid transition temperature of overpressurized liquid helium 4? Some of these questions are already under experimental and theoretical investigation.

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References

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