

Very fast growth and melting of ^4He crystals

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Abstract

High intensity ultrasound waves can be used to study the nucleation of solid ^4He far above the liquid–solid equilibrium pressure. In such conditions, crystals grow and melt in a surprising way at velocities close to the sound velocity. We consider various physical mechanisms which may control the crystal dynamics.

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Keywords: Solid helium; Nucleation; Crystal growth; Shock waves

Helium is a model system to study the metastability of liquids. We have shown [1] that helium can stay liquid down to -9 bar, far below the liquid–gas equilibrium line $P_{\text{lg}}(T)$. We have also studied liquid helium several bars above the liquid–solid equilibrium line $P_{\text{m}}(T)$ [2]. To achieve high degrees of metastability, one has to avoid heterogeneous nucleation. We do this by focusing ultrasound pulses so that an intense pressure or density oscillation is produced for a short time in a small region which is free of impurities, cosmic rays, etc. Our main goal is to understand how far liquid helium can be de- or over-pressurized. Of particular interest is the possible existence of an instability line for the liquid–solid transition [3].

Of course, when liquid helium is far from equilibrium and when a more stable phase nucleates, it grows very fast. In our study of acoustic crystallization [2], we observed small crystals growing at 100 m/s, a significant fraction of the sound velocity (366 m/s in the liquid at P_{m}). The purpose of this paper is to describe this growth which is followed by even faster melting and seems to be generating shock waves.

We use a hemispherical piezo-electric transducer. It is excited at the resonance frequency of its first thickness mode (1 MHz) with a short voltage burst, typically 3–6 periods (3–6 μs). At the center, which is the acoustic focus, the amplitude of the sound wave may be as large

as ± 20 bar. In order to calibrate this amplitude as a function of the excitation voltage, we inserted a glass plate. The transducer was gently pressed against it so that the acoustic focus was at the glass/helium interface. The static pressure in the cell was P_{m} . An Ar^+ laser beam was focused on the glass surface by a small lens in the cell. The waist of the laser beam (14 μm) was small compared to the acoustic wavelength (366 μm) which was the typical size of the acoustic focus. We measured the reflection and the transmission of light at the glass/helium interface. The reflected light intensity mainly depends on the index of liquid helium, which is related to its density through the Clausius–Mossotti relation. A careful calibration allowed us to measure the local density of helium at the center of the acoustic focus. For this we averaged on 10 000 bursts because only a small fraction of the light is reflected, the part of it which is modulated by the sound wave is even smaller, and large laser powers would warm up the cell. Fig. 1 shows two pairs of signals. One of the two signals labelled “reflection” is a selective average where all bursts leading to nucleation—45% in this case—have been suppressed. It shows the sound amplitude. It was made possible thanks to the “transmission” signals which are single shot recordings and clearly discriminate between nucleation and no nucleation. The other “reflection” signal, which is superimposed on the first one, is a full average which shows the nucleation of solid helium since its density is larger than that of the liquid.

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From the amplitude of the reflected signals, we estimated the average size of crystals. At very large excitation, they grew larger than the laser waist, and the signals saturated at a the solid density. We found a saturation at 0.191 g/cm^3 , meaning that our crystals are HCP. At intermediate excitation amplitude, since we knew the density difference between liquid and solid, and the size of the laser waist, we could measure the crystal radius as a function of time. In the case of Fig. 1, the maximum radius is about $3 \mu\text{m}$. At higher excitation (and lower temperature, Fig. 2), it is $9 \mu\text{m}$.

Let us now examine the time evolution of crystals on Fig. 1. Since the nucleation probability depends exponentially on the liquid density, nucleation takes place very close to the wave maximum for bursts close to the

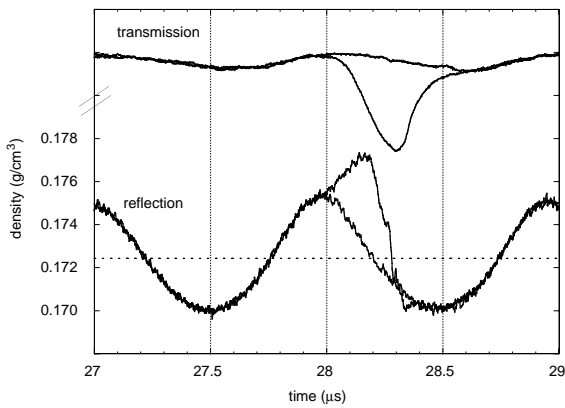


Fig. 1. The reflected and transmitted signals at low amplitude with an acoustic burst of 6 oscillations. The time origin is at the beginning of the excitation burst. The flight time from the transducer surface to the acoustic focus is $22 \mu\text{s}$. $T = 600 \text{ mK}$.

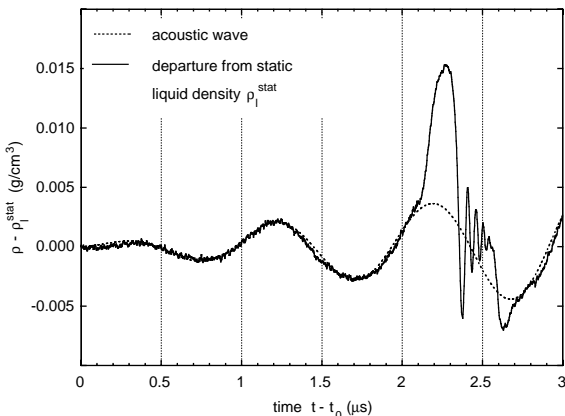


Fig. 2. At large sound amplitude, and 100 mK the crystal collapse generates an oscillating shock wave in the liquid (see text). The time t_0 is when the acoustic burst reaches the acoustic focus.

nucleation threshold (here, 0.003 g/cm^3 above the static liquid density ρ_1^{stat}). The maximum growth velocity is 16 m/s . The crystal melts as soon as the negative swing of the wave starts, i.e. 250 ns later. Melting proceeds even faster than growth and the density reaches a value lower than produced by the acoustic wave only. At this time, $28.3 \mu\text{s}$ on this figure, the crystal has completely melted but the little negative overshoot of the recorded density shows that a depression in the liquid accompanies the crystal collapse. This is likely to be a consequence of the fast mass flow which is produced by the melting. At that time, the “transmission” signal is still large, but this might be due to the time constant of the photomultiplier tube used for the detection of the transmitted light. For the reflected light an avalanche photodiode was used which had a much faster response time. It would be interesting to calculate the time evolution of the density, pressure and velocity fields, in order to see if the above scenario is correct.

Let us finally consider the signal at larger excitation and lower temperature (Fig. 2). Crystals now nucleate before the acoustic wave reaches its maximum. The growth velocity reaches 100 m/s . It is surprising to see that crystals start melting 150 ns before the negative acoustic swing starts. A future calculation could explain if this is due to some variation of the pressure in the solid, or to a local heating produced by the very fast growth, or to something else. Furthermore, the crystal collapse now shows an oscillating structure which is superimposed on a rebound followed by another depression before the density goes back to the level of the acoustic wave alone. The oscillation could be a shock wave generated in the liquid by the crystal collapse. If true, the wavelength of this shock wave should be related to the typical length scale in this problem, that is the crystal radius. In fact the time period being $\tau \approx 50 \text{ ns}$ on Fig. 2, this corresponds to a wavelength $\lambda = c\tau \approx 18 \mu\text{m}$, i.e. twice the maximum crystal radius. We have checked that the oscillation period is roughly proportional to the maximum crystal size at even larger excitation. As above, we hope that this scenario can be supported by a calculation.

We are grateful to M. Ben Amar, M. Brenner, J. Rice and H. Stone for stimulating discussions on this subject.

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