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Propagative modes along a superfluid helium-4 meniscus

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Abstract. – We have studied the dynamics of a superfluid helium-4 meniscus on a solid substrate. In a pseudo–non-wetting situation, there is no hysteresis of the contact angle. We show that distortions of a liquid meniscus do propagate along the contact line. We have analyzed the propagation of pulses. We find a good agreement with theoretical predictions by Brochard for the dispersion relation of oscillation modes of the contact line.

For an ordinary liquid, the motion of the contact line, where the liquid-vapour interface meets the substrate, is strongly overdamped. This may be due to viscous dissipation associated with shear stress in the liquid wedge, or pinning of the contact line (CL) on defects of the substrate. As a consequence, the oscillation modes of the CL exhibit a purely diffusive relaxation [1, 2]. The theoretical prediction by Cheng *et al.* [3] that cesium is not wetted by helium-4 at low temperature has triggered a large number of experiments since 1991. Indeed, superfluid helium-4 can be considered as a model system for studying wetting and prewetting transitions, since it is an extremely pure liquid, whose thermodynamic properties are both well documented and well understood. However, many observations have revealed that the disorder of the cesium substrate is responsible for hysteresis and dissipation [4, 5]. Despite the liquid superfluidity, the pinning of the CL on surface defects prevents any observation of inertial effects. For instance, propagative oscillation modes of the contact line ("triplons") have never been observed.

Recently, we have shown that pseudo-dewetting of superfluid helium can occur on ordinary wettable surfaces [6]. This is an unconventional situation where a meniscus with a finite contact angle does coexist with a thick film. This is due to a superfluid current in the meniscus which leads to a decrease in the disjoining pressure. In the context of CL oscillation modes, pseudo-dewetting has two important features. First, we did not measure any hysteresis. Second, the Bernouilli pressure modifies the meniscus profile with respect to an equilibrium one only in close vicinity of the contact line (the size of the matching region between the equilibrium meniscus and the thick film is of the order of $1\,\mu$m). Thus, as long as the wavelength of the CL deformation is much larger than the core region of the CL, one is allowed to forget the core structure of the CL, and this pseudo-contact line should behave as an ordinary CL

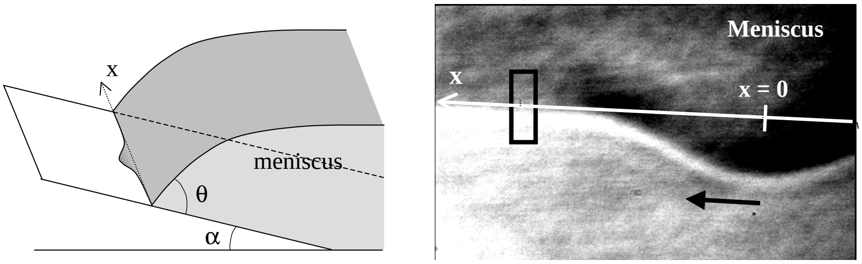

Fig. 1 – Left: schematic representation of the meniscus. Right: image of the distorted meniscus from above ($\theta = 3°$); we have also shown the geometry of the PM slit (the slit size is 0.38×1.1 mm^2).

in a partial wetting situation. Pseudo-dewetting of superfluid ^{4}He thus provides a unique opportunity to check the existence of triplons. In this paper, we report on the first observation of those propagative modes. We have analyzed the propagation of deformation pulses, which is in good agreement with theoretical predictions by Brochard [7].

Experiments are performed in an optical helium-4 cryostat. The substrate is tilted with respect to the horizon by an angle α, which can be varied from 1 to 10° (see fig. 1). The pseudo-contact angle θ between the substrate and the liquid-vapour interface can be varied from zero at the superfluid transition up to 6° at $T = 1.1$ K.

Thanks to a low-temperature interferometer, we can obtain the profile of the whole liquid-vapour interface (see [8] for details). A more accurate determination of the CL location is done with white-light illumination and standard strioscopy techniques which increase the contrast between the parts of the substrate covered by the film and those covered by the meniscus (fig. 1). However, the low value of the optical index of liquid helium-4 has prevented us from using values of θ smaller than 3°.

A local distortion of the CL is produced by heating the substrate with a laser beam. This increases the liquid height due to the fountain effect. When using a short illumination pulse, the distortion propagates along the CL. The typical duration of the illumination is 10 ms. It produces an initial bump of the CL of typical amplitude 200 μm, and of typical width 1 mm (see fig. 1). In order to measure the propagation of the distortion, a photomultiplier tube (PMT) equipped with a slit is positioned in the image plane of the substrate, at a distance x from the center of the laser spot, the slit being perpendicular to the mean direction of the CL. The output $S_x(t)$ of the PMT is thus approximately proportional to the displacement $\eta_x(t)$ of the CL with respect to its equilibrium position. As soon as x is larger than 1 mm, the signal amplitude is in a range from 5 to 50 μm, which is comparable to noise due to residual vibrations. Thus, we had to average the signal over typically 50 runs. Very long averaging is forbidden because of a slow drift of the interface. This drift causes the laser spot to move with respect to the CL and changes the magnitude of the initial bump. Together with large-scale inhomogeneities of the contrast, this drift leads to a slow variation of $\partial S/\partial \eta$, and explains why the amplitude of the PMT signal $S_x(t)$ is only approximately proportional to the displacement $\eta_x(t)$ of the CL.

An example set of signals $S_x(t)$ is shown in fig. 2, for several values of x ranging from 1 to 6 mm. The propagation is clearly dispersive. Despite a possible slow variation of the sensitivity, a strong attenuation is observed for $x < 1$ mm. For such values of x, the analysis is difficult because a second pulse is emitted in the opposite direction. We thus focus on signals obtained for $x > x_0 \simeq 1.5$ mm. As explained by Brochard [7], two different regimes are expected for triplons, depending on whether the wave vector q is smaller or larger than

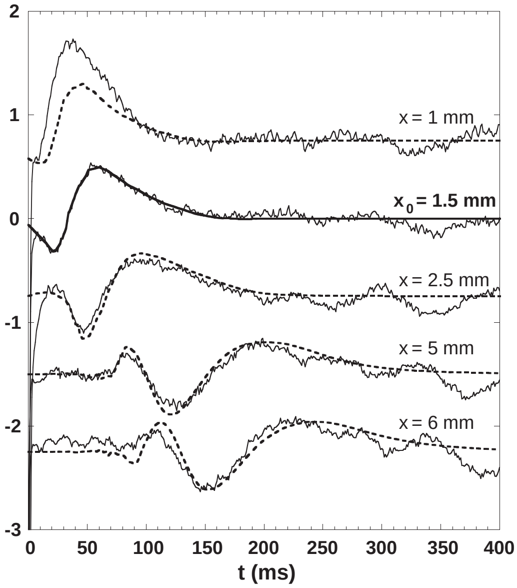

Fig. 2

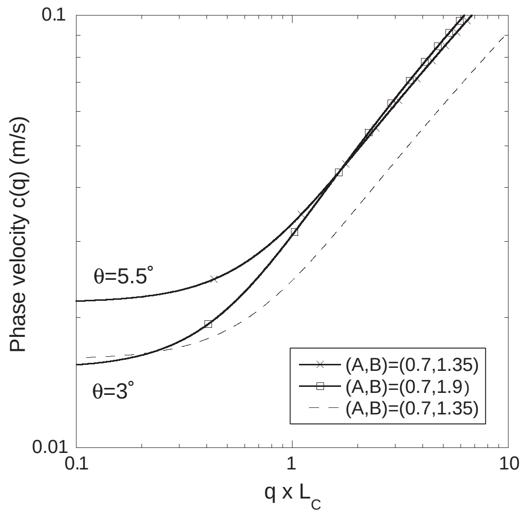

Fig. 3

Fig. 2 – PMT signals $S_x(t)$ are plotted as a function of time t for various positions x along the CL. The solid lines are computed from the reference signal at $x_0 = 1.5\,\mathrm{mm}$, using the interpolated dispersion relation for triplons.

Fig. 3 – Phase velocity $c(q)$ of triplons. The solid lines correspond to the best fits to experimental data for $\theta = 5.5°$ and $\theta = 3°$ (the fitted parameters (A, B) are respectively equal to (0.7, 1.35) and (0.7, 1.9)). The dashed line is the expected $c(q)$ at small angle for $(A, B) = (0.7, 1.35)$. The experimental range for qL_C is 0.3–1.5.

the inverse of capillary length $L_\mathrm{C} \equiv \sqrt{\gamma/\rho g}$; γ is the liquid-vapour surface tension, ρ is the liquid density and g is the acceleration of gravity. At low temperature, $L_\mathrm{C} \simeq 0.5\,\mathrm{mm}$. For $q > 1/L_\mathrm{C}$, the restoring force is due to the surface tension and one expects the dispersion relation to be: $\omega \sim \sqrt{\gamma\theta/\rho}\, q^{3/2}$. For $q < 1/L_\mathrm{C}$, the restoring force is the gravity and one finds that the propagation is non-dipersive with a velocity $c \sim \sqrt{g\theta/L_\mathrm{C}}$. The initial bump size is of the order of the capillary length, so that those asymptotic expressions for the dispersion relation cannot be used to analyze the experimental data quantitatively. We have derived an interpolated expression for the dispersion relation. An exact expression for the elastic energy f_el associated with a CL distortion has been derived by Sekimoto *et al.* for $\alpha = 0$ [9]. For a perturbation of wave vector q and amplitude u_q, they find $f_\mathrm{el} = \gamma\theta^2[(q^2 + L_\mathrm{C}^{-2})^{1/2} - L_\mathrm{C}^{-1}]u_q^2$. The dispersion relation then reads: $f_\mathrm{el} = m_q\omega^2 u_q^2$, where m_q is the mass per unit length of the moving part of the meniscus. At high q, one expects m_q to scale like $\rho\theta/q^2$; at low q, one expects m_q to scale like $\rho\theta L_\mathrm{C}^2$ [7]. To our knowledge, the exact expression for m_q has not been calculated. Thus, we have arbitrarily chosen the following simple interpolation: $m_q = A^2\rho\theta/(L_\mathrm{C}^{-2} + B^2q^2)$, where A and B are numerical constants, expected to be of order 1. This allows us to obtain the following analytical expression for the dispersion relation:

$$\omega(q) = A^{-1}\sqrt{2g\theta L_\mathrm{C}}\, q \sqrt{\frac{1 + B^2q^2L_\mathrm{C}^2}{1 + \sqrt{1 + q^2L_\mathrm{C}^2}}}\,. \tag{1}$$

Comparison with the experimental data is done in the following way. First, we smooth the signal $S_{x_0}(t)$ in order to remove the high-frequency components (solid curve in fig. 2), and Fourier-transform it to obtain $\widetilde{S}_{x_0}(\omega)$. Then, the signal $S_x(t)$ at any position $x > x_0$ is computed by propagating the components of $\widetilde{S}_{x_0}(\omega)$ with the phase velocity $c(\omega) \equiv \omega/q$, without any attenuation. As shown in fig. 2, the shapes of the computed signals do fit quite well the experimental ones. For this particular experiment, we find that the best fit is obtained for $A = 0.70 \pm 0.05$ and $B = 1.35 \pm 0.05$. These values are of order one, as expected. We can also propagate the pulse backwards, and compute $S_x(t)$ for $x < x_0$. The shape of the pulse is rather well described, but the calculated amplitude is too small. As explained before, this is likely to be due to the emission of a symmetric pulse.

In order to test the contact angle dependence of the dispersion relation, experiments have been performed for θ in a range from 3° to 6°. The same fitting procedure has been applied. For $\theta > 4°$ we find the same values for (A, B), within experimental uncertainties. For smaller angles $\theta \simeq 3°$, we still find $A \simeq 0.7$, but the best value for B is about 1.9. Our results are summarized in fig. 3. We have plotted the velocity $c(q)$ obtained from the interpolated dispersion relation and from the fitted parameters for two values of the contact angle. We find that $c(q)$ decreases with θ in the gravity regime ($q < 1/L_{\mathrm{C}}$), and this decrease has the predicted amplitude. For q larger than $1/L_{\mathrm{C}}$, the velocity does not seem to depend on θ. We have checked that this conclusion is not sensitive to the shape of the crossover between the gravity and the capillary regime. However, one should realize that the wave vector range is restricted in our experiment. This range is related to the shape of the pulse and is limited between $0.3/L_{\mathrm{C}}$ and $1.5/L_{\mathrm{C}}$. Moreover, the generation and detection of pulses is more difficult for small contact angle, and uncertainty in the fitted parameters is larger. A precise test of the $\theta^{1/2}$-dependence of $c(q)$ would require also a larger range of contact angles.

The quantity $L_{\mathrm{C}}\theta$ which appears in the dispersion relation is nothing but the meniscus height h. Thus, the dispersion relation of triplons is similar to the one of surface waves in shallow water, h being the liquid height: triplons can be considered as surface waves localized at the contact line. As a consequence, one may wonder whether we do observe a true line (1D) wave, or simply the edge of a surface (2D) wave propagating all over the helium pool. Indeed, the technique that we use to create the initial bump of the CL does generate both an oscillation of the CL and an oscillation of the liquid-vapour interface. Images of the velocity field can be obtained by subtracting two successive interferograms of the liquid-vapour interface. This is shown in fig. 4, where successive images are displayed. After the pulse emission, a fast travelling 2D wave is clearly visible. We also observe a 1D wave propagating along the meniscus; its velocity is noticeably smaller than the 2D wave, as the triplon can be observed after the surface wave has disappeared. Let us also stress that we obtain a good fit of experimental signal without any attenuation, as soon as the distance from the pulse center is larger than 1 mm (see fig. 2). This is different from a 2D situation, for which one expects a $1/x$ decrease of the signal.

In order to check quantitatively whether the propagation along the contact line is different from the propagation of the surface wave, we have repeated the experiments for different tilt angles α of the substrate: 1.5° and 10° (in the first experiment $\alpha = 4.5°$). We have chosen to keep $\theta \simeq 5°$, which makes the signal detection easier. When α increases, so does the liquid height away from the CL, and so does the velocity of the surface wave. We have measured the velocity 5 mm away from the CL, and we have found that the typical velocity is about 3 times larger for $\alpha = 10°$ than for $\alpha = 1.5°$. However, the pulse propagation along the CL is only weakly sensitive to the value of α. For small tilt angle ($\alpha = 1.5°$), signals are well fitted with the same dispersion relation. We find that the best value for (A, B) is (0.7,1.35),

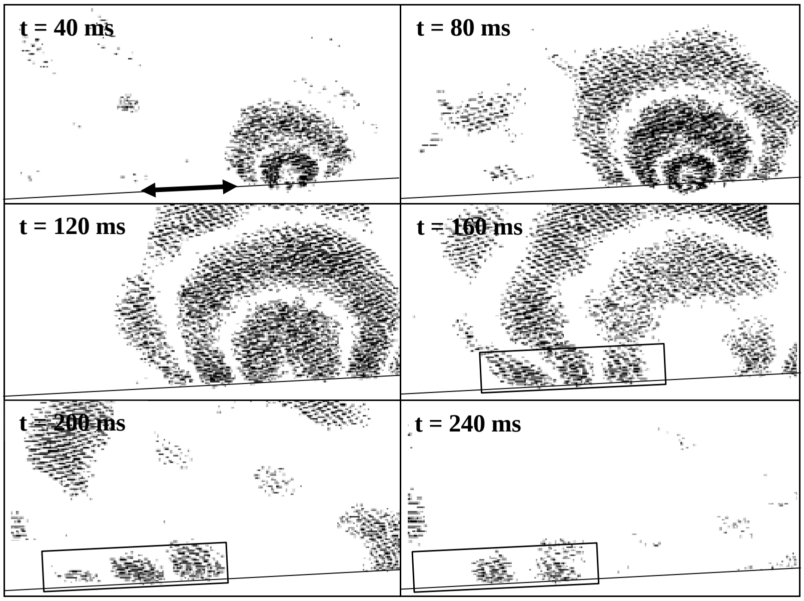

Fig. 4 – Interferometric images of the liquid surface during the propagation of a pulse (time interval: 40 ms; actual image size 23×17 mm^2). The velocity of the surface wave is higher than the velocity of the disturbance along the line (in the rectangular box). The decoupling between the 2D and the 1D wave demonstrates that we measure the propagation of a 1D mode localized at the CL. The arrow in the first image corresponds to the typical range for the PM position.

the same as in the first experiment. For large tilt angle ($\alpha = 10°$), the best fit is found for $(A, B) = (0.7, 1.9)$. This value of B means that, at high q, the 1D wave propagates faster at large tilt angle than at small tilt angle. As previously, the numerical values of (A, B) should be considered as estimates, because of the narrow experimental range in q. Yet, it is clear that there is some dependence on α at fixed contact angle $\theta \simeq 5°$.

One may notice that we find the same fitting parameters for $\alpha = 10°$ and $\theta = 5°$ than for $\alpha = 4.5°$ and $\theta = 3°$. We have made further measurements for other values of α and θ. It turns out that we found $(A, B) \simeq (0.7, 1.35)$ when $\theta \geq \alpha$, and a higher value of B when $\theta < \alpha$. This could mean that the precise features of either the elastic energy f_{el} or the velocity field depend on the curvature of the meniscus. Indeed, f_{el} has been calculated for $\alpha = 0$, and the inertia associated with the 1D wave is evaluated using scaling arguments.

In summary, we have observed for the first time the propagation of contact line oscillation modes. These triplons can be considered as a localized surface wave in shallow water. Pulse propagation is well described by a dispersion relation derived by interpolating in an empirical way between the gravity and the capillary regime. However, this dispersion relation does not accurately account for the dependence on the contact angle. We also observe an unexpected tilt angle dependence. A more precise calculation of the inertia associated with triplons would be needed to allow a precise comparison with the experimental results.

As a final remark, let us compare the present experiment with the CL dynamics on disordered substrates. It was shown by Prevost *et al.* [10] that the CL moves through fast jumps (avalanches) from a pinned configuration to the next one. The edge of depinning area was found to move laterally with a velocity v_{lat} of about 4 cm/s for $\theta = 10°$ (fig. 6 in ref. [10]).

We have analyzed depinning events for $\theta = 6°$, and found $v_{\rm lat} \simeq 2.5\,{\rm cm/s}$. Those values of the velocity are close to the velocity of triplons at low q. This is a strong evidence that the inertia plays an important role in the avalanche dynamics, as suggested by Prevost.

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