Experimental Measurements of ^{4}He Solid-Liquid Interface Inertia

To cite this article: J. Poitrenaud and P. Legros 1989 *EPL* **8** 651

EUROPHYSICS LETTERS 1 April 1989

Europhys. Lett., 8 (7), pp. 651-656 (1989)

Experimental Measurements of ^{4}He Solid-Liquid Interface Inertia.

J. POITRENAUD and P. LEGROS

Laboratoire d'Ultrasons (*), *Université Pierre et Marie Curie*
Tour 13, 4 place Jussieu, 75252 Paris Cedex 05, France

(received 14 December 1988; accepted 30 January 1989)

PACS. 67.80 – Solid helium and related quantum crystals.
PACS. 64.70D – Solid-liquid transitions.
PACS. 81.10F – Growth from melts.

Abstract. – We have measured the transmission of acoustic waves through a rough ^{4}He superfluid interface at 15, 45 and 75 MHz between 0.4 and 1.1 K. The phonon transmission is enhanced at low temperatures for the higher frequencies, in place of rapidly decreasing with T as explained by the high mobility interface theory. These experimental results are very well interpreted with the help of the surface inertia introduced by Puech and Castaing.

1. Introduction.

We report measurements of the temperature dependence of the transmission coefficient of high frequency (15, 45 and 75 MHz) sound waves at the rough ^{4}He superfluid-solid interface, and we give their interpretation. Previous experiments of Castaing, Balibar and Laroche (CBL) [1] reinterpreted by Castaing (C) [2] at 1 MHz and of Moelter, Manning and Elbaum (MME) [3] at 10 MHz show that sound transmission is a very good tool to study ^{4}He crystal growth. For temperatures above the roughening transition, melting is a very fast process and the transmission of sound is affected. It was found to rapidly decrease as the temperature is lowered although the acoustic mismatch theory predicts temperature independence. However, in the case of infinite interface mobility at low temperatures the transmission is expected to be partially restored if the work of tension forces at the interface is taken into account. This theory due to Marchenko and Parshin [4] predicts a frequency dependence of the sound transmission and a T^{-5} variation of the Kapitza resistance R_K as experimentally observed. But the order of magnitude of the calculated value of R_K is too high. In a modified version of fast melting theory Puech and Castaing (PC) [5] have introduced the notion of growth-inertia. This new concept, purely phenomenological, reconciles the experience and the theory. But the calculation incorporates the effect of a wide band of phonons. This fact triggered our interest to investigate directly the transmission of a high-frequency monochromatic ultrasound wave through a rough ^{4}He interface.

(*) Associated with the Centre National de la Recherche Scientifique.

2. Theory.

According to PC and Uwaha and Nozières [6], in the hydrodynamical regime, a very small difference between the chemical potentials between liquid and solid $\Delta\mu$ results in a mass current J through the interface such as

$$\Delta\mu = (\sigma/\rho_L \rho_C)\dot{J} + K^{-1} J ; \tag{1}$$

K^{-1}, a friction coefficient, is the inverse interface growth coefficient; σ can be interpreted as the interface mass per unit area. ρ_L and ρ_C are, respectively, the densities of the liquid and of the crystal. We add to eq. (1) the mass conservation equation $J = \rho_C(V_C - V) = \rho_L(V_L - V)$, where V, V_C and V_L are the components of, respectively, the interface velocity and the solid and liquid phase velocities perpendicular to the interface and the momentum conservation equation $\delta p_L = \delta p_C$, where δp_L and δp_C are the pressure variations in the liquid and in the solid. The amplitude τ of the transmitted energy is easily deduced:

$$\tau = 4 z_L z_C / |z_L + z_C + z_L z_C/\zeta|^2 ; \tag{2}$$

z_L and z_C are the acoustic impendances of the liquid and the crystal and ζ can be defined as a complex interface impedance which is the sum of an inertial impedance ζ_σ and a friction one ζ_K:

$$\zeta = \left(\frac{\rho_C \rho_L}{\rho_C - \rho_L}\right)^2 \left(K^{-1} + \frac{i\omega\sigma}{\rho_C \rho_L}\right) = \zeta_K + i\zeta_\sigma . \tag{3}$$

More rigorously we have to consider the heat emission on both sides of the interface associated to melting or growth. The full calculation [7] shows that the isothermal growth coefficient K has to be replaced by an effective growth rate K_{eff}. This correction can be neglected at least in a first approach [8]. From eqs. (2) and (3) τ can be written

$$\tau = \frac{4 z_L z_C}{(z_L + z_C + z_L z_C \zeta_K/|\zeta|^2)^2 + (z_L z_C \zeta_\sigma/|\zeta|^2)^2} . \tag{4}$$

Keshishev, Parshin and Babkin (KPB) [9], who deduced K from the damping of crystallization waves, have shown that the mobility of a ^{4}He rough interface is limited by the bulk thermal excitations, that is, by the rotons of the liquid and the phonons of the liquid and the solid according to the first ideas of Andreev and Parshin [10]. This was confirmed by subsequent sound transmission experiments [1-3] or by the Bodenshon-Leiderer (BL) [11] and Leiderer (L) [12] analysis of the relaxation of the interface when the ion pressure is released. K^{-1} consists in three terms:

$$\rho_C K^{-1} = A + BT^4 + C \exp[-\Delta/T] . \tag{5}$$

The first term is interpreted as a residual damping varying from sample to sample. Δ is the minimum roton energy. Equation (5) shows that the growth resistance and consequently ζ_K rapidly decrease when the temperature is lowered. Using the previous experimental value of K^{-1} and PC estimation of σ it can be calculated that ζ_σ becomes larger than ζ_K at $T \leq 0.5$ K if the frequency $\nu = 30$ MHz. Consequently it is expected that at sufficiently high frequency the ultrasound transmission coefficient instead of decreasing continuously when T is lowered tends towards a constant value.

3. Experimental conditions.

The experiments have been performed at three frequencies 15, 45 and 75 MHz and between 0.4 and 1.1 K. Melting or growth are controlled by subtracting or adding ^{4}He at constant pressure through a capillary. Ultrasound pulses, 5 μs width, were generated and detected by two 15 MHz lithium niobate transducers. The acoustic path length (1.65 cm) between the two transducers has been determined using the existing sound velocity data of liquid helium [13]. The thickness h_C of the as-grown crystal and the velocity af sound C_C have been deduced from the analysis of successive transmitted pulses. The crystallographic orientation of the sample is determined from the sound velocity [14]. We have observed the amplitude dependence of the attenuation α above some incident power level P_{max} and always used incident power lower than P_{max}. α expressed in dB can be written under the form: $\alpha = 10\log(\tau/\tau_0) + h_L\alpha_L + h_C\alpha_C$, where α_L and α_C are the attenuation coefficients of the bulk liquid and solid in dB/cm, h_L is the height of liquid and τ_0 which depends on the setting of the apparatus has to be determined for each sequence. α_L has been measured when the cell is full of ^{4}He liquid. Our results were in complete agreement with the very accurate measurements of Roach *et al.* [15]. If α_L is very small (< 0.1 dB/cm) at low temperatures (< 0.6 K), α_L reaches 20 dB/cm at 75 MHz and $T = 1$ K. We have measured in the same way α_C in the cell full of solid for different samples. At low temperatures the interface mobility becomes very important and surface vibrations redhibitory. To sum up we have evaluated the precision on α to be ± 2 dB.

4. Results.

Figure 1 shows an example of the temperature dependence of τ_0/τ for three samples at different frequencies, after correction for α_L and α_C effects. Keeping in mind that the vertical shift τ_0 is arbitrary and does not vary with T, one remarks the different behaviours of τ with T at different ν: for the same sample at high temperatures (> 0.8 K) the variation is identical whatever the frequency; on the contrary at low temperatures we distinguish between the frequencies: at 15 MHz τ continuously decreases with T until becoming unmeasurable; for the higher two frequencies τ tends towards a constant value. If we shift vertically the curves to superpose them at high temperatures (as we do for sample *c* in fig. 1), it appears more clearly that τ is a function of frequency. Hence we have been very tempted to interpret this behaviour as the liquid-solid interface inertia signature.

Six coefficients A, B, C, Δ, σ and τ_0 are to be determined from the $10\log\tau/\tau_0$ data. Our method has been as follows: as a function of temperature two limit-domains can be settled. For high temperatures $T > 0.8$ K the rotons monitor the interface mobility and the inertial interface impedance ζ_σ is negligible, consequently from (4) and (5)

$$\frac{\tau}{\tau_0} \cong \frac{4\,z_L\,z_C/\tau_0}{(z_L + z_C + \eta/(C\exp[-\Delta/T]))^2}. \tag{6}$$

We introduce $\eta = z_L z_C(\rho_C - \rho_L)^2/\rho_C/\rho_L^2$. At low temperatures $T < 0.8$ K the acoustic impedances z_L and z_C become negligible with regard to ζ_K and ζ_σ, then

$$\tau/\tau_0 \cong 4z_L z_C/\tau_0[(A + BT^4 + C\exp[-\Delta T])^2 + (\sigma\omega/\rho_L)^2]/\eta^2. \tag{7}$$

Taking $\Delta = 7.2$ K which is the real roton gap from neutron measurements we deduce A, B, C and σ from (6) and (7) by least-square adjustments. The subsequent fit between experimental points and calculated τ curves is illustrated by fig. 2. Table I gives A, B, C and σ values.

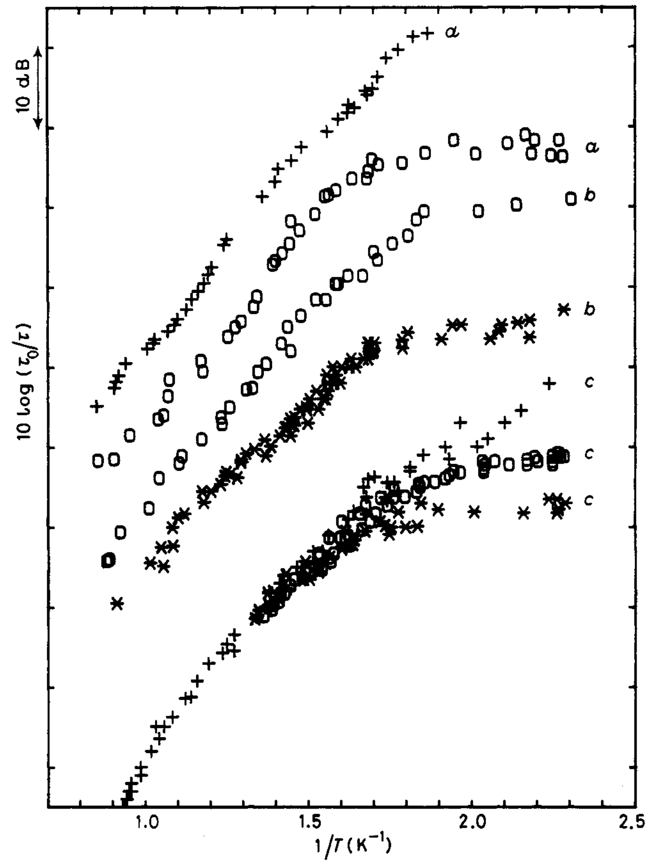

Fig. 1. – Experimental dependence of 10 log(τ_0/τ) *vs.* $1/T$ for samples *a*, *b*, *c*, at 15 MHz (+), 45 MHz (○), 75 MHz (*).

5. Discussion.

The pre-exponential factor C is calculated by other authors using $\Delta = 7.8$ K. They found (for $\rho_C K^{-1}$ in cm/s): $C = 3.3 \cdot 10^5$ (KPB), $C = (4.6 \pm 0.9) \cdot 10^5$ (C, L), $C = (5.3 \pm 0.4) \cdot 10^5$ (MME).

TABLE I.

Sample	C_C (m/s)	Frequency (MHz)	A (cm/s)	B (cm/s/K^4)	$C \cdot 10^{-5}$	$\sigma \cdot 10^{10}$ (g/cm^2)
a	538	15	0.04 ± 0.04	5.4 ± 0.6	0.72 ± 0.13	3.1 ± 0.2
		45	0.65 ± 0.2	0.02 ± 0.01	0.72 ± 0.13	3.1 ± 0.2
b	520	45	0.6 ± 0.2	8.5 ± 0.8	2.9 ± 0.3	7.1 ± 0.4
		75	1.34 ± 0.2	18 ± 2	2.5 ± 0.3	7.1 ± 0.4
c	540	15	0.04 ± 0.2	1.95 ± 0.2	0.29 ± 0.10	1.6 ± 0.2
		45	0.00 ± 0.01	3.3 ± 0.1	0.29 ± 0.10	1.5 ± 0.1
		75	0.06 ± 0.02	3.1 ± 0.2	0.29 ± 0.10	1.7 ± 0.1

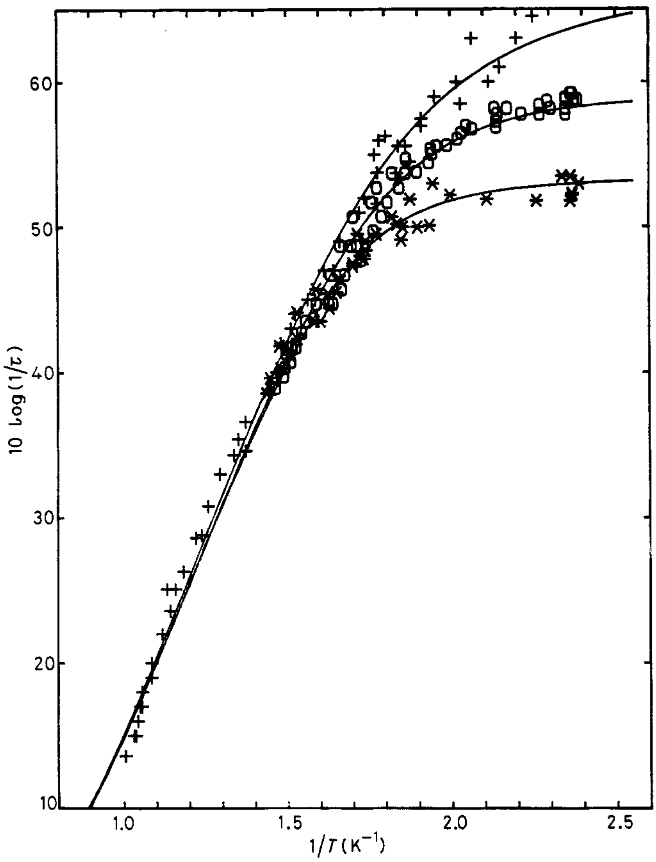

Fig. 2. – Comparison between the temperature dependence of the sound transmission data for sample c and the fit which is described in the text. $\Delta = 7.2$ K.

MME also give $C = (3.3 \pm 0.2) \cdot 10^5$ with $\Delta = 7.2$ K. On the other hand, PC estimation of σ is $2.4 \cdot 10^{-10}$ g/cm^2. For comparison our C and σ values for $\Delta = 7.8$ K would be as given in table II.

The value of Δ is a problem: either one fits Δ as a free parameter or one introduces the value deduced from neutron data; as KPB suggested, difficulty comes probably from a temperature dependence of C.

Clearly the ultrasound method is not the best way to measure Δ. Its great interest is to give directly σ. We emphasize that for the same sample the same σ value permits to take into account the variation of τ_0/τ at all the frequencies. This is illustrated in fig. 3 where it can be seen that the extrapolated values at $T = 0$ of $\tau\eta^2/(4z_L z_C)$ at 15, 45 and 75 MHz vary quadratically with ν as is expected (eq. (7)).

TABLE II.

Sample	Frequency (MHz)	$C \cdot 10^{-5}$	$\sigma \cdot 10^{10}$ (g/cm^2)
a	15; 45	2.3 ± 0.4	4.6 ± 0.5
b	45; 75	7.2 ± 1	10.5 ± 0.5
c	15; 45; 75	1.5 ± 0.3	3.9 ± 0.5

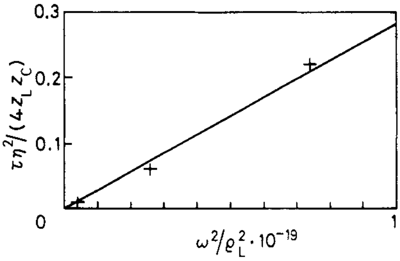

Fig. 3. – $T = 0$ extrapolated values of $\tau\eta^2/(4z_L z_C)$ *vs.* ω^2/ρ_L^2 for sample c at $\Delta = 7.2$ K. The slope of the obtained straight line is σ^2.

Furthermore the anisotropy of σ has been put in evidence, contrary to R_K analysis, because R_K measures an average thermal phonon transmission.

6. Conclusion.

We have presented an extension of previous measurements of ultrasound transmission through a rough ^{4}He interface at frequencies which allow one to get a clear evidence of liquid-solid interface mass inertia σ and its anisotropy. Additionally the values of the mobility coefficient K determined from our data agree with those of previous studies. Nevertheless it would be eminently desirable to have at our disposal a complete theory of the temperature dependence of the K roton contribution to confrontation between experimental and theoretical values of σ.

* * *

We gratefully acknowledge J. JOFFRIN who has suggested this study and paid continuous attention, A. LEVELUT for fructuous discussions all along this work, C. FRENOIS for precious advices on ultrasonic technique and J. SERVAIS for his help with the adjustment of the electronic devices. We would like equally to thank S. BALIBAR and F. GALLET for enlightening advice.

REFERENCES

[1] CASTAING B., BALIBAR S. and LAROCHE C., *J. Phys. (Paris)*, **41** (1980) 897.
[2] CASTAING B., *J. Phys. (Paris) Lett.*, **45** (1984) L-233.
[3] MOELTER M. J., MANNING M. B. and ELBAUM C., *Phys. Rev. B*, 34 (1986) 4924.
[4] MARCHENKO V. I. and PARSHIN A. Y., *JETP Lett.*, **31** (1980) 724.
[5] PUECH L. and CASTAING B., *J. Phys. (Paris) Lett.*, **43** (1982) L-601.
[6] UWAHA M. and NOZIÈRES P., *J. Phys. (Paris)*, **46** (1985) 109.
[7] NOZIÈRES P. and UWAHA M., *J. Phys. (Paris)*, **48** (1987) 389.
[8] POITRENAUD J. and JOFFRIN J., *Phys. Rev. B*, **37** (1988) 3963.
[9] KESHISHEV K. O., PARSHIN A. YA. and BABKIN A. B., *Sov. Phys. JETP*, 53 (1981) 362.
[10] ANDREEV A. and PARSHIN A., *Sov. Phys. JETP*, 48 (1978) 763.
[11] BODENSHOHN J. and LEIDERER P., *Proceedings of the IV International Conference on Phonon Scattering in Condensed Matter* (Springer Verlag, Berlin) 1984, p. 266.
[12] LEIDERER P., *Physica B+C*, **126** (1984) 92.
[13] MAYNARD J., *Phys. Rev. B*, **14** (1974) 3868.
[14] CREPEAU R. H., HEYBEY O., LEE D. M. and STRAUSS S. A., *Phys. Rev. A*, 3 (1971) 1162.
[15] ROACH P. R., KETTERSON J. B. and KUCHNIR M., *Phys. Rev. A*, 5 (1972) 2205.